Acoustic/GPS measurements of seafloor crustal deformation study in Taiwan

H. Y. Chen, M. Ando, C. H. Lin, S. B. Yu

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GPS

何謂GPS及其發展
其全名為”NAVigation Satellite Timing And Ranging/ Global Positioning System”是一種以衛星為主的無線電定位及時間傳播系統，由美國國防部設計、出資、使用及運轉的系統。

無論如何，這個系統以目前使用者來說，民間使用者是明顯的多過於軍方使用者

汽車導航

- GPS提供準確的位置(時間系統)
- GIS提供圖籍(座標系統)
- AI智慧的連結
- Update定期更新

GPS定位基本理論

GPS衛星測量是利用GPS衛星所發射的無線電訊號，以測定點位的三度空間坐標的定位系統，基本上是距離的量測，亦即量測未知點與已知位置衛星之間的瞬時距離，主要的觀測量為:虛擬距離觀測量及載波相位觀測量。

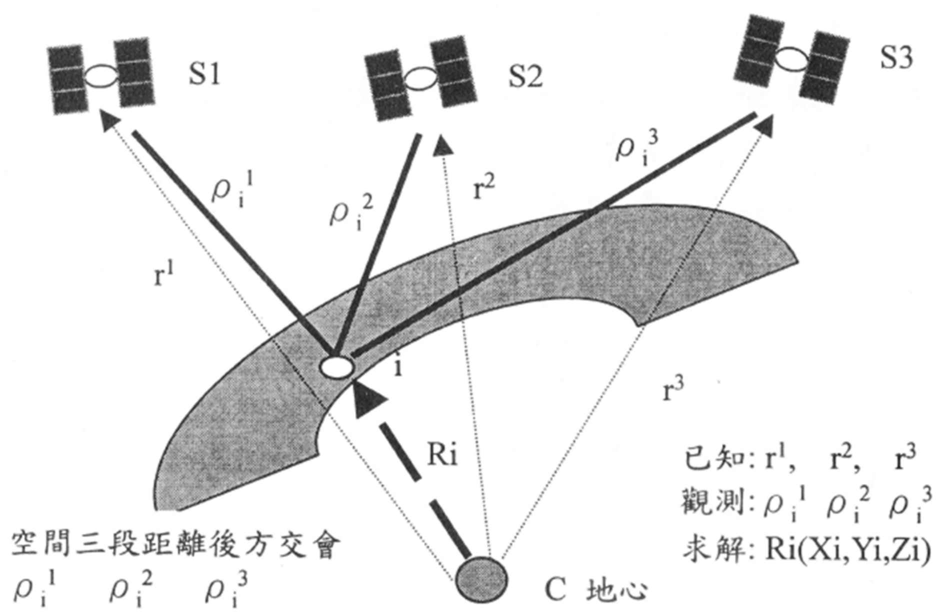
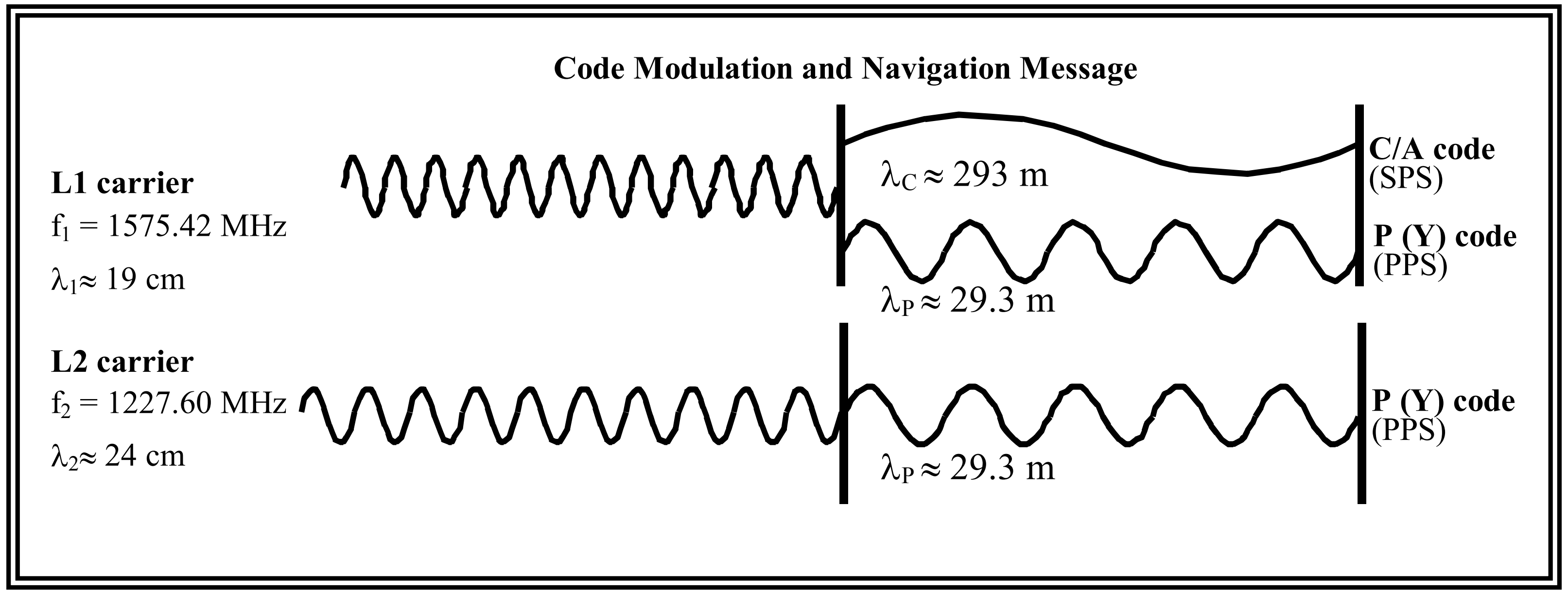


圖 4-1 衛星定位基本概念

GPS Signal


Code Modulation and Navigation Message
L1 carrier
f_1 = 1575.42 MHz
$\lambda_1 \approx$ 19 cm
$\lambda_C \approx$ 293 m
C/A code
(SPS)
P (Y) code
(PPS)
$\lambda_P \approx$ 29.3 m
L2 carrier
f_2 = 1227.60 MHz
$\lambda_2 \approx$ 24 cm
P (Y) code
(PPS)
$\lambda_P \approx$ 29.3 m

觀測誤差

- 此誤差主要來源為，觀測的分辨誤差及接收儀天線相對測站的安置誤差。一般觀測的分辨誤差約為訊號波長的1%~0.1%，因此， GPS電碼和載波相位的觀測誤差如下表，而觀測誤差屬偶然誤差，適當增加觀測量可明顯減少影響。

觀測的分辨誤差

訊號種類	波長	觀測誤差
P code	29.3 m	0.3~0.03 m
C/A code	293 m	2.9~0.29 m
L1	19.05 cm	1.9~0.19 mm
L2	24.45 cm	2.~0.24 mm

$$\rho_1 = R + c\cdot(dt - dT) + dtrop + dion_1 + dmp + \varepsilon_{\rho 1}$$
$$\rho_2 = R + c\cdot(dt - dT) + dtrop + dion_2 + dmp + \varepsilon_{\rho 2}$$

其中

ρ_i: 虛擬距離

R: 接收儀到衛星間的真實距離

c: 真空中的光速

dt: 接收儀的時錶誤差

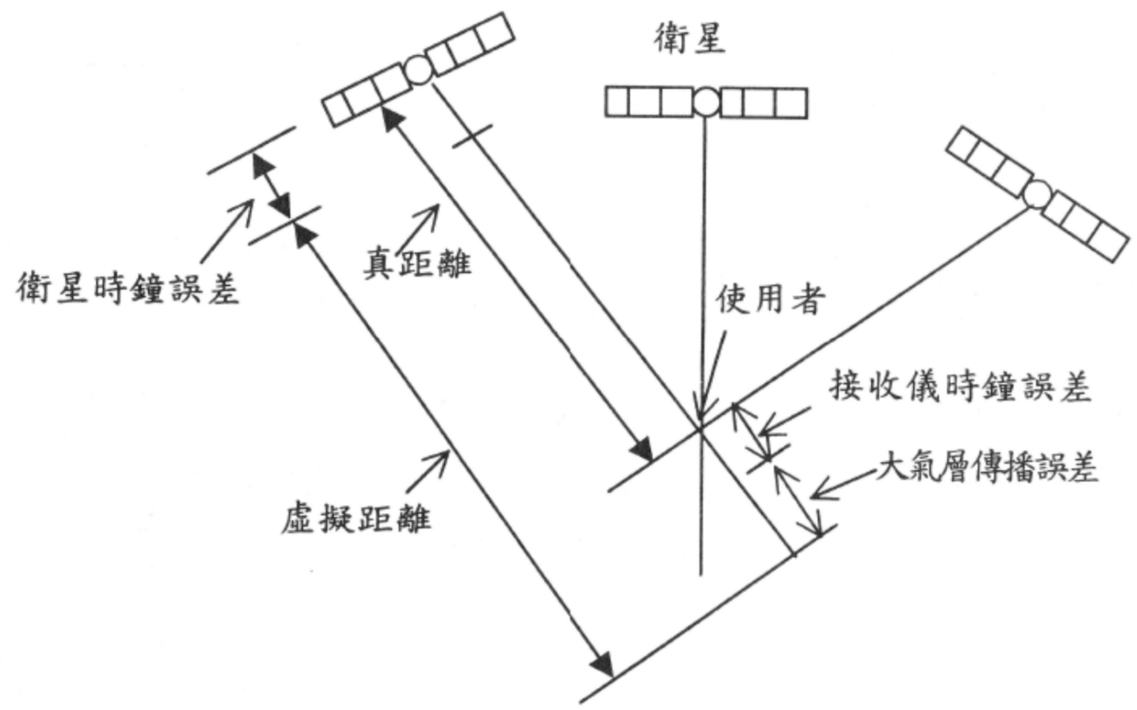
dT: 衛星的時錶誤差

dtrop: 對流層延遲

$dion_i$: 電離層延遲

dmp: 多路徑效應

$\varepsilon_{\rho i}$: 觀測量雜訊



Background and the main factors of the long-range GPS kinematic positioning

The double-differenced carrier phase observations that are used in standard GPS data processing can be expressed as:

$$\Delta\nabla\phi_1 = \Delta\nabla\rho + \Delta\nabla O - \Delta\nabla I + \Delta\nabla T + \Delta\nabla M + \lambda_1\Delta\nabla n_1 + \Delta\nabla\varepsilon_{\Delta\nabla\phi_1}$$

$$\Delta\nabla\phi_2 = \Delta\nabla\rho + \Delta\nabla O - \frac{f_1^2}{f_2^2}\Delta\nabla I + \Delta\nabla T + \Delta\nabla M + \lambda_2\Delta\nabla n_2 + \Delta\nabla\varepsilon_{\Delta\nabla\phi_2}$$

Distance dependent errors: Orbit, Ionospheric and Tropospheric errors.
Distance independent errors: Mulipath, Centring …

$$\Delta\nabla I = \left(\frac{f_2^2}{f_1^2 - f_2^2}\right)\left[(\Delta\nabla\phi_1 - \Delta\nabla\phi_2) - (\lambda_1\Delta\nabla n_1 - \lambda_2\Delta\nabla n_2) - (\varepsilon_{\Delta\nabla\phi_1} - \varepsilon_{\Delta\nabla\phi_2})\right]$$

$$\Delta\nabla T = \left(\frac{f_1^2}{f_1^2 - f_2^2}\right)\left[(\Delta\nabla\phi_1 - \lambda_1\Delta\nabla n_1 - \varepsilon_{\Delta\nabla\phi_1})\right] - \left(\frac{f_2^2}{f_1^2 - f_2^2}\right)\left[(\Delta\nabla\phi_2 - \lambda_2\Delta\nabla n_2 - \varepsilon_{\Delta\nabla\phi_2})\right] -$$

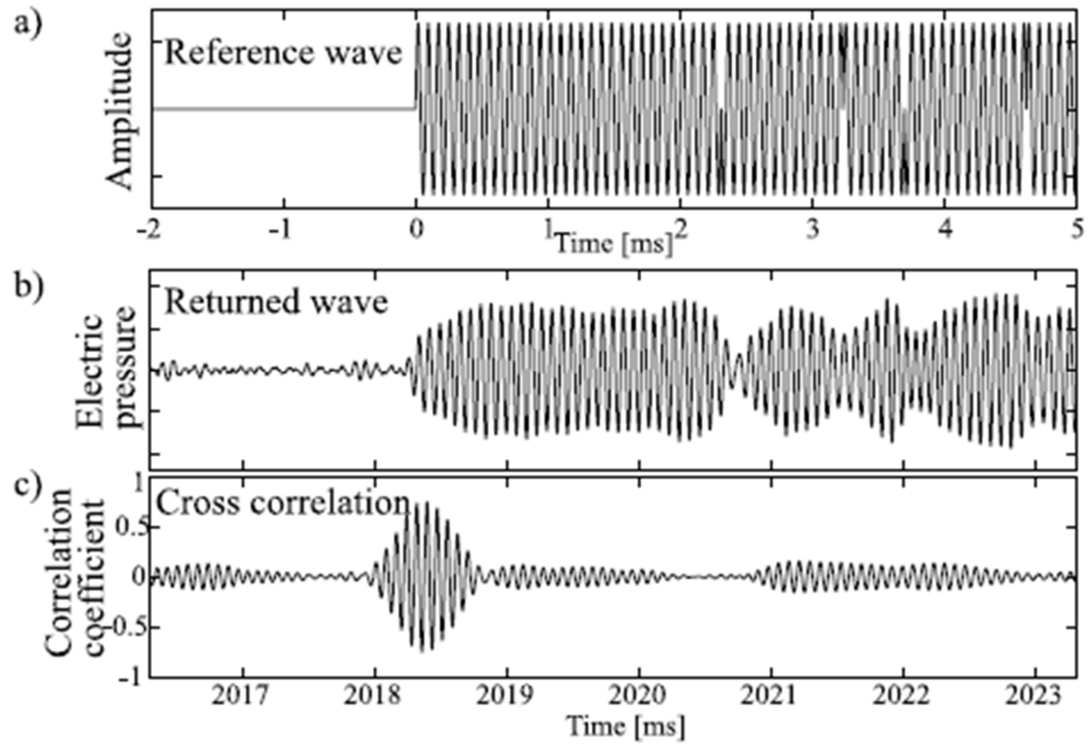
$$(\Delta\nabla\rho + \Delta\nabla O + \Delta\nabla M)$$

For the reference stations, the coordinates can be precisely estimated in the static mode. After careful selection of the reference stations, and using both hardware and software multipath error reduction techniques, multipath error can be assumed to have been reduced. Therefore the accuracy of the tropospheric delay is slightly limited by the station coordinate error, orbit error and multipath.

Basic information for acoustic signal

- Fc = 13 kHz
- Fs = 512 kHz
- Ncycle = 6 cycles
- Length of the signal = 14 ms
- Speed of sound ≈ 1500 m/s
- Doppler shift rates were at most 0.3%
- Corrections of the round-trip travel times were less than 0.02 ms
- Corresponds to a distance of only 1.5 cm

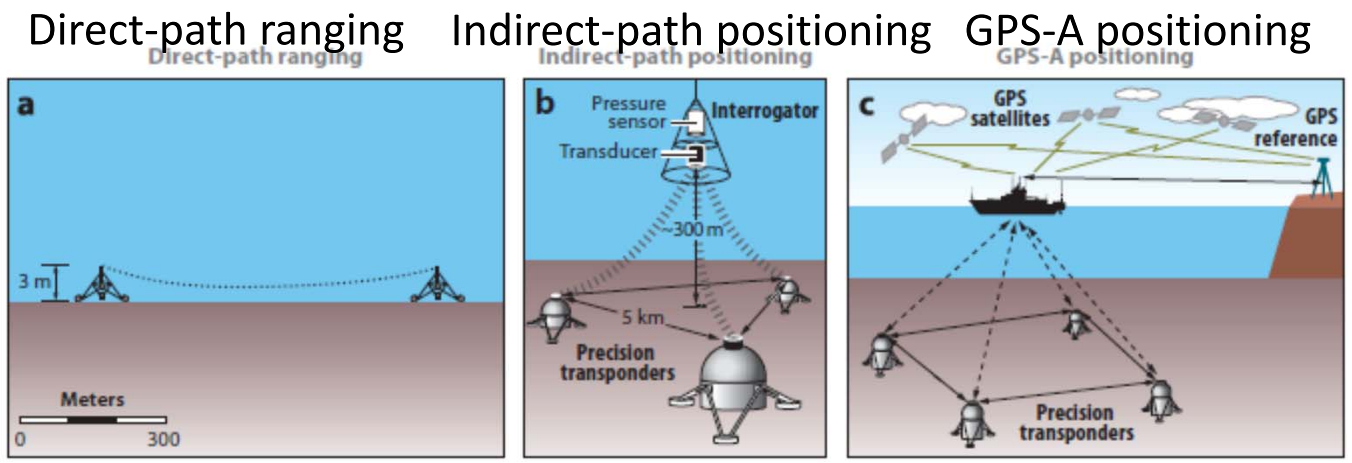
Except for the time of the measurement, the transponders were in sleep mode until they received the wake-up code that arrives in front of the signal part.



The main signal for acoustic ranging. (a) The initial 5 ms of the emitted wave (synthetic waveform). The sinusoid changes polarity in the manner of a maximal length sequence. (b) The initial few milliseconds of the observed returned signal. The horizontal axis is the time after the transducer generates the sound signal. The regions of polarity change in Fig. a reveal constriction. Switches in polarity are not obvious. (c) Cross-correlation sequence of the previous two waveforms. A group of peaks corresponding to the arrival of the returned wave is found around 2018.3 ms.

Seafloor crustal deformation methods

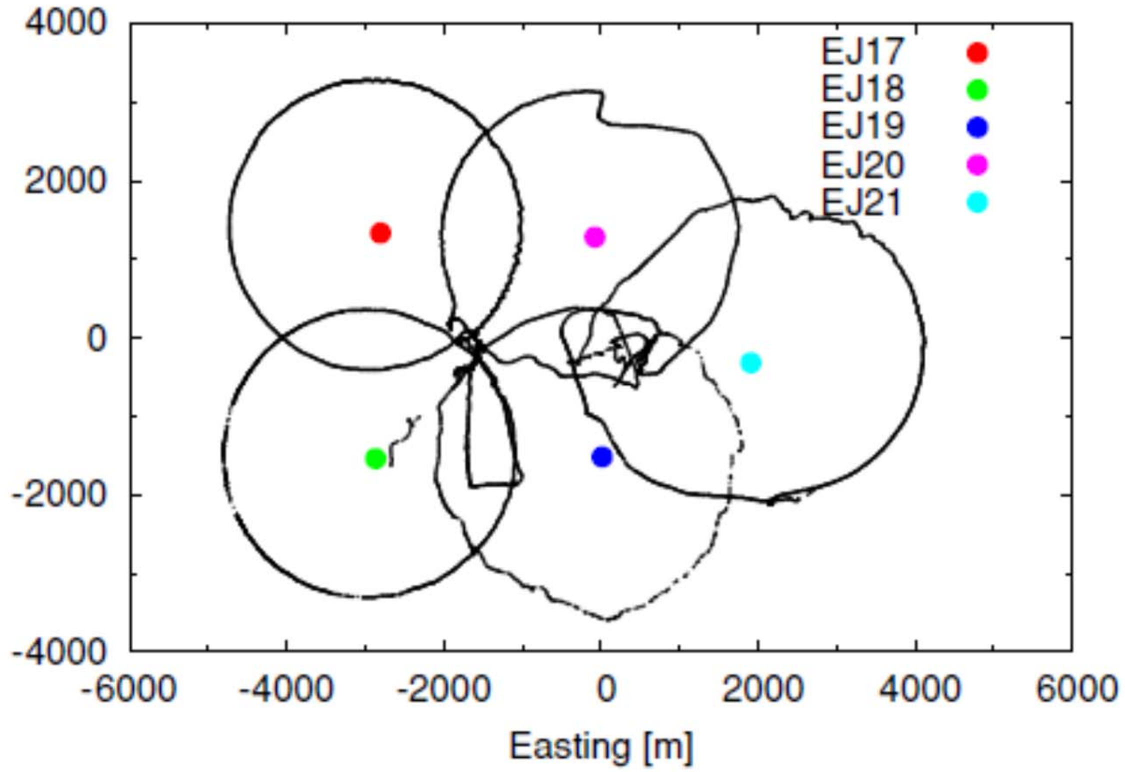
- Three methods as follows:
  - (1) Observations of strains by strain meters and tiltmeters installed in seafloor boreholes (e.g., Shinohara *et al.*, 2000).
  - (2) Acoustic measurements of the distances between two stations fixed on the seafloor (e.g., Fujimoto *et al.*, 1995).
  - (3) Determining positions of stations fixed on the seafloor by accurate acoustic measurements of distances between an observation vessel and stations on the seafloor.



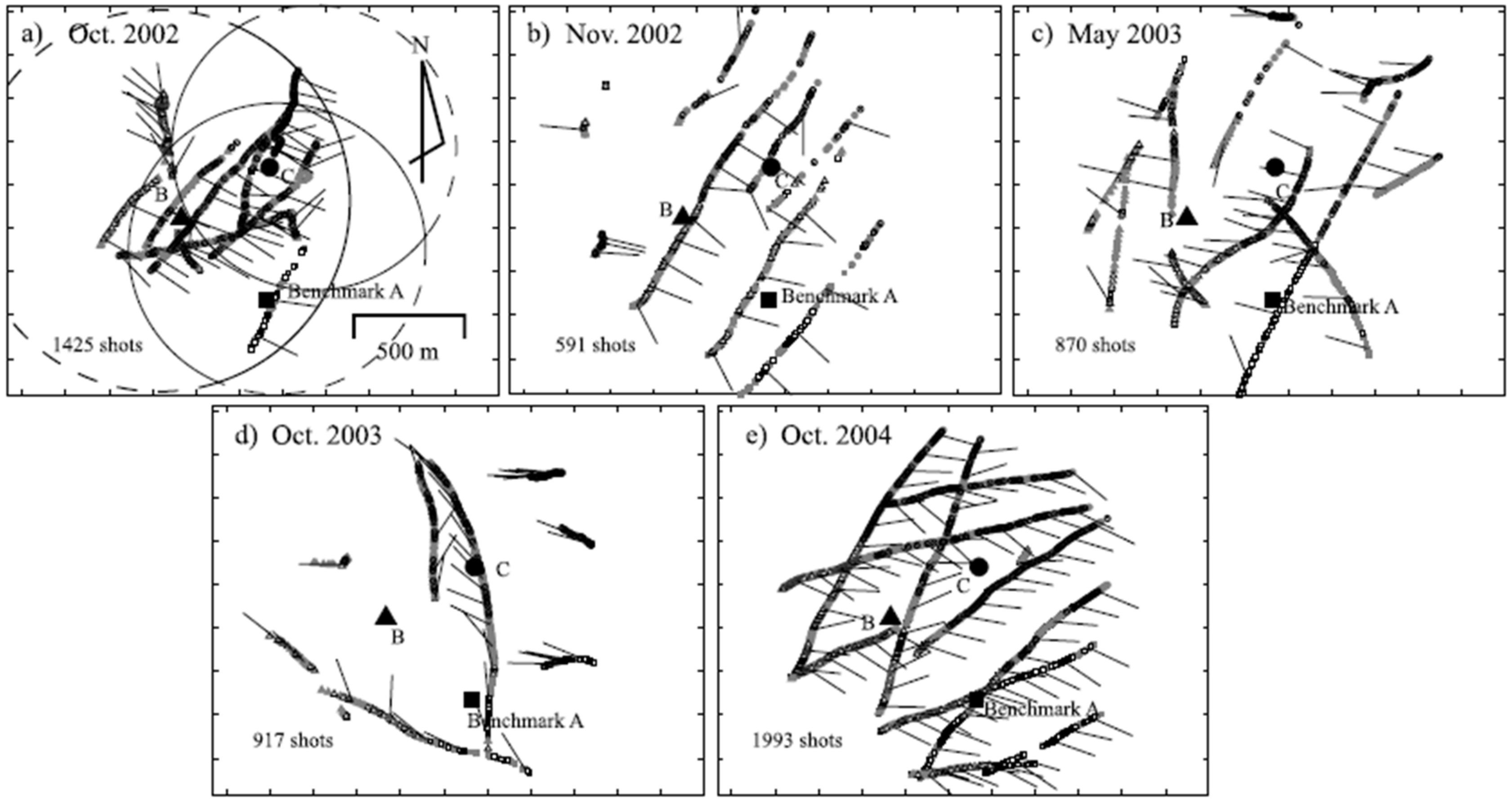
Schematic diagrams of acoustic ranging methods for seafloor deformation measurements (modified from Chadwell & Sweeney 2010).(a) Direct-path ranging between two raised transponders. The baseline length is limited by upward refraction of the acoustic signal.(b) Indirect-path system using an interrogator to increase range between transponders. (c) GPS-A using kinematic GPS positioning of a ship or buoy to precisely determine the location of a transponder array on the seafloor in a global reference frame.

Category of Acoustic/GPS methods

- Keeping the survey vessel about the center of the configuration, and determined the horizontal components of the center.(Fujimoto et al.,1995; Spiess et al.,1998; Gagnon et al.,2005; Kido et al., 2006)
- Drifting over a certain area over the benchmark unit transmitting and receiving the signal. (Tadokoro et al., 2001; Yamada et al.,2002; Ikuda et al., 2008)



Track of the buoy during the moving survey
around the five PXPs (precision transponder)
(M. KIDO et al., 2006)



Trajectories of the vessel Suruga-maru at SNE. The large symbols marked A, B, and C correspond to three seafloor transponders. The small circles represent the points where the vessel sent and received the acoustic signal. Gray and open circles represent positive and negative traveltime residuals. Lines depict the direction of orientation of the vessel's bow (IKUTA et al., 2008)

2. Seafloor geodesy

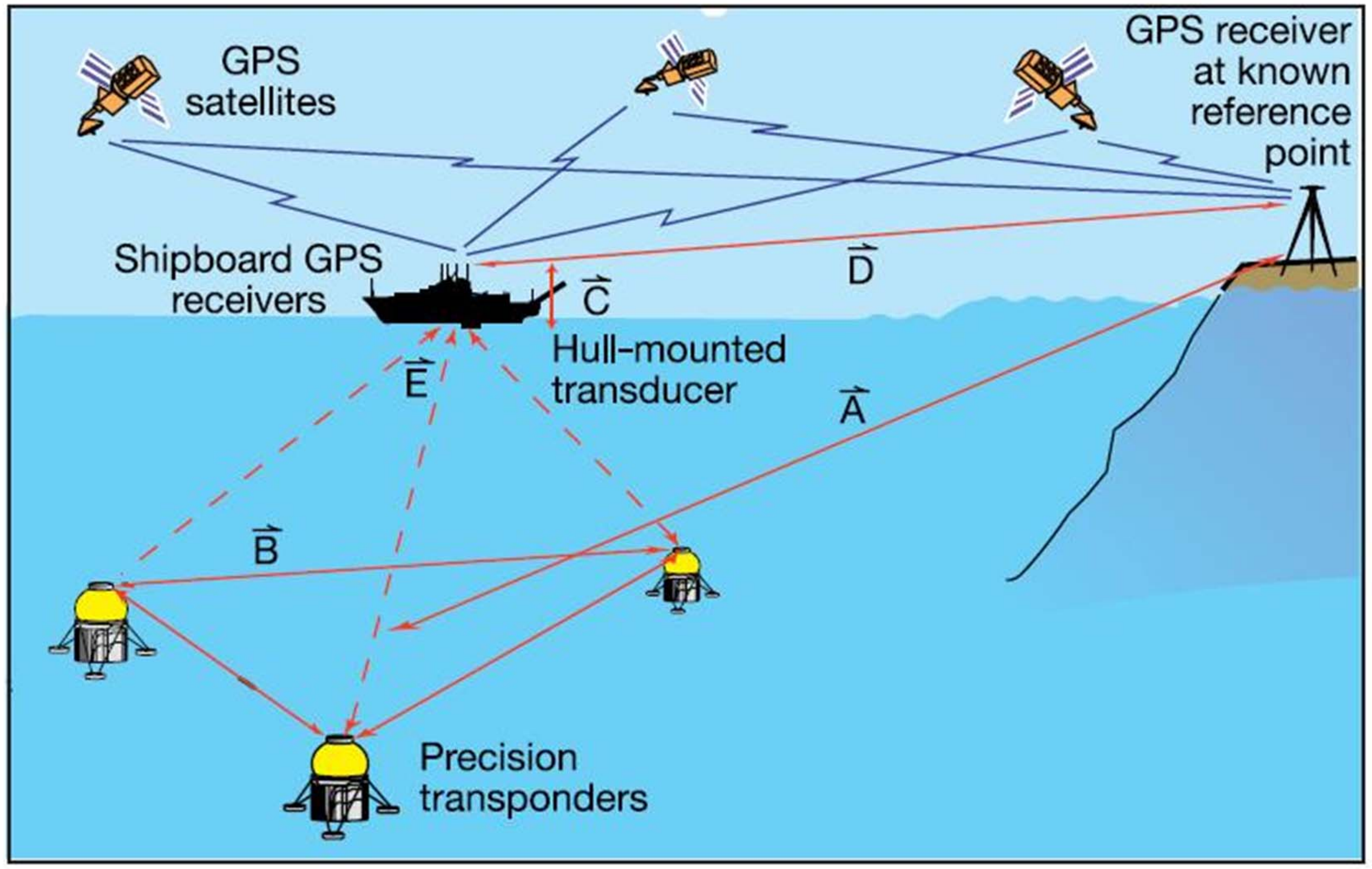
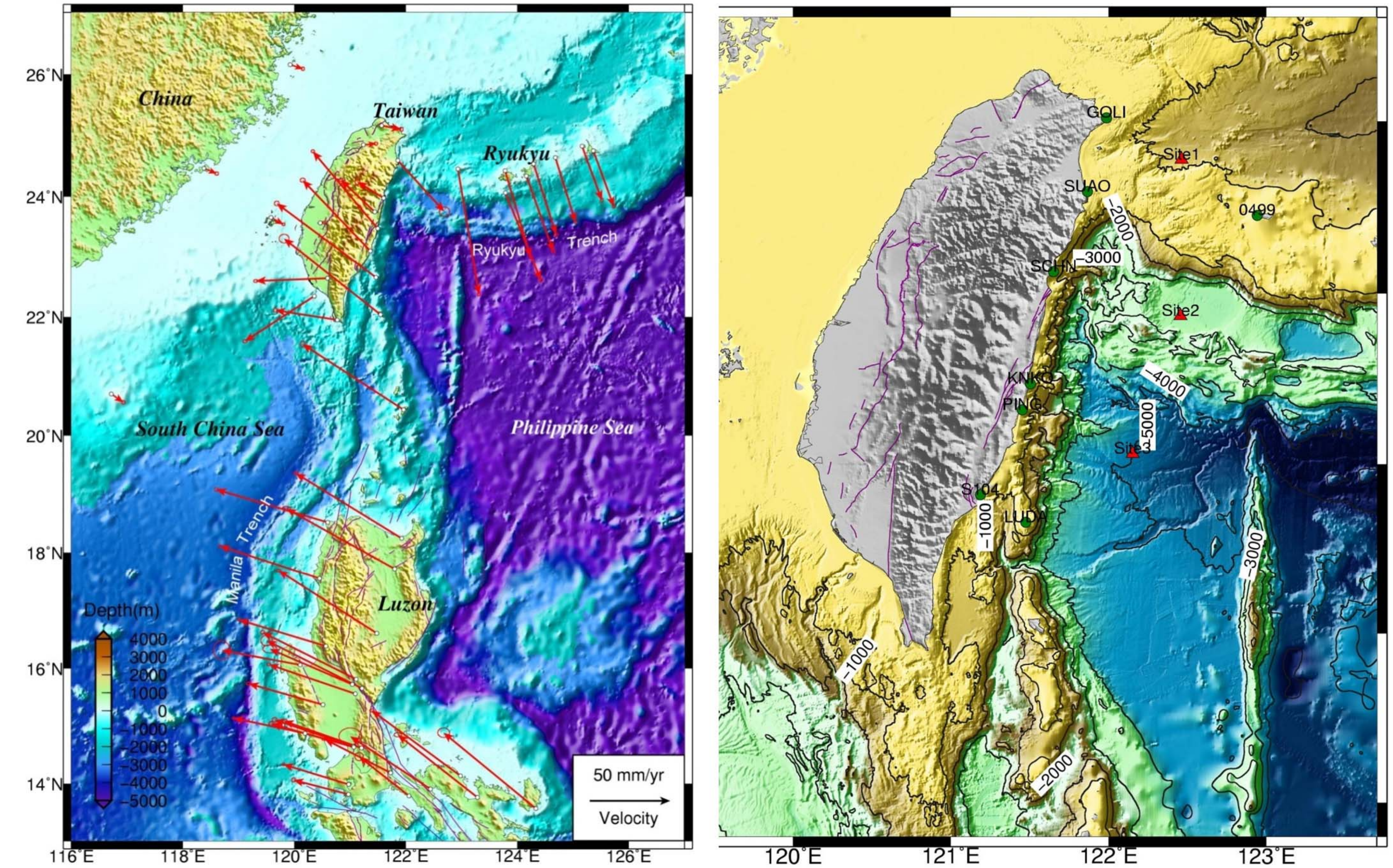
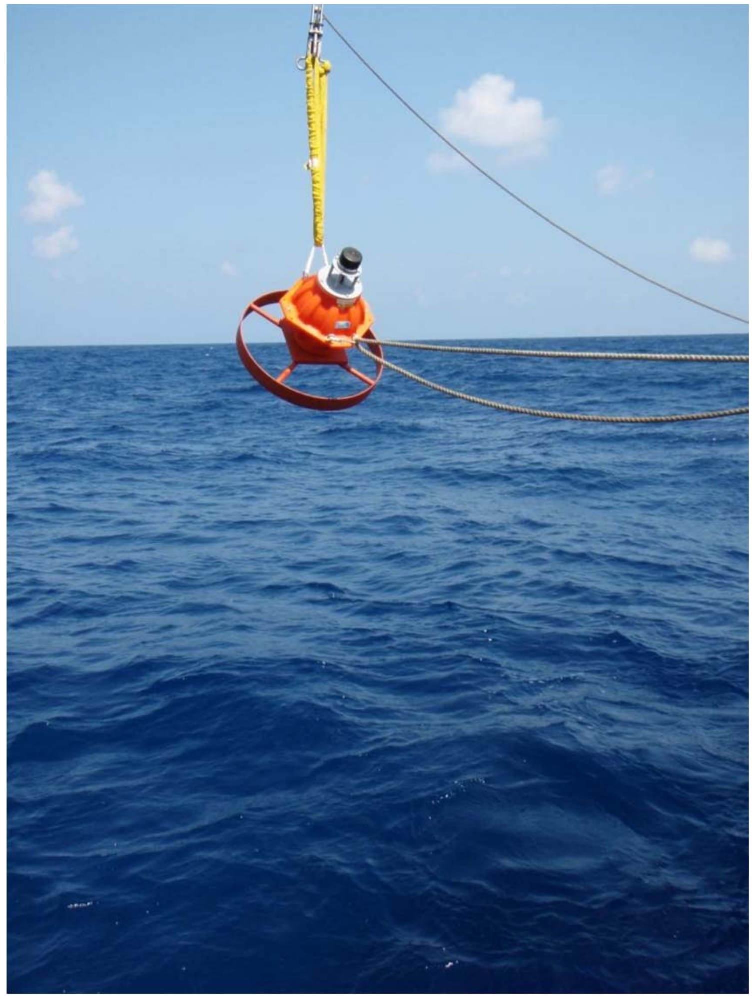


Diagram of seafloor geodesy (excerpt from Gagnon et al., 2005)

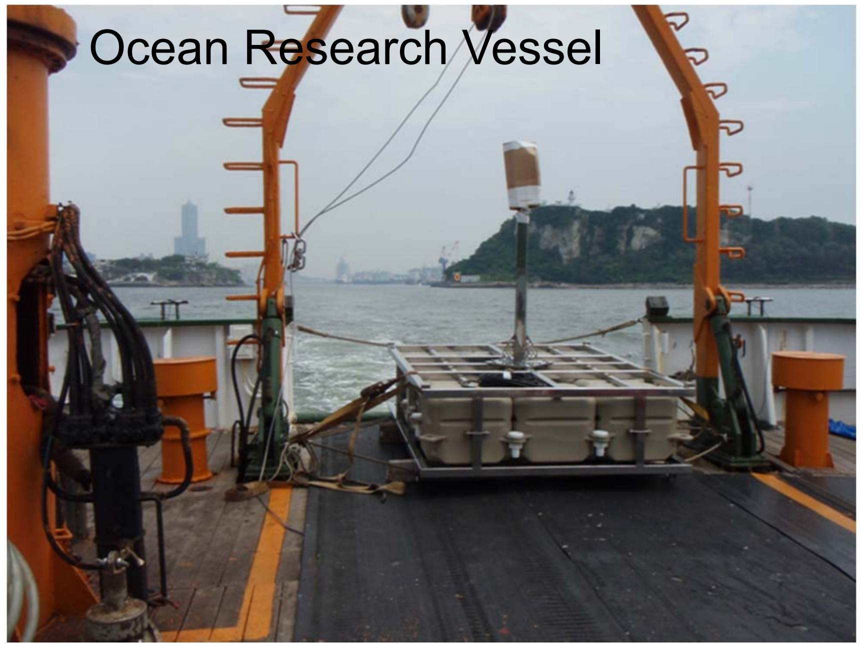
Requirements for Seafloor crustal deformation study

- 4 basic requirements:
  - Estimate the relative position between reference stations on-land and vessel or buoy placed at sea.
  - Determine the instantaneous transducer positions at all time by means of attitude determination of the vessel or buoy.
  - By measuring the two-way travel time between the transducer fixed in the vessel or buoy and the transponder placed on the ocean bottom to estimate the relative ranges.
  - Measure the velocity of sound while advancing, considering the depth and the horizontal difference correlated with time.


China
Taiwan
Ryukyu
Ryukyu Trench
South China Sea
Philippine Sea
Manila Trench
Luzon
Depth(m)
4000
3000
2000
1000
0
−1000
−2000
−3000
−4000
−5000
50 mm/yr
Velocity
26°N
24°N
22°N
20°N
18°N
16°N
14°N
116°E
118°E
120°E
122°E
124°E
126°E
GOLI
Site1
SUAO
0499
SCHN
Site2
KNKO
PING
Site3
S104
LUDA
−1000
−2000
−3000
−4000
−5000
120°E
121°E
122°E
123°E



CTD is an acronym for **Conductivity, Temperature, and Depth**, the three main parameters that the instrument measures.

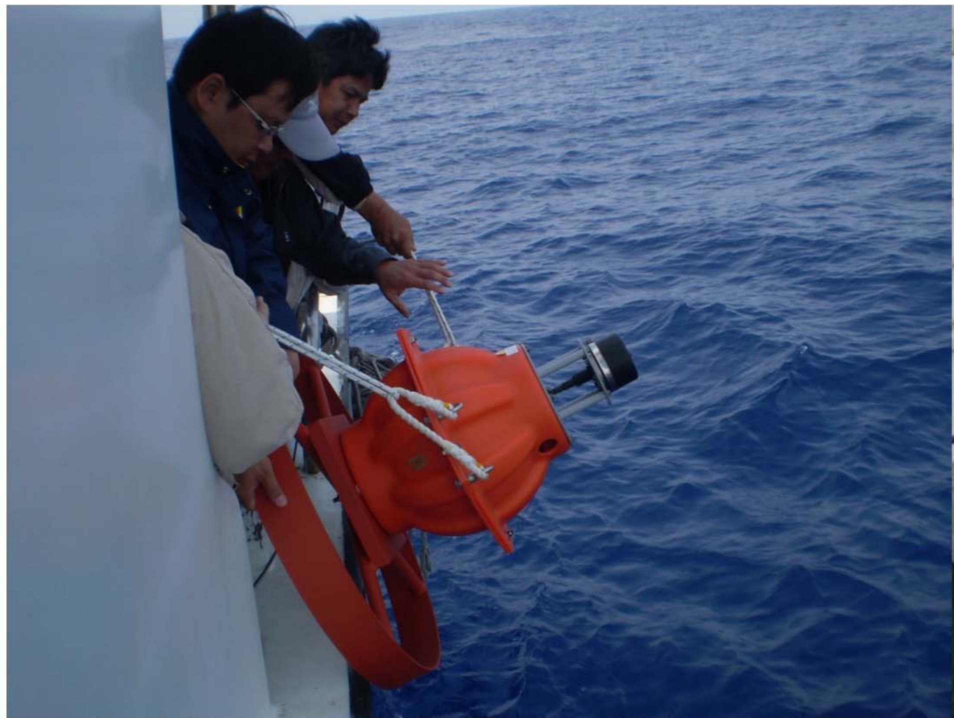

Ocean Research Vessel

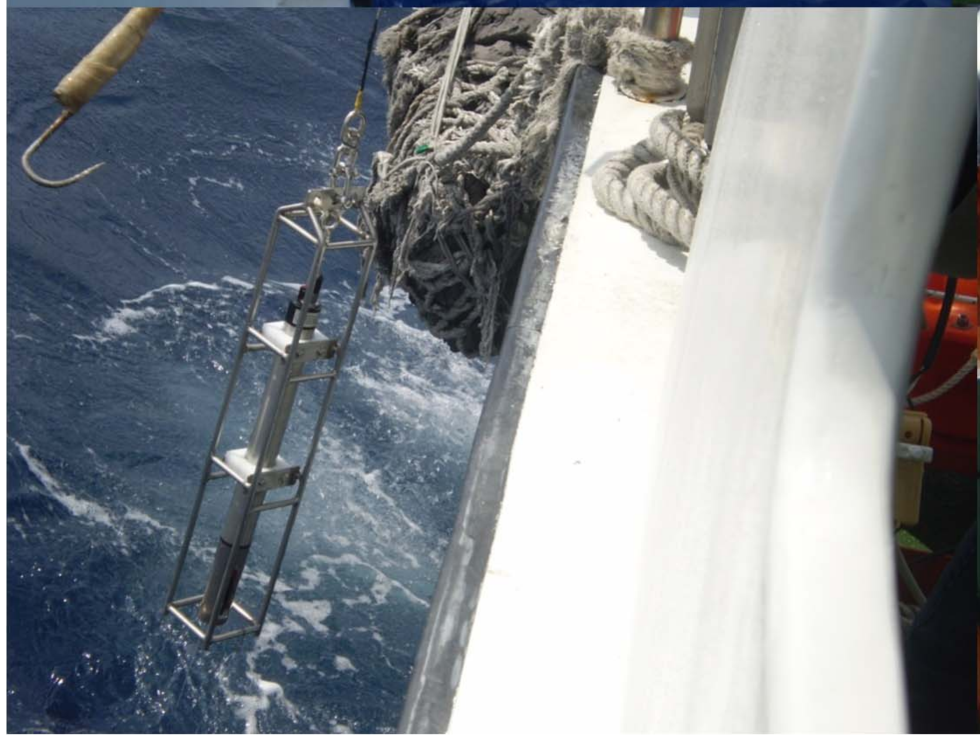

Fishing boat


鯨 世界
鯨世界三號

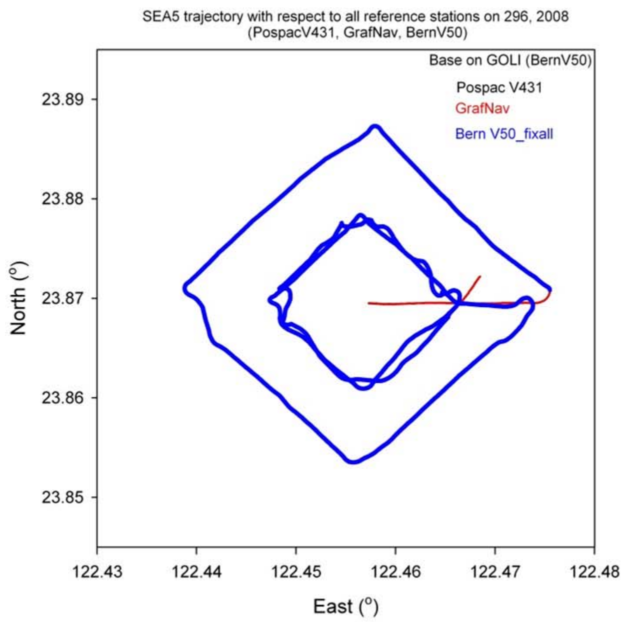

鯨 世界三號

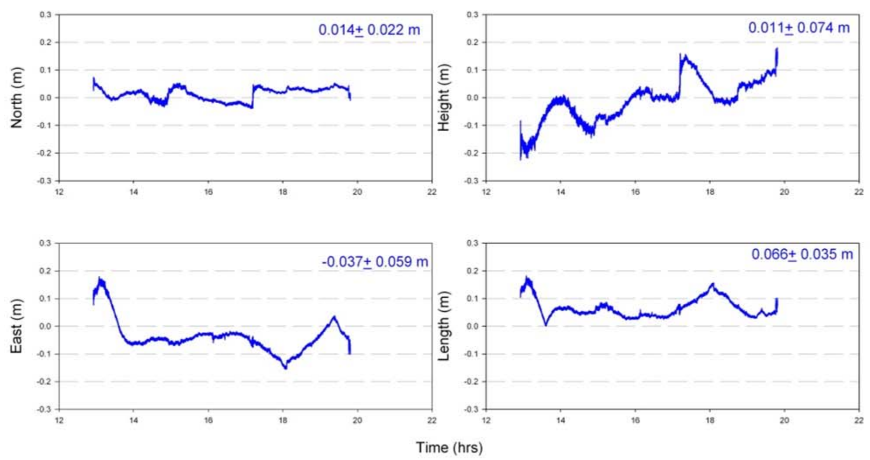

界

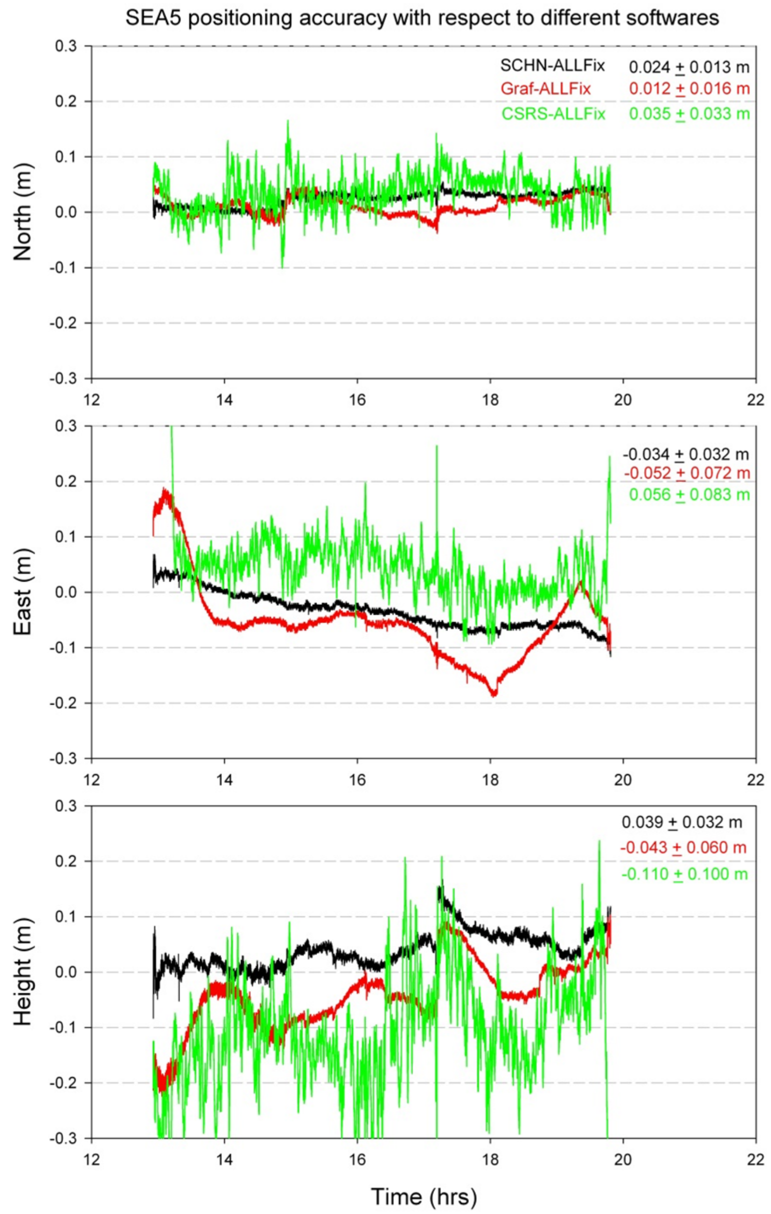




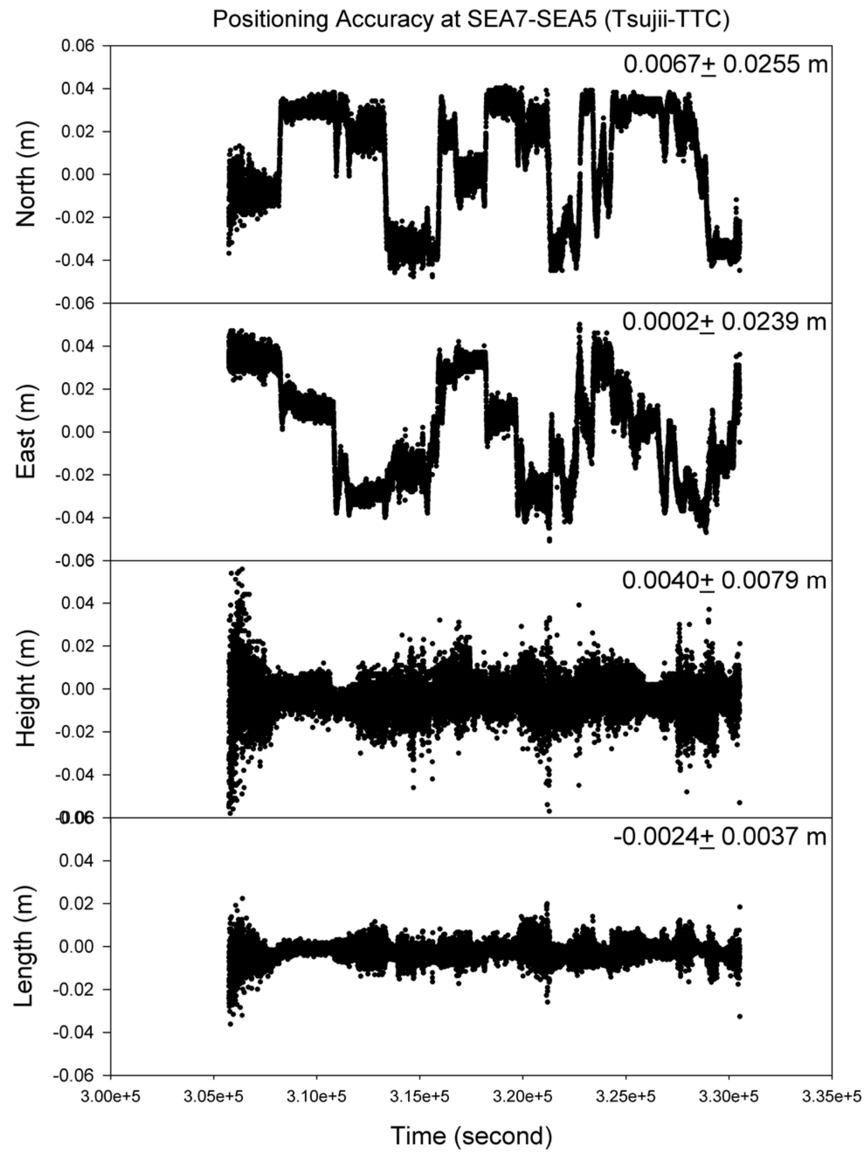

Experiment 1(Oct. 2008)

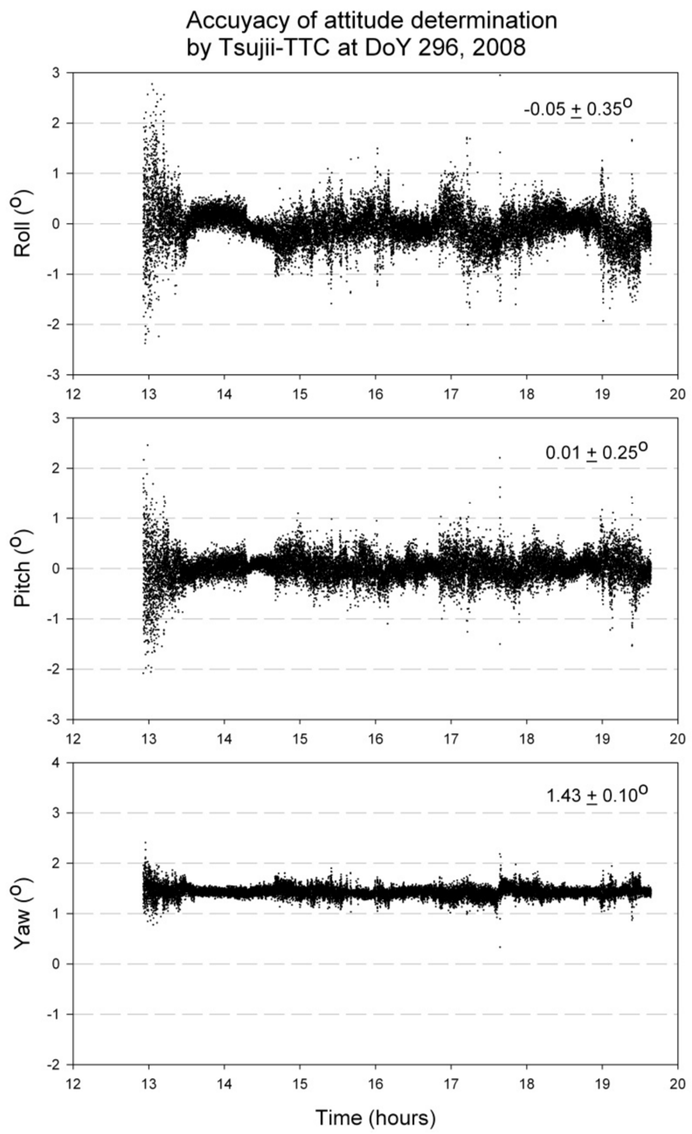




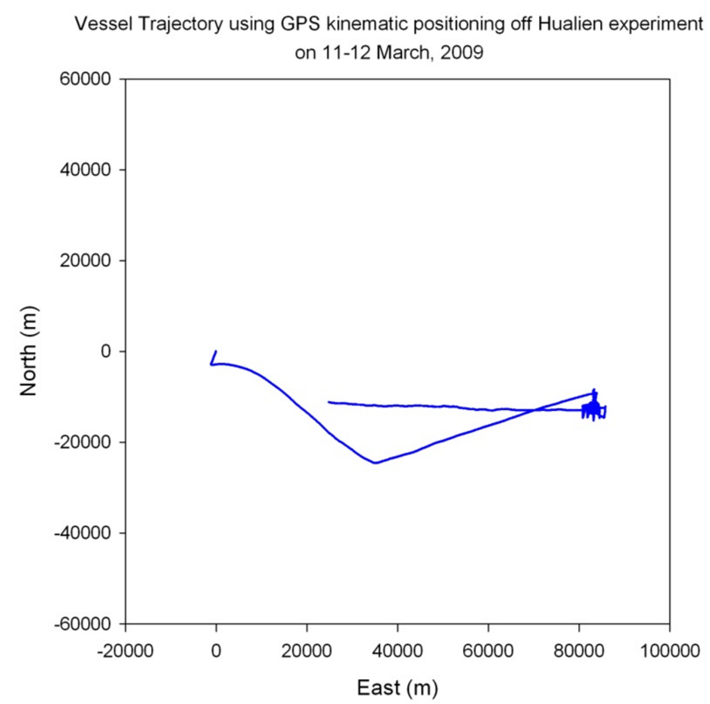


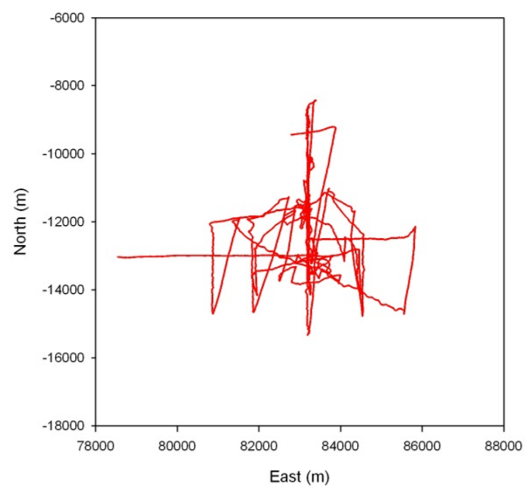
Experiment 1(Oct. 2008)

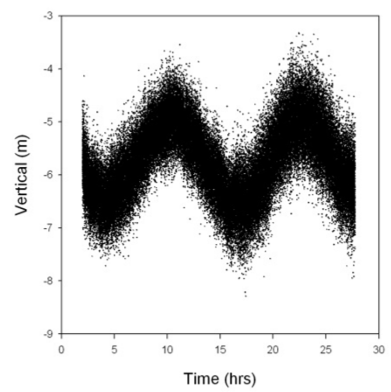




Experiment 2 (Mar. 2009)







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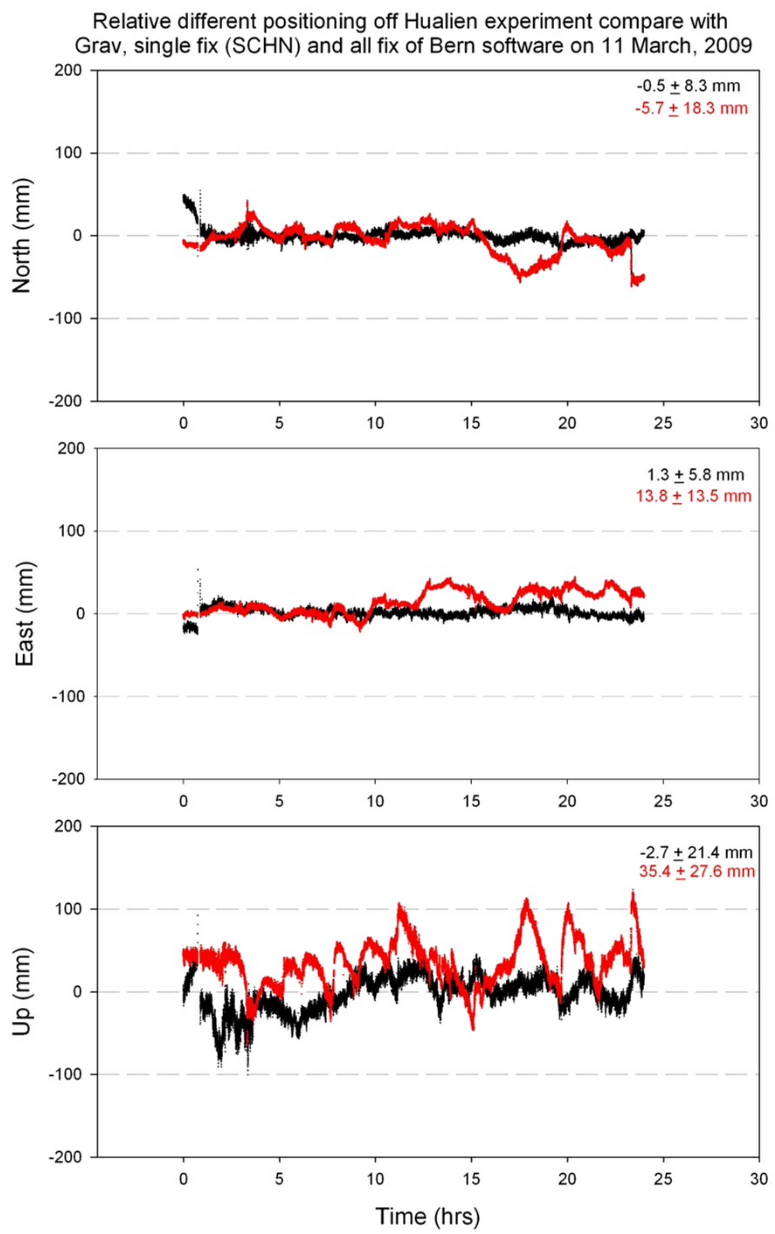

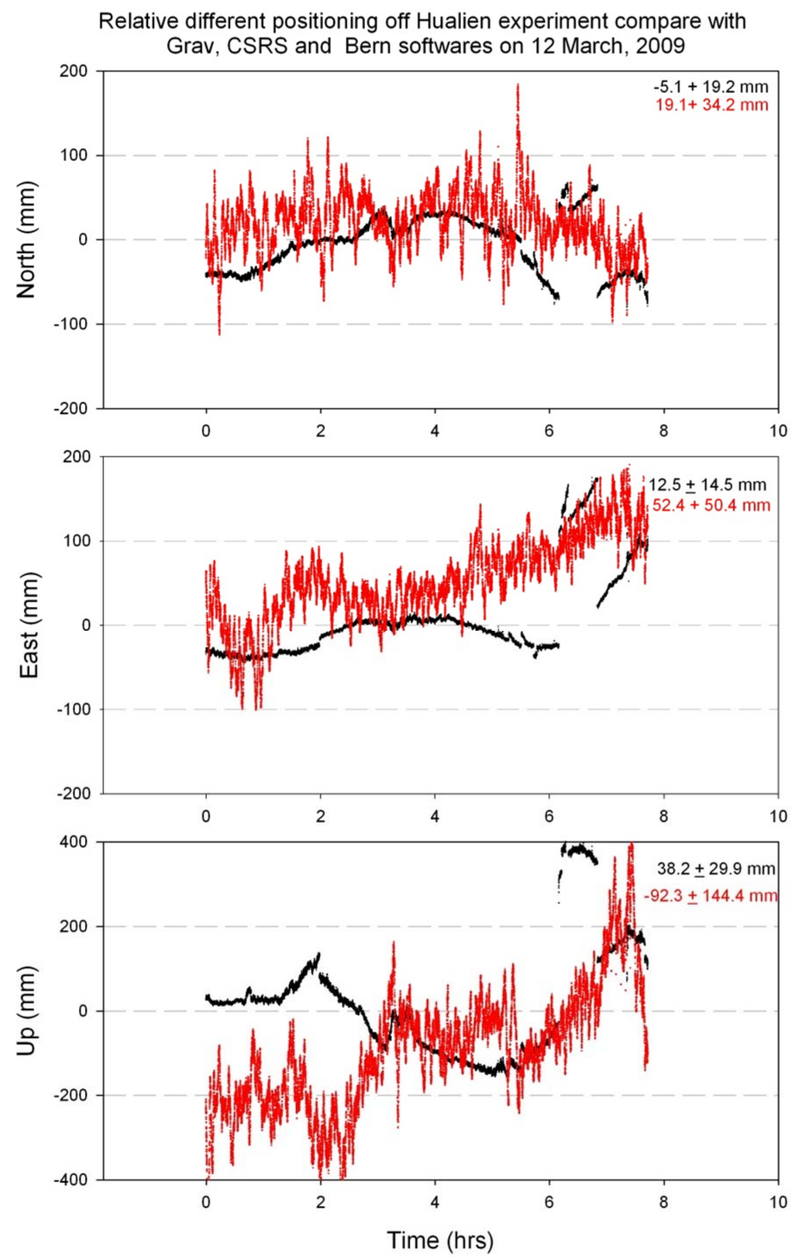

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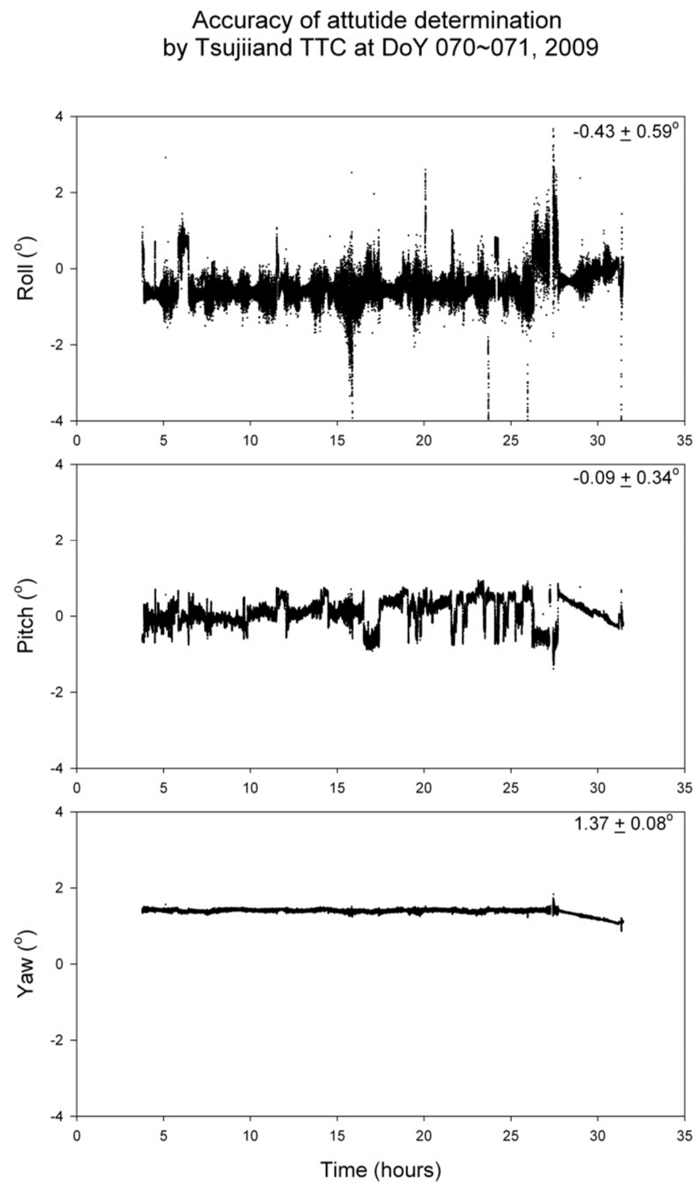
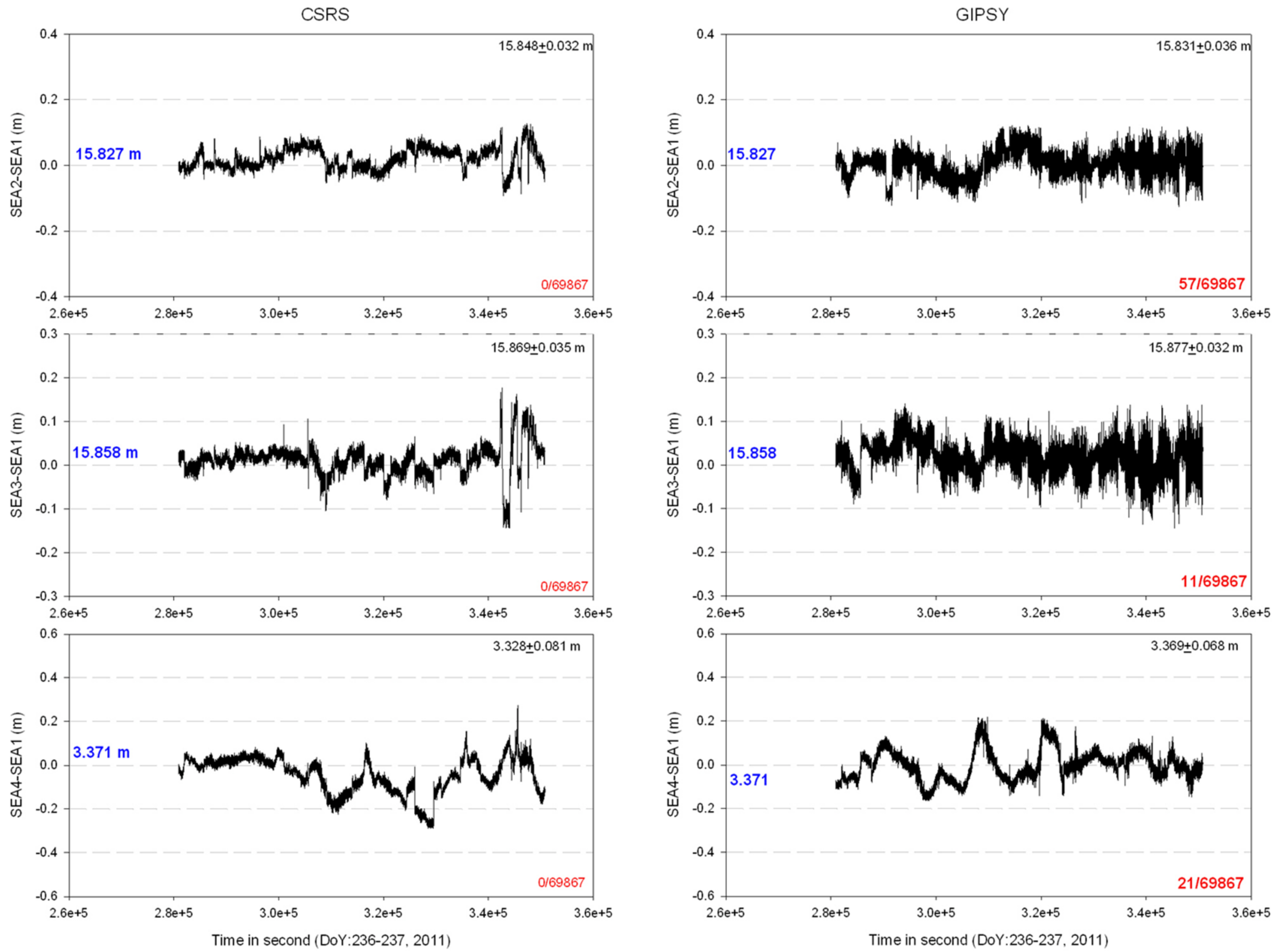
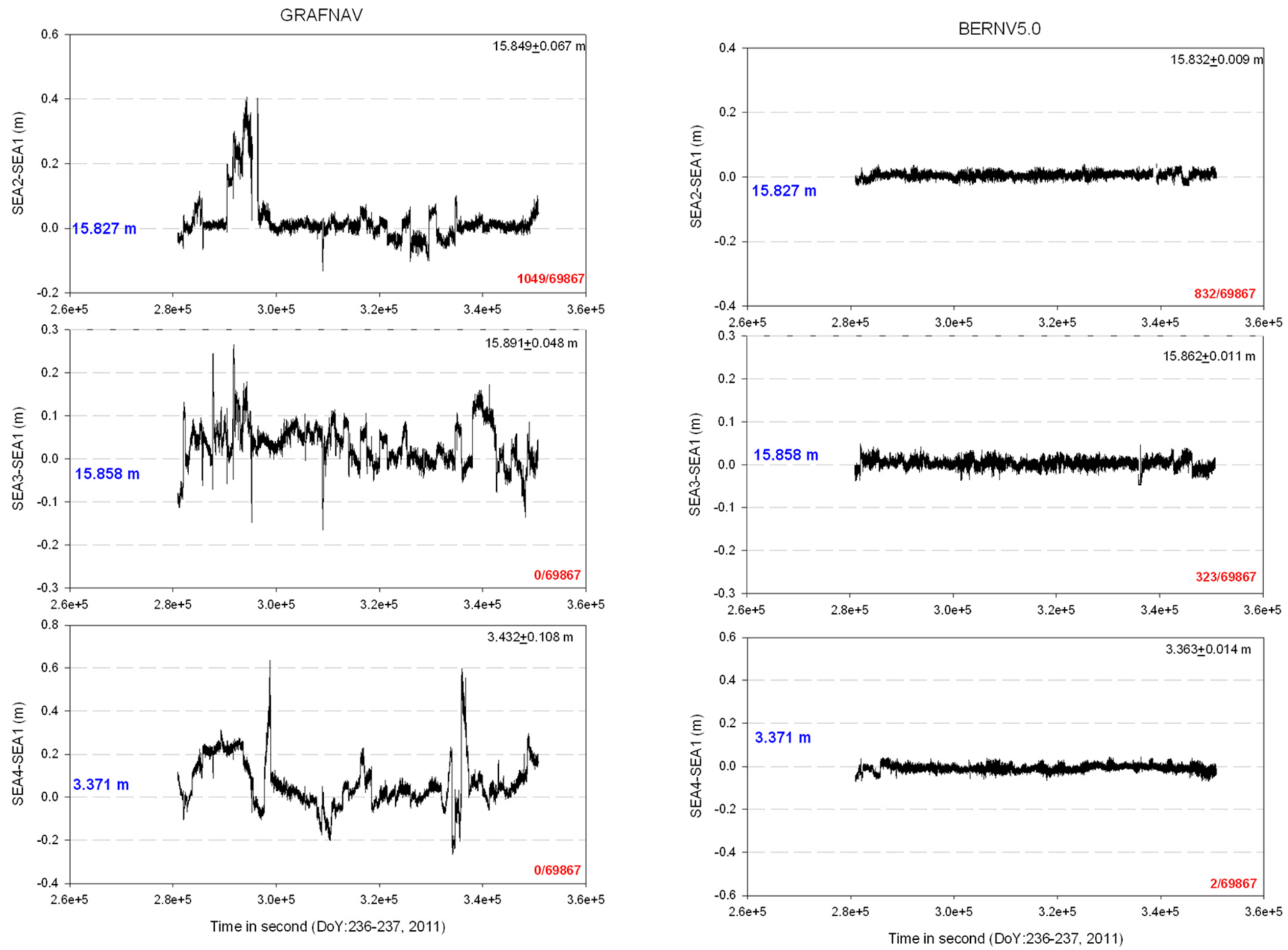
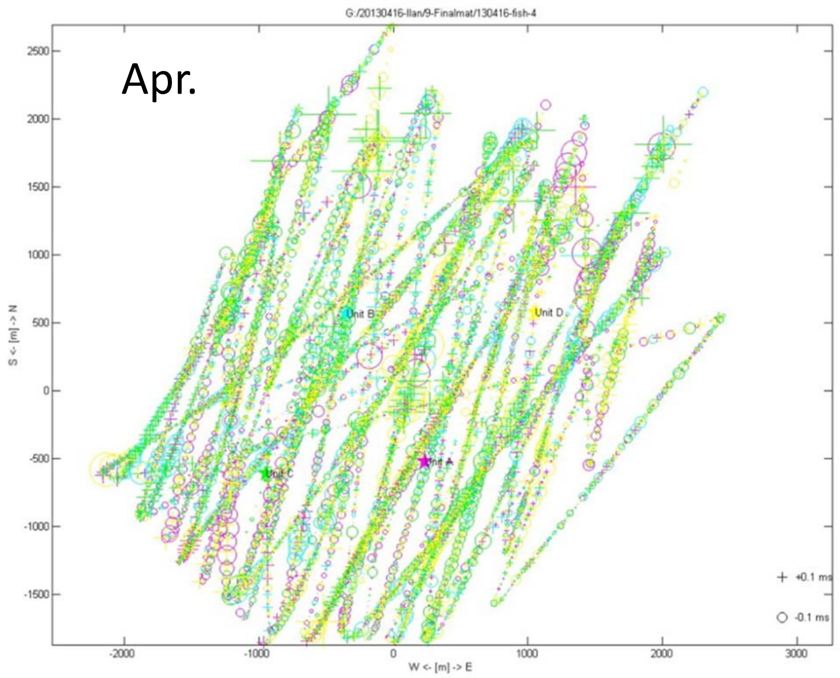


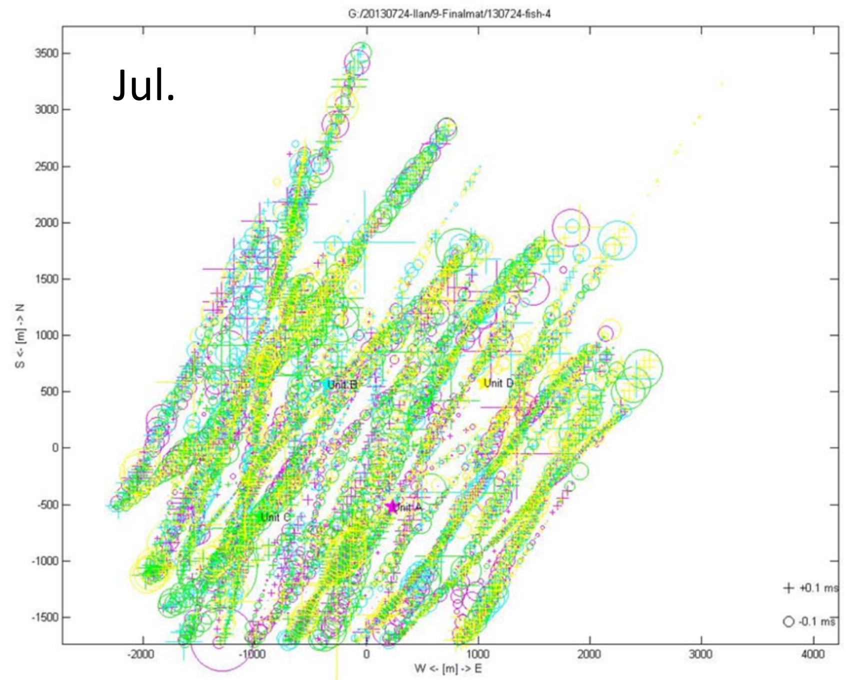
Estimation on different software

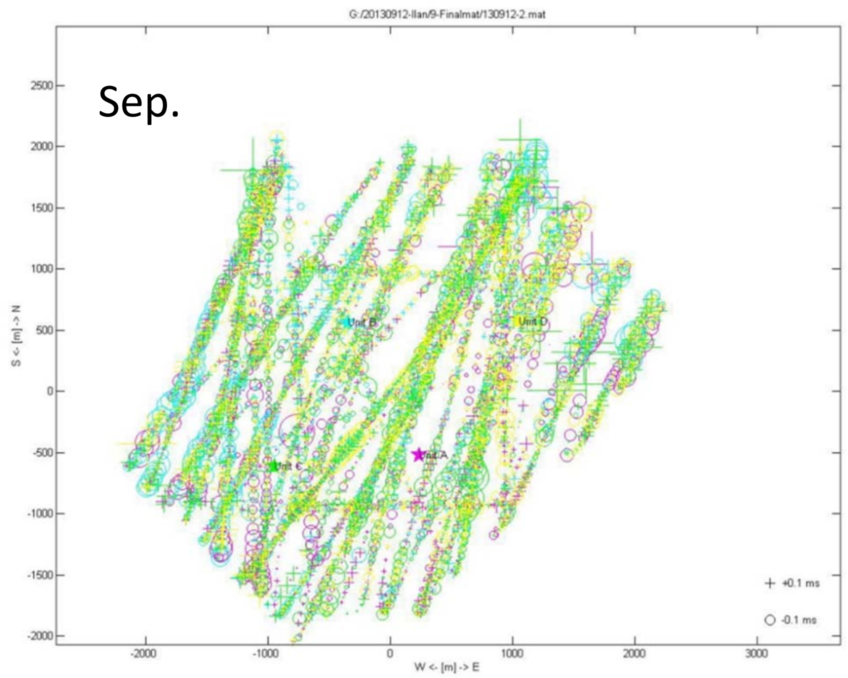




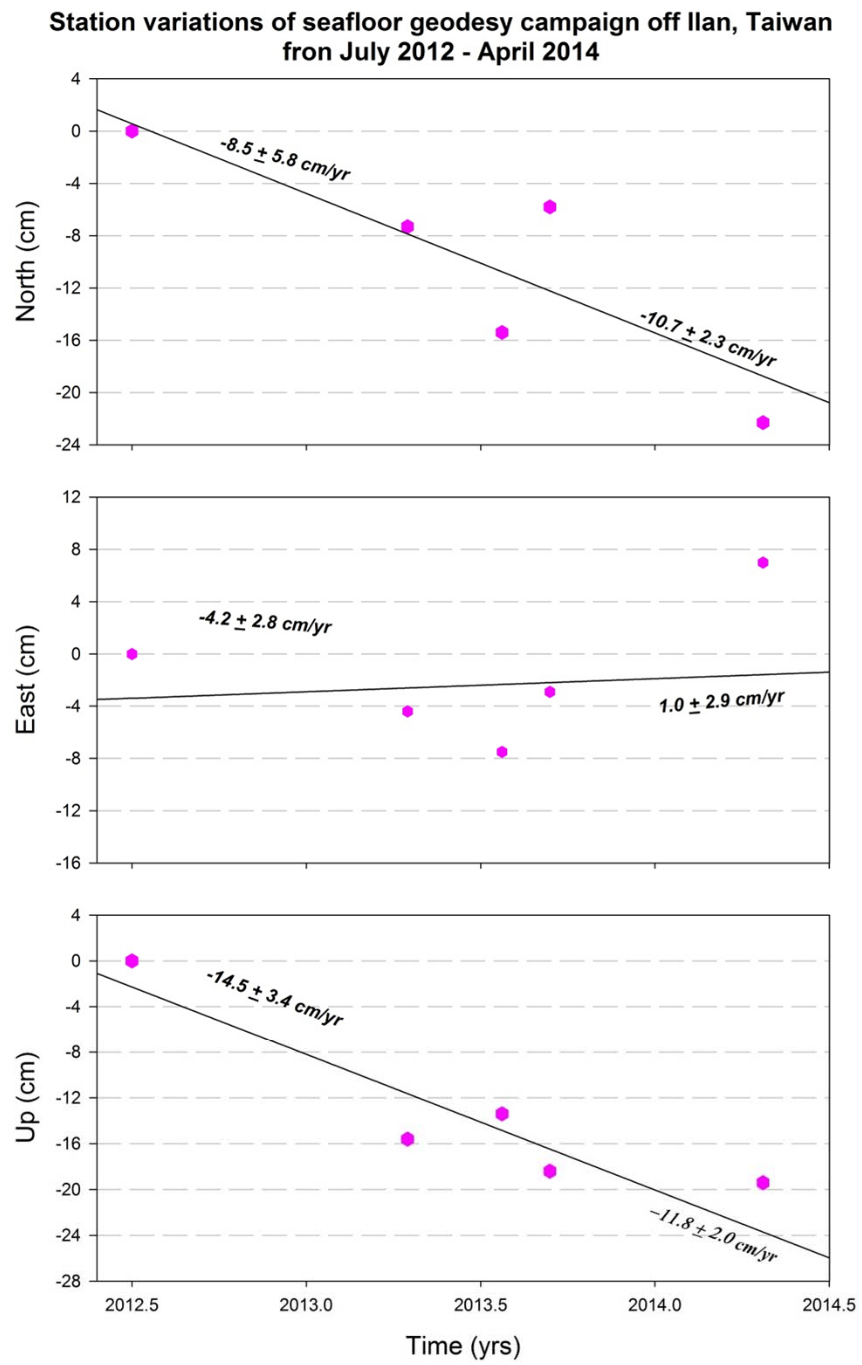
GRAFNAV
BERNV5.0
SEA2-SEA1 (m)
SEA3-SEA1 (m)
SEA4-SEA1 (m)
15.849±0.067 m
15.891±0.048 m
3.432±0.108 m
15.832±0.009 m
15.862±0.011 m
3.363±0.014 m
15.827 m
15.858 m
3.371 m
1049/69867
0/69867
0/69867
832/69867
323/69867
2/69867
Time in second (DoY:236-237, 2011)



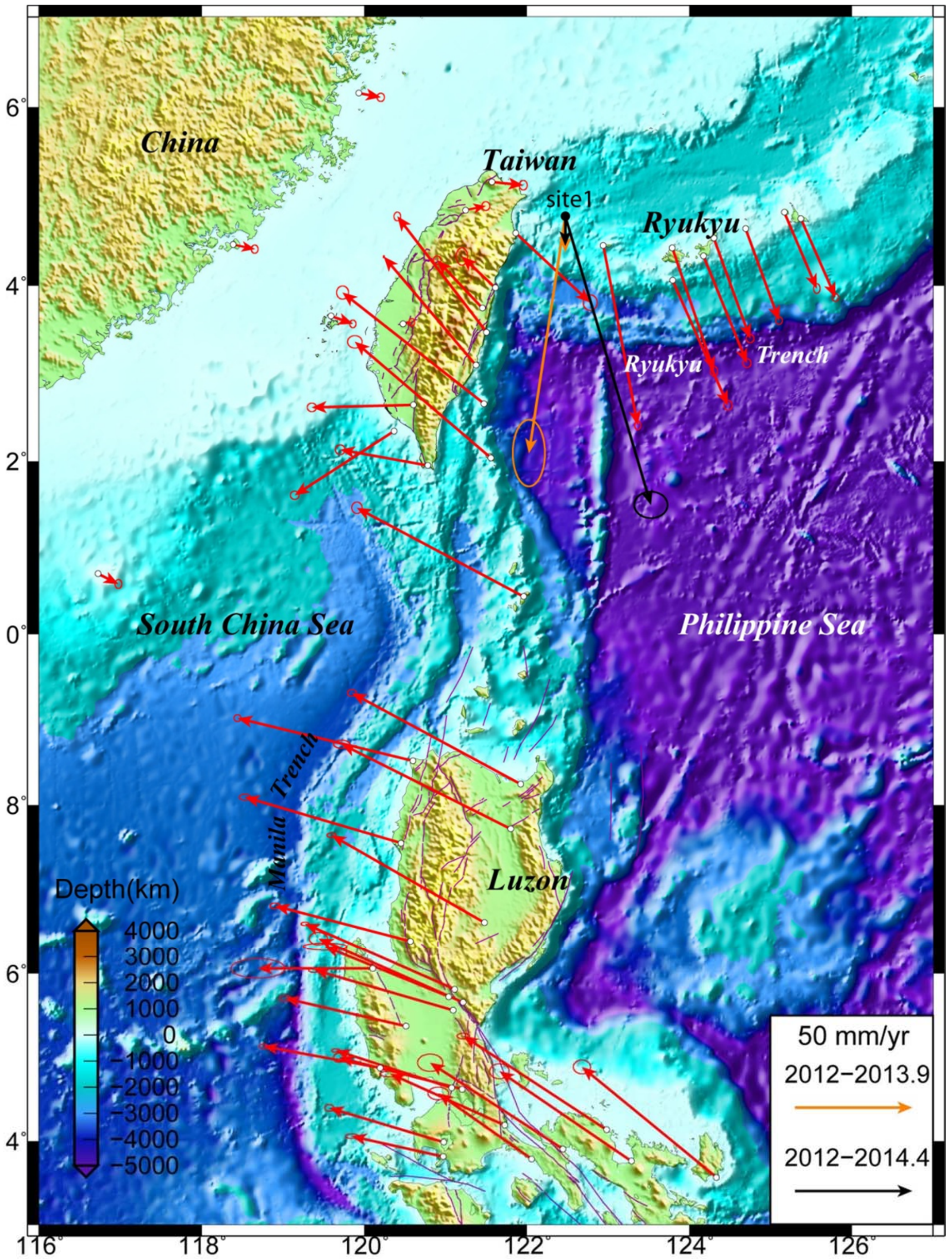




Date	Obs.	Used	Rates (%)	RMS (ms)	Accuracy (cm)
15-17 April	11221	10721	95.5	0.07	5
23-25 July	9559	8202	85.9	0.10	7
11-13 Sep.	8874	7936	89.4	0. 08	6

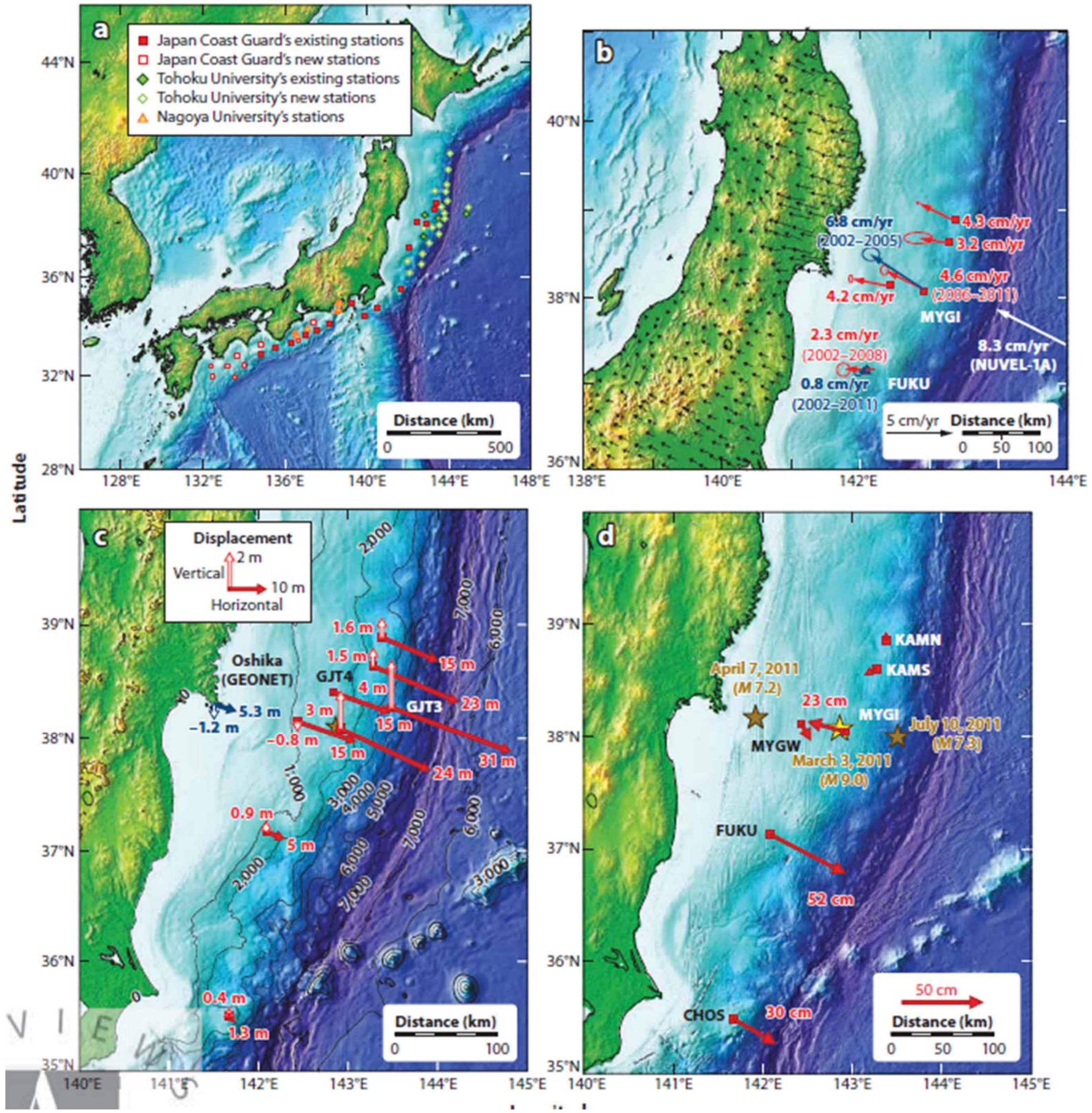


Station variations of seafloor geodesy campaign off Ilan, Taiwan
fron July 2012 - April 2014
North (cm)
-8.5 ± 5.8 cm/yr
-10.7 ± 2.3 cm/yr
East (cm)
-4.2 ± 2.8 cm/yr
1.0 ± 2.9 cm/yr
Up (cm)
-14.5 ± 3.4 cm/yr
-11.8 ± 2.0 cm/yr
Time (yrs)



China
Taiwan
site1
Ryukyu
Ryukyu
Trench
South China Sea
Philippine Sea
Manila Trench
Luzon
Depth(km)
50 mm/yr
2012−2013.9
2012−2014.4

	No. sites	transponders/site	Accuracy in cm single trend	Vessel	TD attach	No. of shots/transponder	AC data picking
Taiwan	3	3	10 cm ?	different even for same site	buoy or shipside	400-1500	manual
Coast Guard	16	4	2-3 cm 1-2 cm	Same ship for all sites	ship bottom	1300	auto
Nagoya Univ.	7	3	5 cm 3 cm	same ship for same site	shipside	1000-2000	auto
Ryukyu Univ.	1	3	5 cm 5 cm	Same ship	shipside	700-2000	manual



(a) Existing and new GPS-A stations deployed by Japan Coast Guard, Tohoku University, and Nagoya University (M. Sato, personal communication).
(b) Interseismic velocities in the North America reference frame measured during 2001–2011 (Sato et al.. 2013)
(c) Coseismic seafloor displacements (red arrows) of the 2011 M 9.0 Tohoku earthquake from GPS-A measurements by Japan Coast Guard (Japan Coast Guard 2011, Sato et al. 2011a) and Tohoku University (GJT3, GJT4) (Kido et al. 2011
(d) Postseismic motions of seafloor stations during a ∼10-month period following the earthquake (Japan Coast Guard 2012
(R.B¨urgmann and D. Chadwell, Annu. Rev. Earth Planet. Sci. 2014. 42:509–34)

Yamada, T., M. Ando, K. Tadokoro, K. Sato, T. Okuda, and K. Oike (2002), Error evaluation in acoustic positioning of a single transponder for seafloor crustal deformation measurements, Earth Planets Space, 54, 871–881.
R. Ikuta, K. Tadokoro, M. Ando, T. Okuda, S. Sugimoto, K. Takatani, K. Yada, and G.M. Besana (2008), A new GPS-acoustic method for measuring ocean floor crustal deformation: Application to the Nankai Trough, *Journal of Geophysical Research,* vol. 113, no. B2, B02401, 2008.
Roland B¨urgmann and David Chadwell (2014), Seafloor Geodesy, Annu. Rev. Earth Planet. Sci. 2014. 42:509–34.