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*A*ccurate *G*PS-based *EN*ergy harvesting *O*perated *R*elative positioning (AGENOR) for Land Deformation Monitoring and Landslide Detection

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ABSTRACT

Land deformation monitoring is one of the most important aspects of landslide monitoring that provides an important basis for identifying landslide risk. The types of sensors used in current practice provide valuable data related to landslides, but incur costs in excess of US$300,000 per site, limiting their deployment to only very high-risk sites. Our system utilizes low cost Global Positioning System (GPS) receivers; each node costs about $100 and, powered by energy harvesting, can be deployed in large numbers providing pervasive coverage of areas that are potentially vulnerable to landslides. Each self-powered sensor records its location periodically and transmits the GPS data wirelessly to a remote collection centre for processing. Taking advantage of the similarity in wireless channel conditions of sensors within close proximity, we are able to accurately compute the relative displacement between any two neighbouring wireless sensors without the need to determine the exact locations of the sensors. Even under harsh conditions where only intermittent GPS data are available, we are able to achieve sub-centimetre accuracy based on our outdoor tests in New Zealand and also at Taiwan's LuShan landslide site.

Keywords: GPS, energy harvesting, landslide detection, land deformation monitoring

INTRODUCTION

The monitoring of landslide movement patterns remains a challenge despite recent availability of techniques such as laser-based geodetic techniques, GPS-based systems and ground-/satellite-based radar (Thiebes, 2012). Most, if not all, existing techniques in use rely on the availability of accurate location information of sparsely deployed monitoring points in the landslide region together with data from other sensing devices (Massey *et al*., 2013). While current practice also use various types of sensors like extensometers, in-place inclinometers, tiltmeters, pressure transducers and rain gauges, all of which provide valuable data related to landslides, their use incurs costs in excess of US$300,000 per site, which limits their deployment to only very high-risk sites due to obvious cost reasons.

We propose an *A*ccurate *G*PS-based *EN*ergy harvesting *O*perated *R*elative positioning (AGENOR) system for land deformation monitoring and landslide detection. Our technique adopts a totally different approach that does not require the knowledge of accurate location information. Instead, we aim to accurately determine the relative displacement between any two neighbouring GPS-enabled wireless sensors without

the need to determine the exact locations of the sensors. Each sensor acquires GPS data periodically and transmits the raw data wirelessly to a remote collection centre. Wireless signals from GPS satellites suffer from various environmental interferences that adversely affect the accuracy of the location estimation. However, when we consider two GPS nodes that are close to each other, we can "cancel out" the inaccuracy that arises from wireless transmission errors because they experience similar channel conditions which we exploit to accurately compute any relative displacement between the two nodes. This approach enables us to use low cost consumer-grade GPS chips in our sensors (incurring costs of about $100 per unit).

Field tests on an actual landslide site showed that our algorithm could achieve accuracy up to 4mm 2DRMS, i.e. twice the Distance Root Mean Squared, which is a single number that expresses the 2-dimensional accuracy with 95% probability (National Research Council, 1995). While 4mm 2DRMS may not be as accurate as sophisticated hardware currently in use, the low cost per node means that we can deploy them in large numbers over areas that are potentially vulnerable to landslides, to provide an indication to warrant the deployment of more accurate systems. When all the relative positions of sensors are correlated to one or more sensors with known locations, e.g. reference/survey point, we can create a map of the entire region being monitored and detect any land movement.

Another advantage that our system provides is that the nodes run off renewable energy sources, like small footprint photovoltaic energy harvesting, and do not require a sustained power source. The lack of a sustained power source implies that GPS data are not continuously available, and can adversely affect the accuracy of a typical GPS-based positioning system. Our system has been shown to operate in harsh conditions where only intermittent GPS data are available, supported by results from outdoor deployments in New Zealand and Taiwan.

GPS BACKGROUND & RELATED WORK

GPS receivers are commonly classified into three different grades: consumer/recreational, mapping and survey. Survey grade GPS receivers are the most accurate of all three types of receivers while consumer grade are the ones typical in cell phones, which people are most accustomed to, and have the poorest accuracy. Survey grade GPS dual band receivers used with phase based differential static survey methods can produce solutions with accuracies less than 1 cm (GPS Guidebook, 2004), with a price tag of more than US$8,000 each (Andersen *et al*., 2009). Consumer grade GPS receivers are single band with uncalibrated antennas and are usually only intended for autonomous coarse acquisition code solutions with an accuracy of a few meters at best. However, effects such as the atmosphere and structures, inaccuracies in the ephemerides (data used to calculate the position of each satellite in orbit), timing, etc., introduce other errors that degrade the accuracy further.

Being autonomous solutions, the positions are absolute therefore useful for telling you where you are in the world, but not particularly suited for land deformation monitoring where relative solutions which are more accurate are better suited. While the power of consumer grade GPS receivers is generally low, autonomous solutions cannot be seriously considered as a viable alternative to differential phase based methods where accuracy is demanded. Despite the fact that consumer grade GPS receivers are not intended for precise work does not imply that they lack the capability; some modules output pseudo-ranges and phase data, such as, SiRF IV (SiRF Technology, Inc.), Ublox's LEA-6T, NEO-6P and NEO-7P (u-blox), thus allowing differential phase based methods to be used.

Consumer grade single band GPS receivers have been used as a lower cost alternative to survey grade GPS systems (Knecht and Manetti, 2001; Manetti *et al*., 2002a,b). Manetti *et al*. (2002a,b) propose a carrier phase measurement based system where the measurement stations communicate with a control centre and has a predetermined operating sequence of measurements and communication. They report processing delays between 10 and 20 minutes indicating two measurements which is considerably slow response. They claimed 7 mm accuracy in the horizontal plane, presumably 2DRMS. Keeping the GPS receivers continuously on for 15mins to 30mins with a good antenna is a typical time required to get a good solution using phase observables on a single band GPS receiver. However, there is no evidence of the self-powering mechanism and the battery sizes. Both works lack discussion on achieved accuracy and details of the real-life implementation, although the proposed system bears some similarity to our system. To the best of our ability, we have not been able to find any subsequent developments on these ideas by Manetti *et al*.

DESIGN

The core of AGENOR is the inter-node displacement algorithm called the *Code Float Fix Sidereal* (CFFS) algorithm. It is a static relative positioning solution specifically designed for nodes deployed in a harsh environment, communicating data over lossy wireless links. The nodes are powered by photovoltaic energy harvesting and small in size, designed for detecting slow land movement / deformation over a long period of time.

Architecture Overview

CFFS consists of four stages: code, float, fix and sidereal filtering. The code stage makes the first location estimate from the GPS data acquired by the nodes and each subsequent stage (float, fix and the sidereal filtering) is designed to produce a more accurate position solution than the previous stage. The last stage, sidereal filtering, is used to improve inter-day solution precision and also alleviate multipath.

To find a relative positioning solution for any two receivers, e.g. A and B, Figure 1 shows the distribution of the algorithm over different devices and where the data enters the algorithm. The GPS receivers on the sensor nodes can be regarded as data sources supplying the algorithm with their data. The data contain code, phase, time, and navigation information. The node sections of the algorithm take the raw data, process them, and then send the processed data to the main section, via the "Bast Station/Router (BS/R)", across the Internet to a remote server. Each node acquires different phase, code and time data while navigation data are common to all nodes.

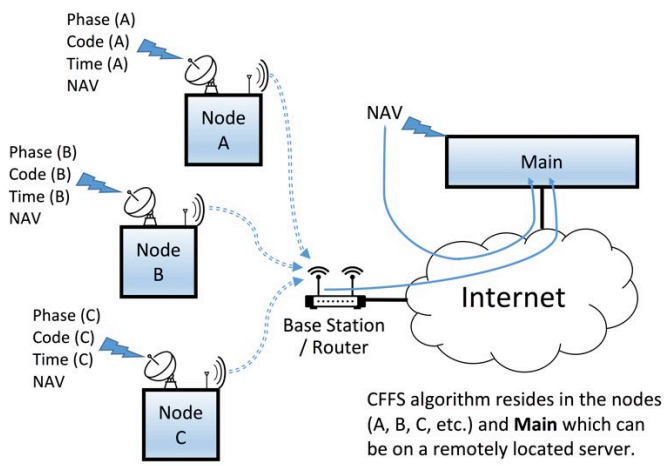


Figure 1. Algorithm distribution and data in flow

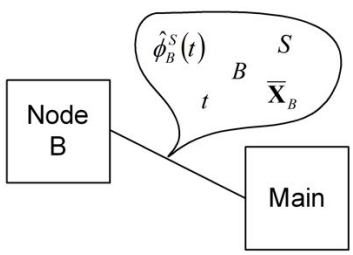


Figure 2. Data from Node B to Main

To keep the data flow between the node sections and the main section of the algorithm to a minimum (especially across the lossy wireless links between the nodes and the BS/R) navigation data and code observations are not passed between the nodes and the main section. The information that is sent from nodes to main component of the algorithm are wrapped phase observations extrapolated to a common second based epoch $\hat{\phi}_B^S(t)$, the satellite number S, the receiver number B and the time t (accurate to a second) that these observation estimates are for. In addition, occasionally averaged autonomous code based solutions $\overline{\mathbf{X}}_B$ are passed to the main section along with the receiver number B, as depicted in Figure 2.

Main Algorithm

Using data from the nodes ($\hat{\phi}_B^S(t)$, t, B, S and $\overline{\mathbf{X}}_B$), the ***code*** stage calculates the first relative position solution between two nodes (e.g. A and B) by simply taking the difference of the two autonomous position solutions calculated in the nodes. If $\mathbf{P}_{IBA}$ denotes the relative position between A and B, then $\mathbf{P}_{IBA} = \overline{\mathbf{X}}_B - \overline{\mathbf{X}}_A$.

The output, $\mathbf{P}_{IBA}$, is passed to the ***float*** stage. First, we determine the double differences to two satellites S_1 and S_2 using receivers A and B. This is repeated using observations at different times, e.g. at times $t_1 \ldots t_k$, limited by the available (harvested) energy. For each unique pair of satellites, we wrap and unwrap the

double difference estimates to produce the phase ambiguity integer *N*. Since we have many sets of equations for each pair of satellites (corresponding to different observations times $t_1 \ldots t_k$) that contain the unknown integer *N* and three unknown position variables, solving the equations using the *Least Squares* (LS) method results in the solution for *N* being a floating point value, hence the name of this stage of the algorithm. The position estimate is fed back into the algorithm iteratively until the value converges. This stage aims to obtain a position estimate $\widehat{\mathbf{P}}_{BA}$with an accuracy of a few centimetres along with the estimates of the carrier phase ambiguity *N* and their covariance information for the next stage.

The ***fix*** stage then takes the real valued *N*s and their covariance and performs *Integer Least Squares* (ILS) using the *Least-squares AMBiguity Decorrelation Adjustment* (LAMBDA) algorithm (Teunissen, 1993) to fix the *N*s to integers. Using the LS method, the fixed *N*s are used to produce a fixed solution. The double differences are then rounded to the nearest solution plane and another solution obtained. A solution plane refers to the position solutions given one double difference for a particular integer ambiguity *N*.

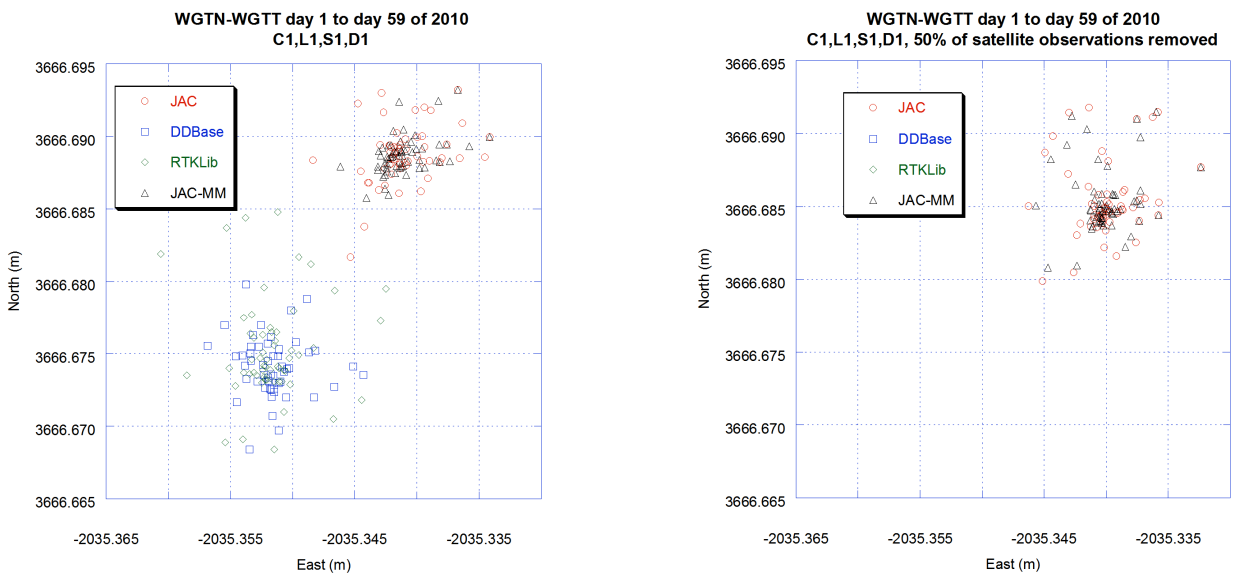
For the ***sidereal*** stage, sidereal filtering is then used to improve daily solution precision. Absolute wrapped residual stacking with respect to a biased location is used in addition to fix solution stacking. Arithmetic averaging of both, when possible, results in daily solution precision improvements due to at least in part the random nature with which observations are obtained, as well as the inability to obtain high rate observations continuously.

CFFS does not need code pseudoranges and the integer component of the phase observable to be sent over the radio link. Consequently, a considerable reduction of bandwidth can be achieved by removing these items before sending the other information over the radio link. This results in smaller packets which in turn results in lower epoch losses, thus mitigating the effect of a lossy wireless channel.

ALGORITHM VALIDATION

A key advantage offered by our CFFS algorithm is the ability for it to operate, i.e. compute the relative location, with intermittent GPS data, while existing systems require continuous availability of high quality GPS data. However, we first needed to validate it under ideal conditions with high quality data. We compared CFFS with open source global navigation satellite system (GNSS) packages RTKLib (RTKlib) and GPSTk (Tolman *et al*., 2004), as these are the only two open source GNSS packages freely available that supported singleband phase based relative position solutions, similar to our approach. In order to show that CFFS is comparable to these solutions when continuous good quality GPS data are available, we used two months of high quality data obtained from GPS receivers, the first located at Te Papa museum in Wellington City and the second at Wellington Airport. The data were obtained from the RINEX data archive of Land and Information New Zealand (LINZ). The data rate was one epoch every 30 seconds. The baseline between these two receivers was around 4 km. To achieve a fair comparison, we use only data that represent singleband GPS receivers (as CFFS is designed for such a system) and also implemented a version of CFFS without the sidereal filtering, which we denoted as "JAC". For GPSTk, we used an application that has been developed using GPSTk, called "DDBase". The full CFFS algorithm with sidereal filtering is denoted as "JAC-MM", although we note that RTKLib and GPSTk can only be fairly compared with JAC as they do not have sidereal filtering. The results of our comparison using continuous high quality data are shown in Figure 3(a) with all approaches producing comparable accuracy.

For our target scenario, where nodes are powered by energy harvesting and the GPS data from nodes are sent via wireless links, it is inevitable that there will most likely be fewer and more intermittent GPS data, increased multipath, and generally poorer quality data. This is tested using two approaches. First, we simulate the phenomenon by randomly discarding 50% of the data from the previous scenario of continuous high quality data. The results of this simulated data loss test are shown in Figure 3(b). It is expected that RTKLib and DDBase failed because they are designed to work on continuous high quality data obtained from receivers that are continuously powered. However, our CFFS algorithm not only continues to operate, there is no degradation in the accuracy. Next, we implemented low cost GPS receiver nodes (earlier versions of our prototype described in the next section.) These nodes were placed outdoors on the ground, with extensive surrounding trees and buildings. The nodes communicated their collected GPS over IEEE802.15.4 radio links to a permanently powered base station placed about 10m away. The experiments were done in

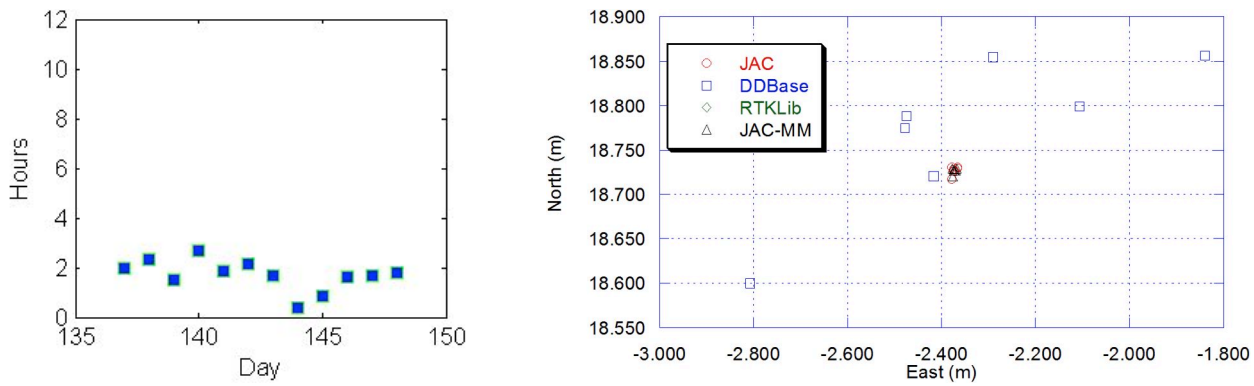


(a) With high quality data

(b) With 50% data loss

Figure 3. Computation of Relative Positions (JAC → CFF, i.e. no sidereal filtering & JAC-MM → CFFS)

winter when the Sun's maximum elevation was 27° at noon and daylight lasted 9.5 hours. The number of hours that the GPS receivers were active is shown in Figure 4(a) and the results computed by the algorithms is shown in Figure 4(b).



(a) Number of hours a day GPS receiver was active

(b) One DDBase solution not plotted due to large variations; RTKLib failed completely (not plotted)

Figure 4. Results using real life intermittent poor quality GPS data.

IMPLEMENTATION AND FIELD TESTS

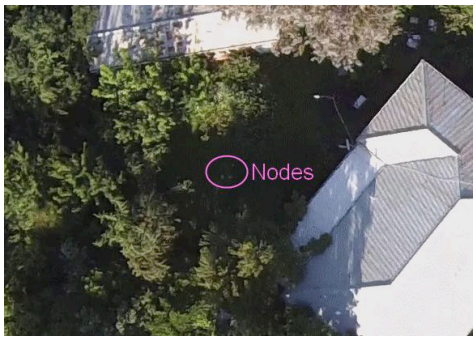
We implemented a proof of concept prototype comprising up to 8 nodes, one BS/R and a few repeaters (where necessary, to improve the communication between nodes and base station.) Each wireless node was easily contained in a $190mm \times 110mm \times 61mm$ casing, as shown in Figure 5 (left), which restricted the size of the solar panel. The aim is to have as small a node as possible so that they can be deployed in large numbers, and operate without any maintenance in harsh conditions (to be elaborated later.) The base station was also contained in a similar sized housing and connected to a sustained power supply. In the event that a sustained power supply is not available, we can easily use a larger solar panel to power it; we note that it is pointless to have it powered on when we are fully aware that the nodes cannot be on like during the night. The BS/R is connected to the Internet via the 3G interface (USB dongle on lower left) to transfer data back to the Main section of the algorithm running on a remote server. IEEE 802.15.4 wireless technology is used for communication between the wireless nodes and BS/R because of its lower power capability and also ability to reach relatively longer ranges, in our case, hundreds of metres.

Figure 5. Sensor Node (left) & Base Station / Router (BS/R) (right)

The prototype was deployed in two locations for validation, viz., static controlled test bed in Paekakariki, New Zealand and the Lushan landslide site in Taiwan.

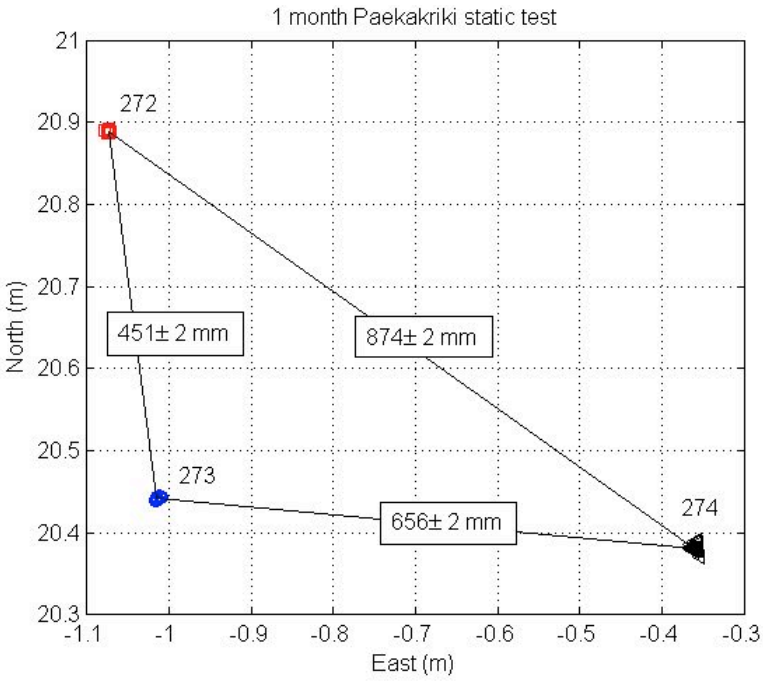
New Zealand Paekakariki Static Test Site

Nodes were placed relatively close to one another as depicted in Figure 6(a) with a close up view in Figure 6(b). In addition, permanently powered GPS receiver nodes were placed on the roof of the building at the bottom right hand corner of Figure 6(a) as a control set. Nodes on the ground have poor visibility of the GPS satellites due to the surrounding foliage while the receivers on the roof have somewhat better visibility. This test site aimed to validate the system in a realistic static environment, and that consistent inter-node displacements can be achieved using low-cost GPS devices. Daily measurements over a one-month period were taken as long as the nodes harvested enough energy during daylight hours to operate. The horizontal distances between nodes computed by the CFFS algorithm are shown in Figure 6(c). The average 2DRMS precision calculated for the three nodes for this one-month static test was 5 mm, which is typical for solution precision using uncalibrated antennas in high multipath environments. Considering that none of the nodes were moved during the entire data collection period, we have been able to get consistent inter-node displacement measurements.



(a) Aerial View (from UAV)

(b) Close Up (in summer)



(c) CFFS solutions for one month

Taiwan LuShan Landslide Site

The LuShan site is a known high risk landslide site on a hill above the town of Renai township in Taiwan's mountainous Nantou region. It is a site studied using satellite imagery, aerial imagery, laser survey and GPS. The active movement zone approximately covers 1 km^2 and resembles the shape of an inverted "V" starting at the top of the hill (Figure 7(a).) The sensor nodes (orange circles #274, #275, #276 and #277) were deployed alongside retro reflectors used for laser based land deformation monitoring using a total station, as shown in Figure 7(a). The base station was mounted in a large pre-existing weatherproof metal cabinet box with mains outlet sockets inside, hence permanently powered. It is shown as the orange oval marked as "Router" (next to #101) in Figure 7(a) and it performs the following functions:

(i) **sink** or **collection point** for the data obtained by the sensor nodes;
(ii) **router** to send the data via a 3G modem back to New Zealand via the Internet for processing; and
(iii) **GPS node** itself to obtain satellite observations.

(a) Node positions

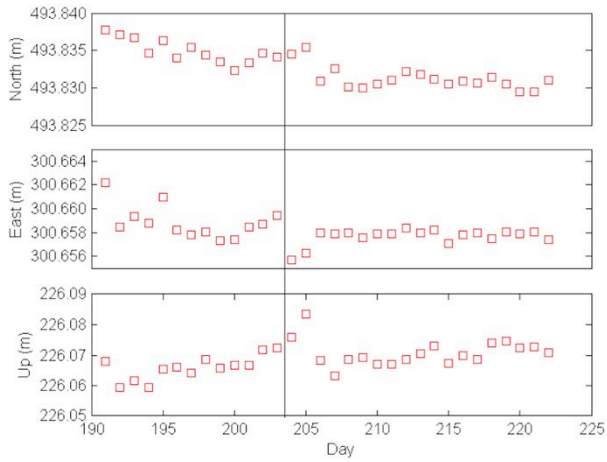

(b) Node / repeater deployed onsite


(c) Vegetation around node 277

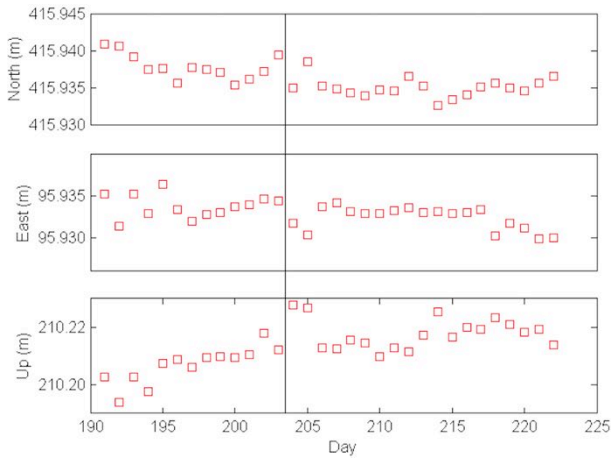
Figure 7. LuShan testbed site (courtesy of National Chi Nan University (NCNU) Taiwan)

Onsite, some of the nodes suffered intermittent interferences to their wireless communication, most likely due to vegetation and foliage, e.g. node #277 as shown in Figure 7(c). This problem was overcome by deploying repeaters (red circles #101 and #104).

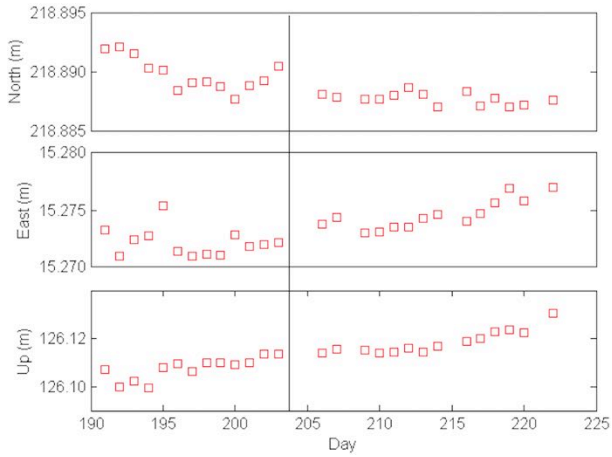
We selected node #277 as a fixed reference as its location is known to be relatively stable (on a non-sliding zone) as compared to the other nodes further north, viz. #275, #276 and #277. In Figure 8, we show the North-East-Up (NEU) time series of the three nodes on sliding zones with respect to node #274. The vertical line around the 204th day indicates the period when observations would be affected by a typhoon that hit the region. The first 14 solutions produced by CFFS after the system started were discarded to allow the sidereal filtering to stabilize. Thereafter, all solutions were recorded. All nodes had a southward trend between 0.12 mm/day to 0.22 mm/day. Node #277 had a slightly eastward component while #275 and #276 showed small westward components; all nodes had an up component of between 0.3 mm per day and 0.7 mm per day. Overall, the system showed an average 2DRMS precision of 3.3mm. After running for a month, #274 succumbed to environmental wear and tear, and failed. As this was a proof-of-concept prototype, the physical housing was not ruggedized for long term deployment.



(a) 275-274 NEU timeseries



(b) 276-274 NEU timeseries



(c) 277-274 NEU timeseries

Figure 8. Nodes' movement relative to node #274

CONCLUSION

We have designed, implemented and field tested an *A*ccurate *G*PS-based *EN*ergy harvesting *O*perated *R*elative positioning (AGENOR) system targeted for monitoring land deformation that can lead to landslides. The unique feature of our system lies in the small, low-cost, batteryless, solar-powered singleband GPS wireless sensor nodes that are able to determine inter-node displacement between any two nodes accurately, up to 4mm 2DRMS, measured from field tests on an actual landslide site. The core of our system is the Code Float Fix Sidereal (CFFS) algorithm which has been successfully shown to obtain reliable solutions using intermittent poor quality phase observable measurements in high multipath sites with minimal radio channel bandwidth requirements. This is achievable with as little as 0.5 hours of GPS "on" time per day and light levels as low as $20Wm^{-2}$ of solar irradiance during daylight hours, which is an extremely dark day. While the accuracy of our system may not be comparable to the sophisticated (and costly) systems currently in use, the low cost (per node) enables them to be deployed in large numbers over areas that are potentially vulnerable to landslides, to provide an indication for the need to deploy more accurate systems.

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