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GPS Medium-Range Kinematic Positioning for the Seafloor Geodesy off Eastern Taiwan

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ABSTRACT

To realize the plate motion of the Philippine Sea Plate (PSP) and the characteristics of crustal deformation in the plate boundary zone between the PSP and Eurasia Plate, three seafloor geodetic arrays using a combination of GPS kinematic positioning and acoustic ranging techniques have been established off eastern Taiwan since 2008. Each array is composed of three transponders deployed on the ocean bottom in a triangular shape and has been observed at least two times since 2009. The GPS kinematic positioning in the relative distance ranging from 80 to 120 km off the eastern coast of Taiwan plays a main role in the whole seafloor geodetic deformation system. Seven stations from Taiwan Continuous GPS Array are taken as reference sites and three or four rover GPS units are set up on the vessel or buoy. Both on-land reference and onboard rover receivers record data in sampling rates of 1 and 5 Hz to determine the instantaneous positions of transducer onboard which transmits and receives the acoustic signal to and from seafloor transponders and the attitude of vessel or buoy in kinematic mode. We compare the results of medium-range kinematic positioning between the on-land reference stations and rovers onboard by the GrafNav and Bernese V5.0 software, respectively. In addition, we determine the attitude at all times by way of computing the inter-distance of rover receivers onboard. Hence there are two positioning results can be estimated which are direct (by short relative distances from onboard) and indirect (by medium-range kinematic mode for each GPS unit from on-land continuous stations) methods, and the difference reveals in decimeter level.

KEYWORDS

medium-range kinematic, seafloor geodesy, attitude determination

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I. Introduction

From 1996 to 2008, a cooperative project between the Institute of Earth Sciences, Academia Sinica (IESAS), Taiwan and Philippine Institute of Volcanology and Seismology (PHIVOLS) has been conducted. The velocity field around the Taiwan and Luzon is acquired and it demonstrated the detail crustal motion in the Taiwan-Luzon region (Figure 1) [1]. To better understand the plate motion and characteristics of crustal deformation in the plate boundary zone between the PSP and Eurasia Plate and PSP and Ryukyu arc, we set up three transponder arrays off eastern Taiwan since 2008 (Figure 2), to discover the seafloor movement behaviors.

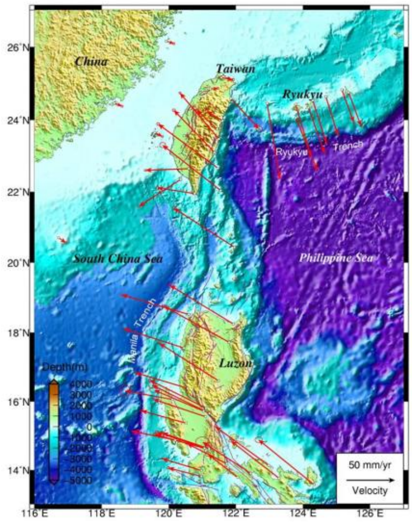

Figure 1
Velocity field around the Taiwan and Luzon region

Since 1985, Spiess proposed the seafloor geodesy determination using acoustic technique [2], and combined the GPS method into the seafloor deformation monitoring [3]. Till 2000, the GPS medium-range kinematic positioning algorithm improves the station accuracy and reliability to lead the enhancement on the application of the acoustic and GPS combination techniques. Hence, geodesy researchers have focused the study on the ocean plate and seismic active areas [4] - [8]. The experiences from above papers indicate the positioning accuracy reaches 3 cm and 10 cm in horizontal and height components, respectively for 100 km relative distance.

In this study, we utilize seven continuously observation reference station (CORS) which presented as green dots in Figure 2. Two positioning results can be estimated which are direct (by short relative distances from onboard) and indirect (by medium-range kinematic mode for each GPS unit from on-land continuous stations) methods, and the difference reveals in decimeter level.

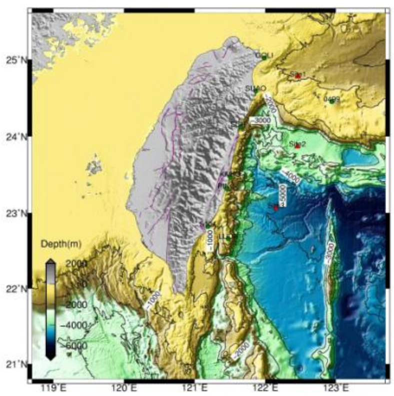

Figure 2
The transponder arrays off eastern Taiwan, denoted in red triangle

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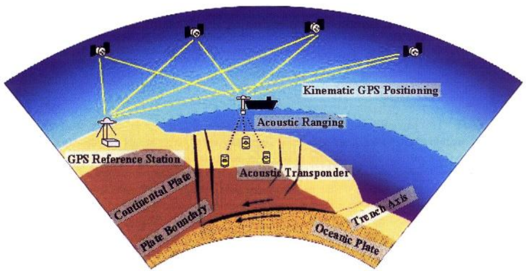
II. Array design and data acquisition

Since 2008, the IESAS has set up three seafloor transponder arrays which located off Ilan, Hualien and Taitung, and each array is composed of three transponders. The relative distance between seafloor arrays to CORS is around 80 km, 100 km and 90 km, and the depths reach 1000 m, 3000 m and 5000 m, respectively. In the acoustic/GPS seafloor study, there are 4 basic requirements: (1) Estimate the relative position between reference stations on-land and vessel or buoy placed at sea. (2) Determine the instantaneous transducer positions at all time by means of attitude determination of the vessel or buoy. (3) 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. (4) Measure the velocity of sound while advancing, considering the depth and the horizontal difference correlated with time (Figure 3). Through the repeated campaigns to obtain the relative positions of different periods between the CORS and the transponders, then the seafloor deformation can be estimated [4], [9].

Figure 3
Acoustic/GPS seafloor deformation monitoring diagram (excerpt from Asada et al., 2004)



2.1 Taitung array

We set up Taitung array to the south of Ryukyu trench to understand the seafloor velocity off Taitung area. Three transponders are placed by suitable equipment and well training technicians in Ocean Researcher 1 (OR3) on September 2009 (Figure 4).

Figure 4
The OR3 (left) and set up the transponder (right) at Taitung array

Taitung array is the deepest network of the current setting arrays in the Taiwan area, and it has 5000 m deep. To reduce the noise from the engine of vessel, we built up the transducer and 3 sets of GPS receivers in a buoy (Figure 5) and drag in the tail of the vessel by 50 m string and cables. When we took the acoustic observation, the vessel kept in drifting hence the buoy was floating freely on the sea.

Figure 5
The transducer (left) and the buoy with GPS antennas and transducer (right).

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2.2 Hualien array

The Hualien array is placed in the middle of the Ryukyu arc and Ryukyu trench, and it is located in the front of the subduction zone between PSP and Ryukyu trench. In the first experiment, we hired a whale-watching boat to place the transponders and fixed the transducer and 4 sets of GPS equipments on the boat on Mar. 2009 (Figure 6).

Figure 6
The transducer (left) and the GPS antennas (right) in the whale-watching boat

Six months later, we made the repeated observation in Hualien array, and the later measurement was taken by OR2 on April 2010.

The vessel kept in drifting freely on sea, when we did the acousticranging.

2.3 Ilan array

Ryukyu arc is located between Okinawa trough and Ryukyu trench, and an obvious velocity change can be found at SUAO (Taiwan) and 0549 (Ryukyu island) (Figure 2), hence we set up the off Ilan array in the southern Okinawa trough to detect the moving behavior of this transition area. Same as the Hualien array, we hired a fishing boat to place the transducers and take the first GPS/acoustic measurement on September 2008

Ilan array is the first ocean bottom transponder array set up in the Taiwan area. Till 2010, more than 3 times repeated observations have been made.

III. GPS medium-range kinematic positioning data processing

The accuracy of GPS medium-range kinematic positioning plays the main role in seafloor geodesy study. The data processing procedures have been proposed, and the positioning accuracy has been analyzed in some experiments in the Taiwan area [9]. The relative positions between CORS and the main GPS antenna at vessel or buoy need to be estimated precisely during the period of acousticranging, since the transducer position need to be corrected at all time by means of attitude determination of the vessel or buoy. Hence, to confirm the results of the medium-range kinematic positioning, we are not only compare the positioning results in different software, but also estimate two positioning methods which are direct (by short relative distances from onboard) and indirect (by medium-range kinematic mode for each GPS unit from on-land CORS). Even though there are two conditions to conduct the medium-range kinematic positioning on vessel or buoy, the requirement for the positioning accuracy is the same. The antennas on vessel or buoy can be estimated on short ranges, and the attitude can be determined precisely [10].

3.1 Comparison with different software

In 2009 off Taitung experiment, we fixed the transducer and 3 sets of GPS receivers in a buoy and drag on the tail of vessel by 50 m string. The relative distances between antennas are around 1.5 m, and about 90 km between CORS and anyone of antennas on buoy. We compare the kinematic positioning on SEA1 (upper graph of Figure 7) and SEA2 (lower graph of Figure 7) by different software.

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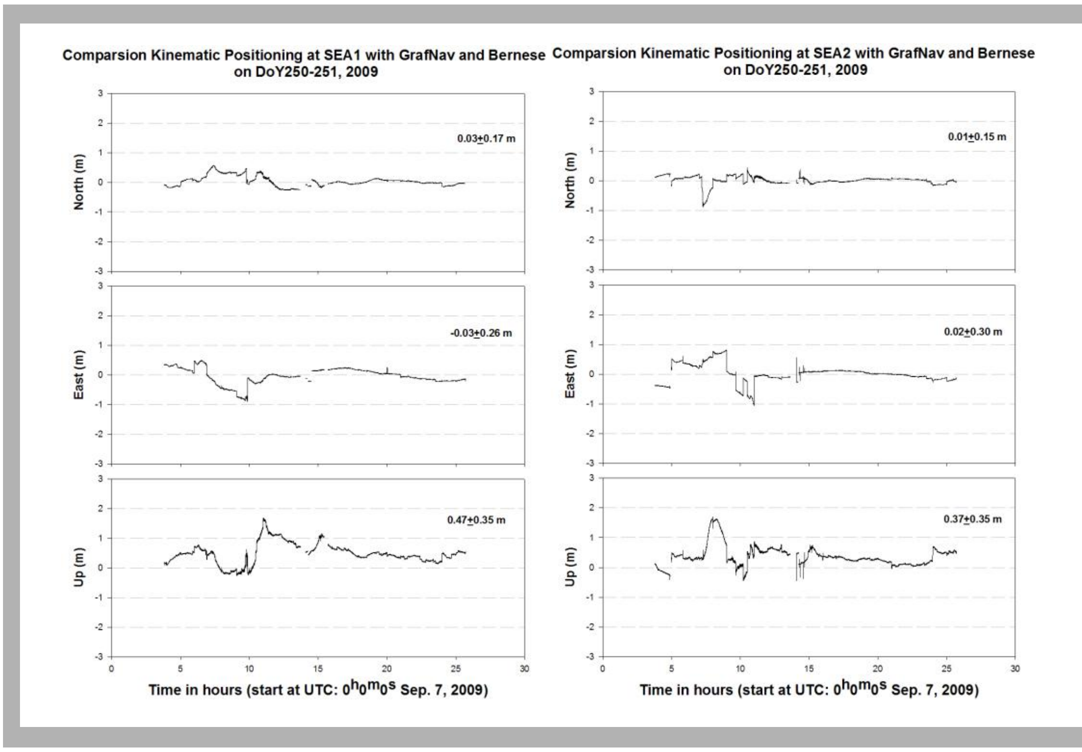

Figure 7
Comparison results on experiment of Sep. 2009 between GrafNav (commercial software by Novetel) and Bernese V5.0 (scientific software by university of Bern)

Figure 7 shows the positioning accuracy between CORS and buoy (the approximate distance is around 90 km) from GrafNav and Bernese V5.0 software. From the Figure 7, the x-axis denotes the time in hours, and the y-axis presents the difference of north, east and up components. The differences are 0.03±0.17m, 0.03±0.26 m and 0.47±0.35m from CORS to SEA1, and there are 0.01±0.15m, 0.02±0.30 m and 0.37±0.35m from CORS to SEA2, respectively.

Compare these two software on medium-range kinematic positioning, there is no obvious difference in horizontal component but reaches 0.5 m in vertical component. The largest difference occurred in time at 7 to 11, and 13 to 14 hours.

3.2 Comparison with different methods

To further estimate the accuracy between software, a difference from an indirect (by medium-range kinematic mode for each GPS receiver onboard from on-land CORS) and direct (by short relative distances between onboard receivers) algorithm on baseline of SEA1 to SEA2 can be seen in Figure 8.

Figure 8 shows the comparison results on experiment of Sep. 2009 between GrafNav (commercial software by Novetel) and Tsujii's (personal development software by Toshiaki Tsujii [10]). The results from GrafNav are estimation of two antennas on vessel from CORS, respectively, then the baseline between two antennas on vessel can be computed in an indirect way. In contrast, Tsujii's software calculates the short baseline on moving vessel directly. In Fig. 8, the x-axis denotes the time in hours, and the y-axis presents the difference of length, north, east and up components. The differences are 0.06±0.21 m, 0.03±0.18 m, -0.05±0.27 m and 0.09±0.39 m, respectively.

Figure 9 shows the comparison results on experiment of September 2009 between Bernese V5.0 and Tsujii's. Same as the procedure of Figure 7, the results from Bernese V5.0 are estimation of two antennas on vessel from CORS, respectively, then the baseline between two antennas on vessel can be computed in an indirect way, and Tsujii's software calculates the short baseline on moving vessel directly. In Figure 9, the x-axis denotes the time in hours, and the y-axis presents the difference of length, north, east and up components. The differences are 0.02±0.09 m, -0.02±0.08 m, 0.04±0.14 m and 0.19±0.21 m, respectively.

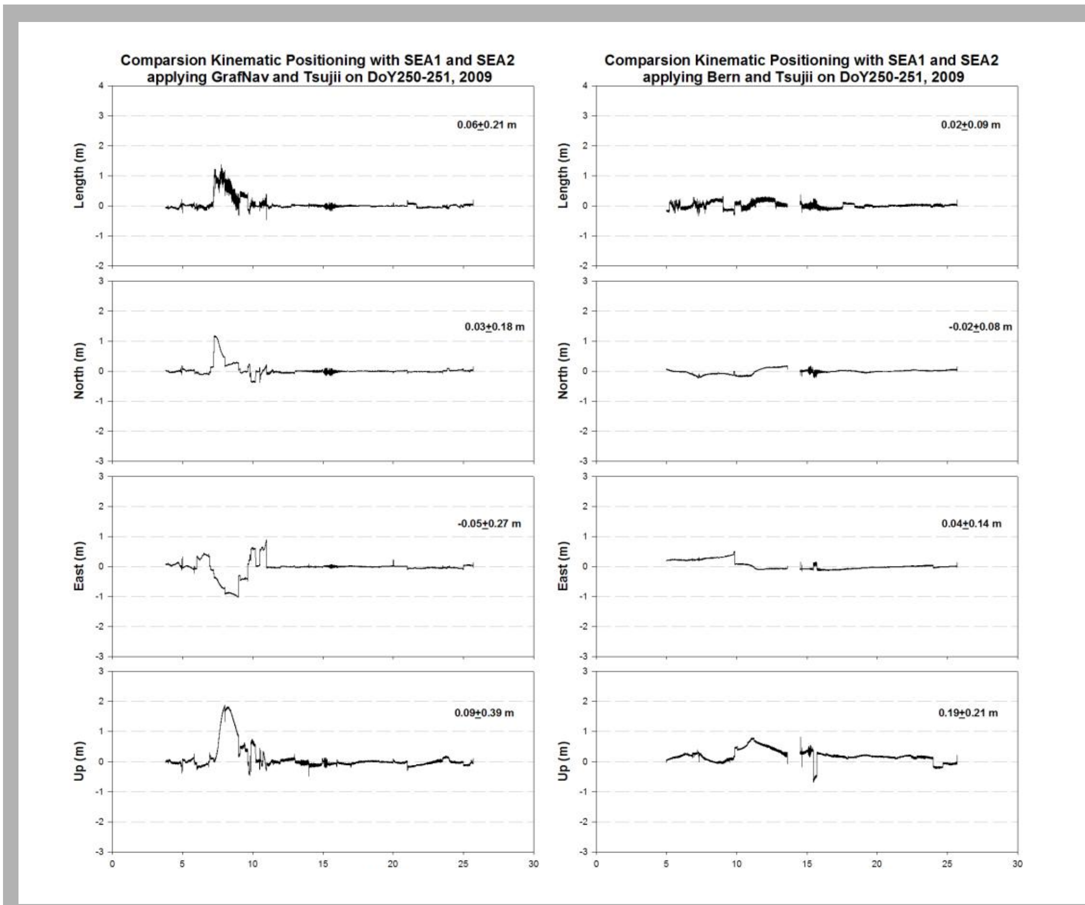

Figure 8
Left. Comparison results on experiment on Sep. 2009 between GrafNav (commercial software by Novetel) and Tsujii's (personal development software by Toshiaki Tsujii).

Right. Comparison results on experiment on Sep. 2009 between Bernese V5.0 (scientific software by University of Bern) and Tsujii's (personal development software by Toshiaki Tsujii).

Compare the results of Figure 8 and 9, Figure 8 shows a big scatter during the time at 7 to 11 hours in all components and caused a bigger uncertainty, and the Figure 9 appears bad solutions during the time at 13 to 14 hours in all components.

3.3 Comparison with 5 Hz sampling rate

To test the performance in high rate positioning, we processed the data on Hualien experiment on Nov. 2009 and plot in Figure 10.

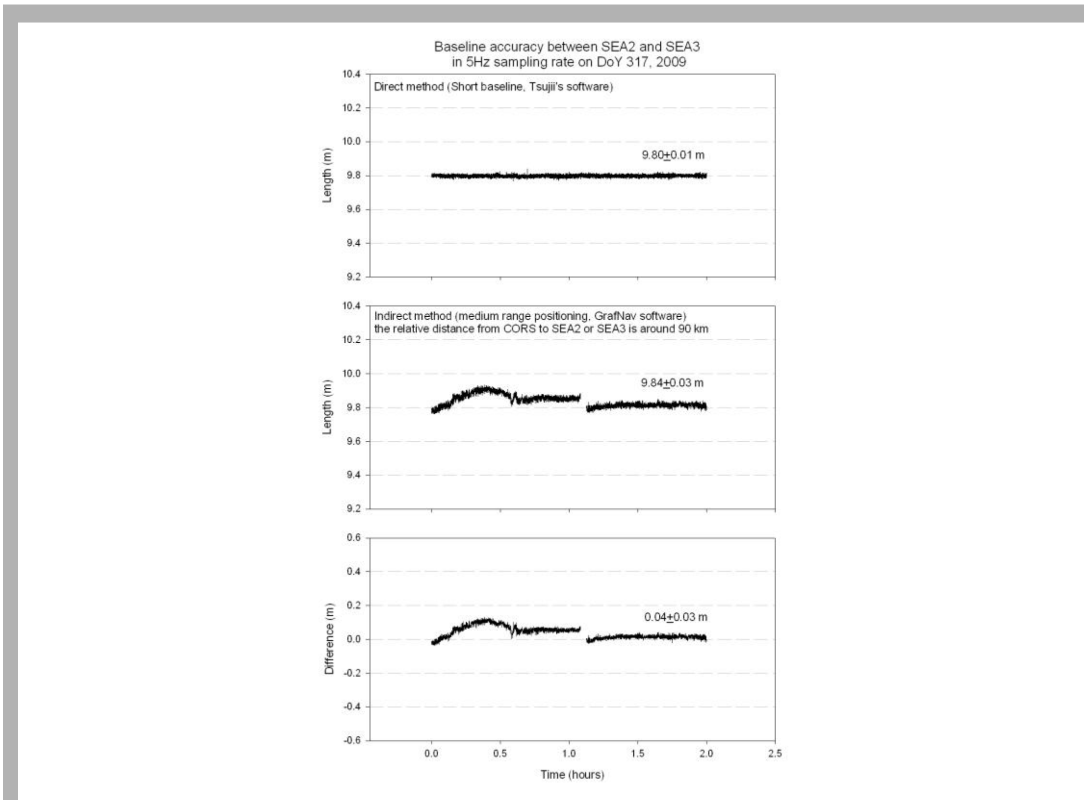

Figure 9
High rate processing results on DoY 317 2009 between GrafNav, Tsujii's and their difference.

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Figure 10 shows the processing results 2009 by GrafNav and Tsujii's, and their difference on DoY 317. The results from Tsujii's software (upper graph) calculates the short baseline on moving vessel directly, and GrafNav estimates two antennas on vessel from CORS, respectively then the baseline between two antennas on vessel can be computed in an indirect way (middle graph), and lower graph shows the difference from these two methods. In Figure 10, the x-axis denotes the time in hours, and the y-axis presents the positioning results and their difference. The variations are 9.80±0.01 m, 9.84±0.03 m and 0.04±0.03 m, respectively.

IV. Preliminary result on Acoustic/GPS positioning

Once we acquire the kinematic positioning result, attitude and acoustic information, the transponders positions on seafloor can be estimated. Figure 11 shows the transponder positioning in Ilan array on July, 2009.

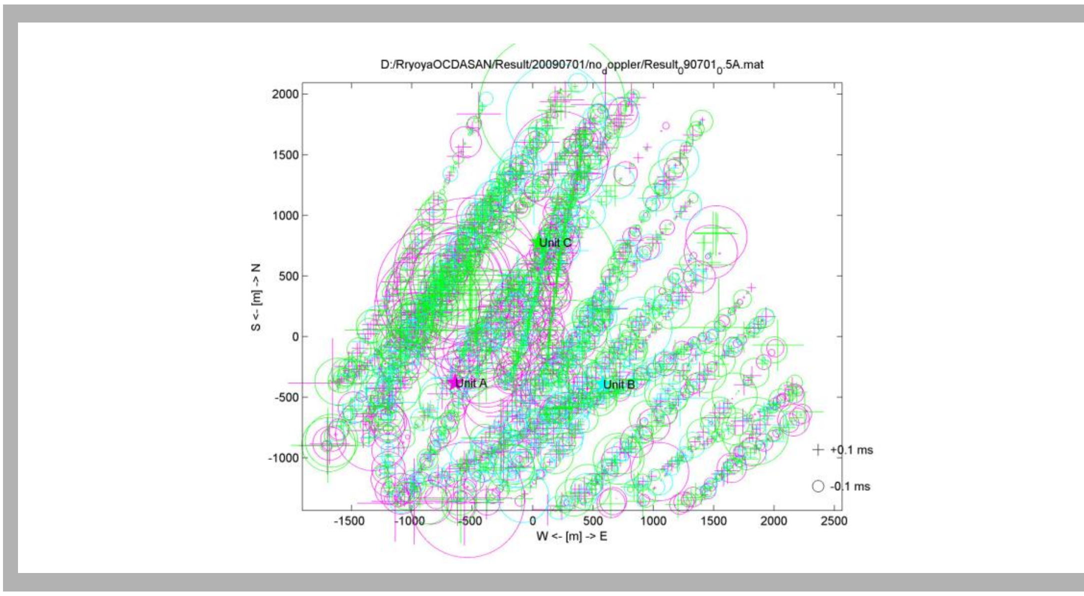

Figure 10
Transponder positioning in Ilan array on July, 2009

From the Figure 11, the transponders position denote in Unit A, B and C, and the cross and circle symbols represent the residual positive or a negative value and symbol size are proportional to the residual value. The overall positioning accuracy is about 20-30 cm.

V. Concluding remarks

After the actual offshore GPS/Acoustic survey, some concluding remarks can be made:

- Compare the results from GrafNav and Bernese V5.0 on medium-range kinematic positioning, there is no obvious difference in horizontal component but reaches 0.5 m in vertical component.
- Compare the indirect and direct methods, the results from GrafNav and Tsujii (Figure 8) presents 0.06±0.21 m, 0.03±0.18 m, -0.05±0.27m and 0.09±0.39 m in the length, north, east and up components, but there are 0.02±0.09m, -0.02±0.08 m, 0.04±0.14m and 0.19±0.21m from Bernese V5.0 and Tsujii, respectively.
- In the high rate experiment, the difference shows 0.04±0.03 m in length.
- The accuracy of transponder position only reaches decimeter level, have not been able to meet the precision (5 ~ 7 cm) of related literature.
- From current testing, the poor precision accuracy may cause by not enough observations, the non-uniform measured points, and instable transducer, etc. It still needs a great improvement on the observation techniques and data-processing strategy.

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