Joint Analysis of GNSS and InSAR for Deformation Monitoring: A Feasibility Study in Johor, Malaysia

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Key words: JUPEM; Geodetic Infrastructures; Deformation Measurement; GNSS / GPS; InSAR; Remote Sensing

SUMMARY

Information about deformation in an area has become vital not only for safety assessment but also for maintenance of geodetic infrastructures. The latter is necessary to support accurate surveying and mapping applications. This research exploits the complementary features of Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) techniques to assess the long-term deformation in Johor, Malaysia, which can be induced by natural and/or anthropogenic activities. Although continuous GNSS offers a complete profile of the surface changes in 3-dimensional view, very often, the technique is limited by the sparse distribution of GNSS stations. The result from InSAR analysis provides essential information for the surrounding area, although the profile is limited to the line-of-sight (LOS) of the satellite. The analysis of five years GNSS data at eight Malaysia Real-Time Kinematic GNSS Network (MyRTKnet) stations revealed deformation that can be explained by plate tectonic movements and earthquakes in the surrounding region. In addition, two LOS velocity maps have been produced from the InSAR time-series to assess the surrounding deformation of Johor. Two sets of ERS-1/2 data, consisting a total of 67 images acquired in two descending tracks (i.e. track 75 and 347), are utilised for the generation of the maps. Moreover, the feasibility of the newly available Sentinel-1 satellites is also tested, which revealed improved coherence owing to their short revisit cycle. Some part of Johor showed subsidence and uplift trends, which also agreed with literature. This information cannot be perceived with the GNSS technique alone due to its limited coverage; hence, further attests to the benefit of their joint analysis. This work is yet another example of the implementation of geospatial information to support effective decision making.

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1. INTRODUCTION

Malaysia is occasionally affected by seismic activities due to its geographical location, which is situated within the buffer zone of the Pacific Ring of Fire. A study by the Department of Survey and Mapping Malaysia (JUPEM) using data from Continuously Operating Reference Stations (CORS) revealed movements up to 25.8 cm, interpreted as the result of co-seismic and post-seismic motions from the 2004, 2005, and 2007 Sumatran earthquakes (JUPEM, 2009). Similarly, Vigny et al. (2005) detected movements ranging from 2 to 17 cm resulted from the 2004 Sumatra-Andaman earthquake. Larger displacements occurred in the northern peninsula and extended more than 3,000 km from the earthquake epicentre. Interestingly, the direction of these movements was towards the west as opposed to the normal velocity, i.e. towards the east at 1.2 ± 0.3 cm per year with respect to Eurasia plate (Michel et al., 2001).

There are other factors that contribute to the growing demand for deformation monitoring in Malaysia. A number of unfortunate tragedies such as the collapse of Highland Tower on 11 December 1993, the tsunami in West Coast of Peninsular Malaysia on 26 December 2004, and major floods that strike almost every year during monsoon season are among the evidence of the need for this monitoring. The rise of public awareness and concern especially with the increasing number and complexity of engineering structures add onto the list. In general, the primary purpose of deformation monitoring is the detection of spatial deformation to provide information on the stability and extent of any movement or deformation of an object occurring over time (Halim, 1995). It is useful for safety assessment as well as predicting and preventing the possibility of failure or disaster in the future. In addition, information about surface changes is valuable for identifying the priority areas as well as the interval for the maintenance of geodetic infrastructures. Regular maintenance is necessary for certain infrastructures such as GNSS reference stations, benchmarks or gravity points as they are subjected to change due to natural and/or human-induced factors.

Two space-based positioning techniques commonly used for monitoring deformation with high precision and accuracy are InSAR and GNSS. InSAR is suitable for monitoring deformation over large areas owing to its spatial coverage. Since InSAR does not rely on ground observation, it has advantages for remote, dangerous or inaccessible sites. The uses of this technique for deformation monitoring have been reported by various researchers such as for monitoring earthquakes (e.g. by Massonnet et al., 1993; Wright, 2002), landslides (e.g. by Refice et al., 2000; Rott and Nagler, 2006), volcanoes (e.g. by Massonnet et al., 1995; Lanari et al., 1998), land subsidence (e.g. by Amelung et al., 1999; Sowter et al., 2013), and engineering structures (e.g. by Wang et al., 2010). Nevertheless, the resultant deformation profile is limited typically to the line-of-sight (LOS) of the satellite.

On the contrary, GNSS gives better representation in a three-dimensional view, but this information is limited only to the observed stations (point-specific deformation profile). Other factors such as the cost of setting up GNSS stations (monument, equipment and operational cost) and the source of the power supply (for continuous monitoring) must also be considered. However, the uses of GNSS for monitoring deformation are increasing owing to the rapid increment of permanent GNSS network in many countries. In Malaysia, JUPEM has established MyRTKnet since 2002. Currently, it consists of 99 stations, with 66 in Peninsular Malaysia and 33 in East Malaysia. Availability of the permanent GNSS network has enabled users, among others, to only use single GNSS receivers for deformation monitoring, hence reducing the overall cost. Many researchers have demonstrated the usages of GNSS for various applications such as for monitoring plate tectonics (e.g. by Vernant et al., 2004; Qu et al., 2014), earthquakes (e.g. by Ergintav et al., 2007; Li et al., 2015), land subsidences (e.g. by Abidin et al., 2001; Baldi et al., 2009), and engineering structures (e.g. by Meng et al. 2007; Yi et al., 2013).

Integrating InSAR and GNSS certainly enable better analysis, covering both surrounding and point-specific deformation profiles. For this reason, various integration techniques were explored and investigated by many researchers. Lagios et al. (2012) utilised results from InSAR and GNSS to achieve a better understanding of seismicity patterns in Cephalonia, Greece, thus enabling a prediction of future earthquakes. Similarly, Tang et al. (2012) used InSAR and GNSS for monitoring subsidence over a coal mining area and concluded that it is more efficient compared to the conventional method, i.e. using the electronic total station and levelling instrument, especially in the mountainous region. On the other hand, Wang et al. (2012) and Cavalie et al. (2013) incorporated InSAR and GNSS results to derived deformation parameters such as the location of the epicentre, the magnitude of the earthquake, and the fault geometry. It is without a doubt that both of these techniques are complementary to each other, and their integration will enable robust analysis to obtain a complete deformation profile. In this work, their joint analysis is demonstrated to be useful for the assessment of the long-term deformation in Johor, Malaysia.

2. GNSS AND SAR DATASET

In the past, investigation on surface changes was greatly hindered by the lack of data owing to the significant cost involved to carry out a continuous measurement. Establishment of CORS opens up new possibilities for this sort of monitoring. A denser CORS network allows improved understanding of the local deformation phenomena. Similarly, InSAR technique has benefited from the long record of SAR images acquired over the past years through various platforms.

2.1 GNSS Dataset

The GNSS data covers five years' period spanning from 2007 to 2011. The data can be categorised into three groups: (1) 27 IGb08 stations that represent the core-site of the IGb08 reference frame; (2) 7 International GNSS Service (IGS) stations to bridge and shorten the baselines length in double difference processing; and (3) 8 MyRTKnet stations in Johor that serve as the target stations. The geographical distribution of the stations is given in **Figure 1**.

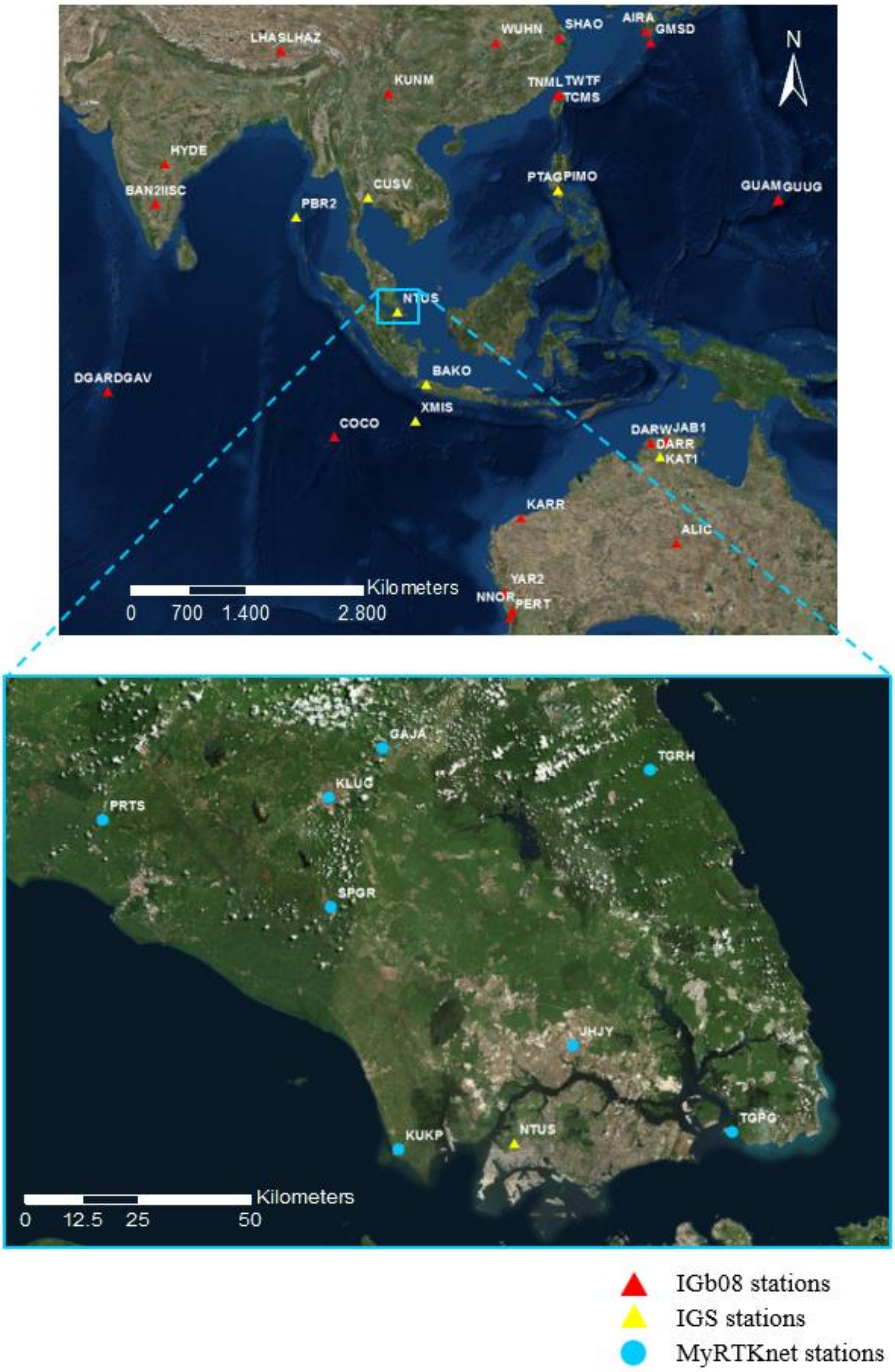

Figure 1: Distribution of the GNSS stations.

2.2 SAR Dataset

The SAR data are from two satellite missions, namely, European Remote-sensing Satellite (ERS)-1/2 and Sentinel-1A/B. These satellites operate in C-band frequency and have approximately 5.6 cm wavelength.

2.2.1 ERS-1/2 images

ERS is the first European Space Agency (ESA) program in Earth observation to provide environmental monitoring in the microwave spectrum. Two ERS satellites, i.e. ERS-1 and ERS-2, were launched into the same orbit at altitude ~785 km in 1991 and 1995, respectively. The ERS-1 mission ended on 10 March 2000 due to the failure of the onboard attitude control system, whereas ERS-2 mission ended on 5 September 2011 after the satellite altitude had been lowered to altitude ~573 km. A total of 67 ERS-1/2 images comprising of 34 ERS-1/2 images in track 75 and 33 ERS-1/2 images in track 347 are used for the generation of the LOS velocity maps. All images are from descending orbit and located in frame 3573. The data in track 75 covers from 5 August 1993 to 23 February 2003, whereas the data in track 347 covers from 4 May 1995 to 12 November 2010.

2.2.2 Sentinel-1 images

The Sentinel-1 mission comprises of two satellites: Sentinel-1A launched on 3 April 2014, and Sentinel-1B launched on 25 April 2016. Both satellites are placed in a near-polar, Sun-synchronous orbit at an altitude of approximately 693 km. The repeat period is 12 days with one satellite in the constellation and reduced to 6 days with the second satellite. The lifespan expectancy of the satellites is seven years with consumables for 12 years. The Sentinel-1 satellites provide continuity of C-band SAR imagery after the ERS-1/2 and ENVISAT missions and offer many benefits for deformation monitoring. Rapid deformation rates can be monitored owing to the short revisit cycle of the satellites (Torres et al., 2012). As a consequence, a shorter time is required to gather a sufficient stack of images (De Zan et al. 2008, Attema et al. 2010) which will be helpful for routine long-term monitoring applications. Furthermore, the swath width of the Interferometric Wide (IW) product is around 250 km, allowing the monitoring of large areas using fewer acquisitions. There are 22 Sentinel-1 images used for the processing, which cover the period from 22 March 2015 to 24 September 2016. This work provides the first assessment of the feasibility of using Sentinel-1 for deformation analysis in Malaysia.

3. GNSS DATA PROCESSING

The GNSS data processing was carried out using Bernese GNSS Software version 5.2. Summary of the strategy adopted for the processing is given in **Table 1**.

Table 1: GNSS data processing strategy.

No.	Item	Strategy
1.	GNSS Processing Package	Scientific using Bernese GNSS Software version 5.2
2.	GNSS Processing Strategy	Double Difference
3.	Primary GNSS Observable	Ionospheric Free (Lc)
4.	Reference Frame	IGS realisation of ITRF2008, i.e. IGb08
5.	Orbits	Final orbit provided by Center for Orbit Determination in Europe (CODE)
6.	Earth Orientation Parameter (EOP)	Final EOP provided by CODE
7.	Elevation Cut-Off Angle	15 degrees
8.	Sampling Rate	30 seconds
9.	Zenith Troposphere	Full Mapping Function
10.	Troposphere Mapping	Vienna Mapping Function-1 (VMF-1)
11.	Solid Earth Tide	TIDE2000
12.	Ambiguity	Default strategy in Bernese 5.2, i.e. according to baseline length
13.	A Priori Coordinates and Antenna Heights	Provided by CODE
14.	Ocean Tide Loading	FES2004
15.	Antenna Phase Centre Offset and Variation	Absolute Antenna Phase Centre Offset and Variation provided by CODE

4. INSAR DATA PROCESSING

The processing of SAR data is carried out using in-house software developed at the Nottingham Geospatial Institute, the University of Nottingham. The software employs the novel Intermittent Small Baseline Subset (ISBAS) algorithm (Sowter et al. 2013; Bateson et al. 2015) that is well-suited to low-resolution, wide-area deformation monitoring over a broad range of land classes, including grasslands, agricultural and forested cover (Cigna et al., 2014; Sowter et al., 2016). In general, ISBAS follows similar principles as the standard Small Baseline Subset

(SBAS) method described in Berardino et al. (2002) but relax the threshold that the pixel must display consistently high coherence, i.e. the degree of similarity between the two images, over the entire interferograms. The standard processing scheme for Punnet is given in **Figure 2**.

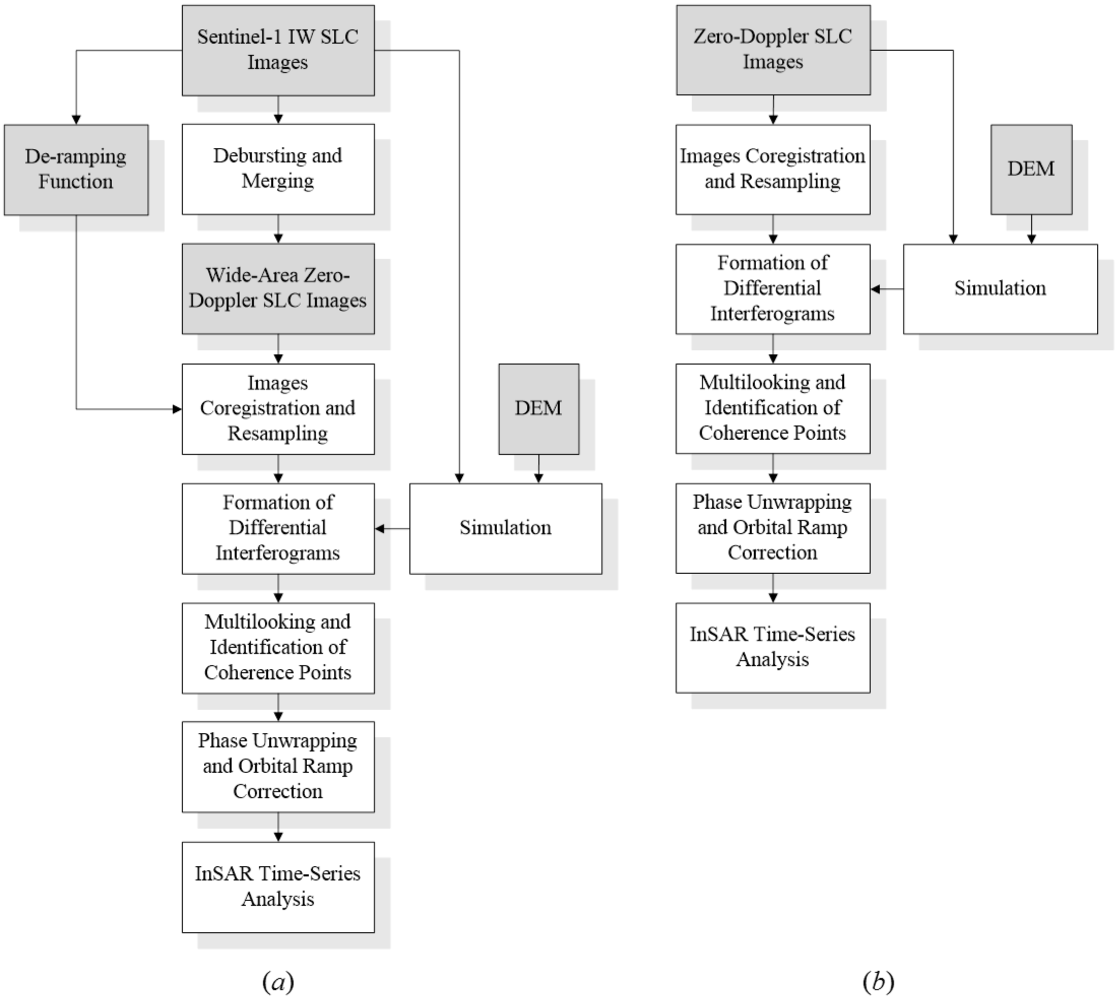

Figure 2: Standard processing scheme for the InSAR software using (*a*) Sentinel-1 dataset, and (*b*) other standard Single Look Complex (SLC) datasets

5. PRELIMINARY RESULTS AND DISCUSSION

5.1 GNSS Results

From the GNSS results, the most significant movement of all MyRTKnet stations in North-South, East-West, and Up-Down components is found at PRTS (-1.25 ± 0.01 cm/year), TGPG (2.06 ± 0.01 cm/year), and KUKP (-0.41 ± 0.01 cm/year), respectively. It implies that the current MyRTKnet stations in Johor have moved by as much as -22.50 cm in North-South, 37.08 cm in East-West, and -7.38 in Up-Down components, as of 1 January 2018, considering their reference epoch (i.e. ITRF2000 at epoch 2000.0). Reviewing these movements, the coordinates of MyRTKnet stations are a due revision to ensure that they are in line with the latest realisation of International Terrestrial Reference Frame (ITRF), as well as to guarantee the provided accuracy and reliability. Currently, the Geodetic Survey Division, JUPEM is working on the next realisation of geocentric datum known as the Malaysia Geocentric Reference Frame 2020 (MGRF2020), which is expected to be ready soon.

For simplicity, only the result of JHJY station is shown here (**Figure 3**) as the trend is quite similar to the rest of MyRTKnet stations in Johor. The figure shows the daily coordinates time-series of JHJY in North-South, East-West, and Up-Down components. On top of that, the RMS for coordinate estimation is also plotted, colour coded to show the value in North-South (dark blue), East-West (green), and Up-Down (cyan). The red dotted lines in the y-axes indicate earthquakes larger than 6Mw.

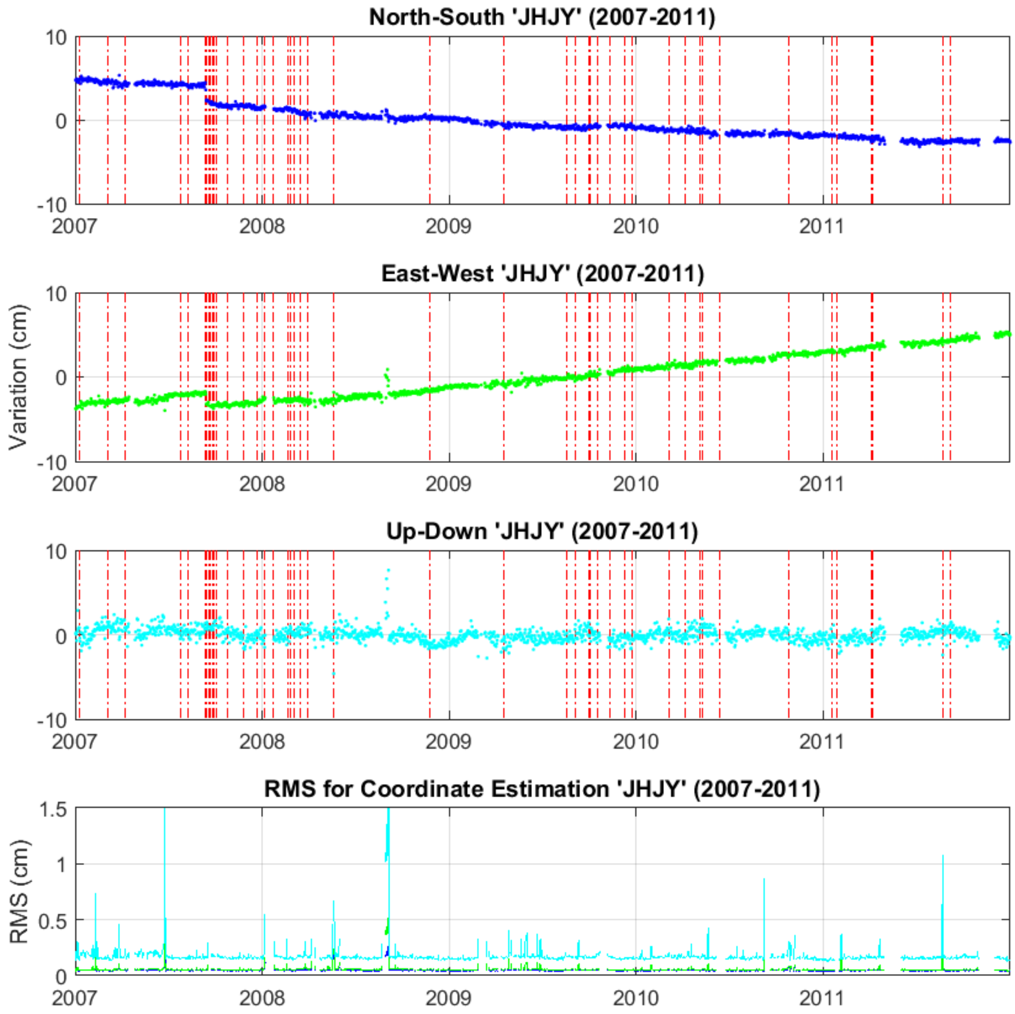

Figure 3: Daily coordinate time-series for station JHJY (2007 - 2011)

5.2 InSAR Results

Discussion of the InSAR results in this paper will only focus on the ISBAS processing of 33 ERS-1/2 images in track 347. One of the advantages of using ISBAS algorithm as opposed to the standard SBAS is improved coverage. There are 293,339 points identified in the ISBAS processing (excluding water body); an improvement of approximately 28.46% compared to the standard SBAS algorithm (**Figure 4**). It is noticeable that the standard SBAS points are very sparse, typically concentrated in the urban areas such as Johor Bahru, Kluang, Skudai, Senai, Kulai, and Pontian. The areas have dense human-made structures, which are convenient targets for the coherent pixels. On the other hand, ISBAS coverage is more distributed across the entire image; thus, allowing better representation of the deformation. It is worth noting, however, that inclusion of more ISBAS points also increases the risk of noisy results.

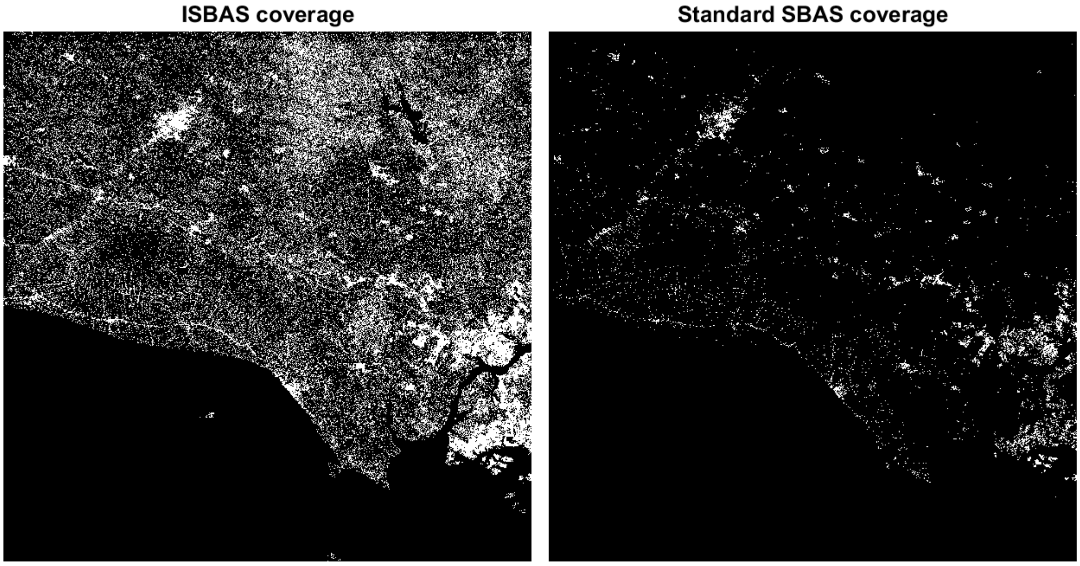

Figure 4: Coverage comparison between the ISBAS and SBAS techniques from the ERS-1/2 (track 347) results. White points represent coherent points in the image.

The LOS velocity map from the InSAR time-series (**Figure 5**) allows assessment of the vertical deformation for areas not covered by MyRTKnet. Location of the 8 MyRTKnet stations is shown as red points. Additionally, the peatland area, as extracted from the International Wetlands (2010), is shown in the black polygon. The map is somewhat noisy as low coherent targets dominate the area. Errors from the phase unwrapping also could propagate to the estimated velocities. The rates range from -1.16 cm/year (subsidence) to 1.03 cm/year (uplift), with the average value of -0.13 cm/year. They are relatively good in the urban areas but deteriorate in the remote/rural regions. The values vary between 0.03 and 0.53 cm/year. Approximately 91.8% of the coherent points have the standard error of less than 0.25 cm/year, but the percentage dropped to about 57.2% for points with a standard error of lower than 0.20 cm/year. The small standard errors suggest that the atmospheric phase, orbital and DEM errors are well reduced in the time-series processing.

It is interesting to note that the peatland area, marked by the black polygon in **Figure 5**, generally shows a subsidence trend. Wösten et al. (1997) have reported a similar pattern, with an average subsidence rate of 2 cm/year. The rate was derived from 17 markers planted in the area. They also reported that the subsidence rate decreases gradually with time and may be divided into an initial, very rapid consolidation component, and a slow oxidation and shrinkage component. Based on the recorded measurement over 21 years, the estimated rate in the earlier period was 4.6 cm/year but reduced to 2.0 ± 1.5 cm/year after 1988. For comparison, the estimated rates from the ISBAS analysis, using data spanning from 4 May 1995 to 7 January 2005, reach up to -1.6 cm/year (subsidence) for the peatland area. On the other hand, the standard errors range from 0.03 to 0.40 cm/year. Therefore, it can be concluded that the rates from the two results are comparable considering their standard errors.

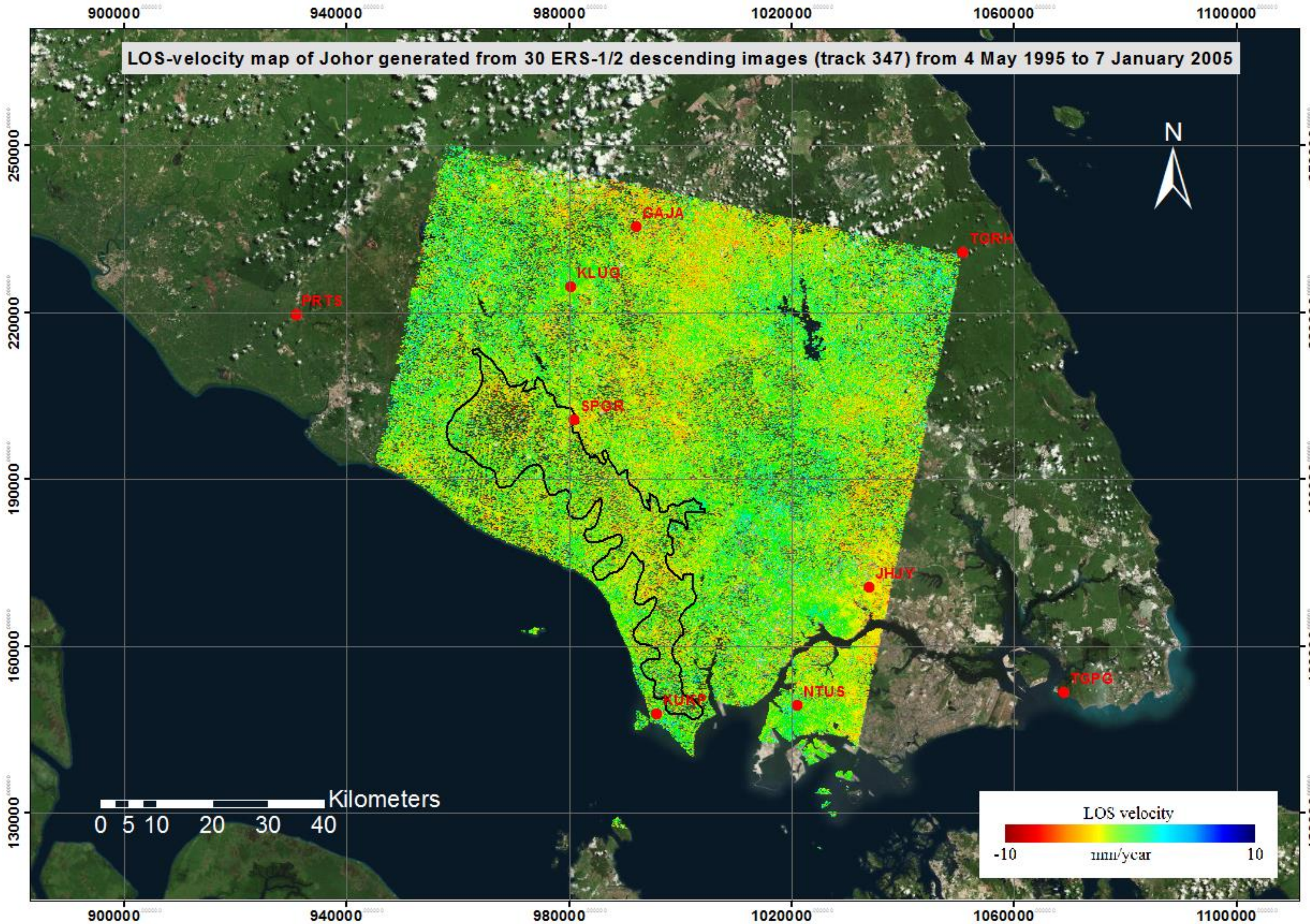

Figure 5: LOS velocity map of Johor from the ERS-1/2 (track 347) processing.

Comparison of the vertical rate from GNSS and InSAR showed agreement in the direction, but the difference in the magnitude. While GNSS observed a trend at a particular point measured by the receiver, the velocity of an ISBAS point represents the movement of an area covered by the multi-looked windows. As the conversion of LOS-velocities to the vertical direction also based on the assumption that there is no horizontal movement, it may cause misinterpretation of the actual ground motion that happens in both horizontal and vertical directions. If the surface displacement were in the SAR azimuth direction, it might be entirely missed from the InSAR LOS measurement.

6. CONCLUSIONS AND RECOMMENDATIONS

It is evident that GNSS and InSAR have complementary features. GNSS has successfully quantified movements from the tectonic motion and earthquakes in the surrounding region, whereas InSAR has identified the local subsidence due to the development of tropical peatland and urbanisation in Johor Bahru City. Information about the derived velocities from GNSS and InSAR time-series will be useful to infer the frequency of maintenance works needed for geodetic infrastructures in the vicinity. It is expected that integration of these two techniques will continue to develop in light of the newly available Sentinel-1 satellites. The satellites have short revisit cycle, and small orbital separation, which is expected to improve the coherence in the area. Moreover, the Sentinel-1 data is accessible for free, which definitely adds to its interest.

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BIOGRAPHICAL NOTES

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- Early career began as a hydrography surveyor at the Fugro Geodetic (Malaysia) Sdn. Bhd. and since then has involved in numerous offshore positioning works such as seismic survey, pipeline route survey and installation, anchor positioning for rig and barge, platform installation, positioning for Remote Operated Vehicle (ROV) etc.
- Joint the Department of Survey and Mapping Malaysia (JUPEM) in December 2007.
- Pursue and completed PhD degree at the University of Nottingham, United Kingdom in 2017.
- Currently engaged with the Geodetic Survey Division, JUPEM.
- Primary research interest is in deformation analysis using GNSS and InSAR.

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