Estimation of Local Subsidence Using GPS and Leveling Combined Data

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ABSTRACT. The leveling measurements have been traditionally made for the monitoring of ground subsidence, but this technique is known to be not time- and cost-effective. Instead, GPS has been recently used as one of the most convenient and precise techniques for the geodetic applications, in terms of high accuracy monitoring. A GPS monitoring network consisting of 52 GPS stations was set up in Yunlin County, the southwestern part of Taiwan, in order to determine the first epoch data set and investigate the feasibility of monitoring the local ground subsidence with the use of GPS. The leveling-derived heights were still required for the estimation of ground subsidence using the integrated models, as the GPS-derived heights based on a long term of observation have not been completely established. It has been found from the estimates that the geoidal height, a parameter of datum between the two height systems, has significant influence on the reliability of subsidence estimated using the integrated models with combined data. The RMS difference of up to 13 cm can be found between the annual subsidence rates estimated by using the so-called 'absolute' and 'relative' modes of integrated model for the study area. However, the 'relative' estimates of the subsidence, in which a differential mode of geoidal information between the two neighboring sites was used, were tested to be consistent with those using two sets of GPS solutions by a RMS difference of around 5 cm.

Introduction

The leveling measurements have been used for the monitoring of ground subsidence on a long-term basis. However, this technique is not well suited to making measurements over the larger scales involved. Space geodetic techniques, particularly the Global Positioning System (GPS), have now almost entirely surpassed terrestrial methods for high accuracy geodetic monitoring. This is because GPS is relatively accurate in three-dimensional positioning and is capable of extending its working range from local, regional, to even global.

Hence, there has been a tremendous interest over the past few years in using GPS to connect the monitoring sites to a geocentric reference frame, and to monitor the crustal deformation or land movement at the monitoring sites. The highest accuracy of GPS can be based on the observations made by the continuously operating GPS arrays, mainly used for the monitoring of crustal deformation related to the earthquakes [Bock et al., 1997] [Tsukahara, 1997]. The episodic GPS monitoring campaigns, normally carried out over 7 days or less, using daily observation sessions of less then 24 hours, enable the measurement of networks of stations to an accuracy of a few millimeters for the monitoring of tide gauge heights [Chang, 1995].

The GPS monitoring campaigns with relatively less days and shorter observation sessions, based on either static GPS or kinematic GPS, are able to more efficiently determine the 3-D coordinates for the monitoring sites. This cm-level of accuracy is basically sufficient for small scale of monitoring applications, such as the landslide or dam deformation [Dominici et al., 1997]. However, the conscious selections of control sites, the tests of stochastic models, and the procedures of datum transformation are probably required to solve for the reliable and consistent monitoring results [Collier, 1997].

When GPS data are first used for the monitoring of vertical ground movement, the height differences between the monitoring sites, obtained by using both GPS and leveling measurements, are normally compared to realize the accuracy of height achieved by GPS [Parks and Dial, 1997][Ollikainen, 1998]. If the feasibility of using GPS to monitor vertical ground movement is confirmed, the models integrating GPS with historic leveling data would be required to detect the changes in height [Liu, 1998].

A significant level of ground subsidence along the southwestern coast of Taiwan has occurred, mainly due to the underground water extraction for inland fishery. In order to monitor the subsidence rate, the government has carried on the leveling measurements in this area for more than two decades. It has been estimated from the historic leveling data that the ground subsidence was accumulated to be 87 - 196 cm from 1975 to 1996. The subsidence value of up to 6 - 15 cm was also found during the recent period of 1994 to 1996, along the coastal area of Yunlin County in Taiwan [Hydraulic Bureau, 1996].

The monitoring of ground subsidence in this area by using GPS was proposed and sponsored by the Water Resources Bureau of the central government in 1997. The project aimed to prove the potential of using GPS for the accurate monitoring of ground subsidence. The first GPS campaign was carried out in 1998 to connect 52 monitoring sites with some of the first-order GPS control stations whose coordinates were well-defined in the TWD97, a GPS-based geocentric reference system in Taiwan [Chang and Tseng, 1998]. The heights of monitoring sites provided from the GPS network adjustments were compared with those measured by precise leveling for the sections selected, in order to assess the accuracy of GPS heighting. A first epoch data set for longer-term studies of ground subsidence in this area was determined.

The preliminary estimation of ground subsidence was also carried out using the first epoch GPS-derived heights and the historic leveling-derived heights. As those heights are referred to different vertical datums, the integrated models connecting the two height systems, based on using the 'absolute' and 'relative' modes of geoidal information, were tested to assess the reliability and consistency of the estimates with those obtained by the two sets of GPS solutions.

Field Campaigns

Yunlin County, with an area of 1,290 square kilometers, i.e. approximately 48 km by 27 km, is located in the southwestern part of Taiwan. The County is comprised of more than 90% of plain, with the elevations below 50 m, where most of the man-made ponds are located in the western side of this County. A total of 52 suitable monitoring sites in the County were selected to investigate the effectiveness of using GPS for the monitoring of ground subsidence. These monitoring sites included three first-order GPS control stations in the TWD97, eleven GPS stations of the Central Geological Survey for deformation monitoring, and thirty-eight GPS stations set up by the project. The selection of the monitoring sites was based on the criteria that the sites should be well distributed, and preferably have more years of height data. The latter criterion is necessary in order to estimate the subsidence using the first epoch GPS data set and historic leveling data. The monitoring stations used by the project are shown in Figure 1.

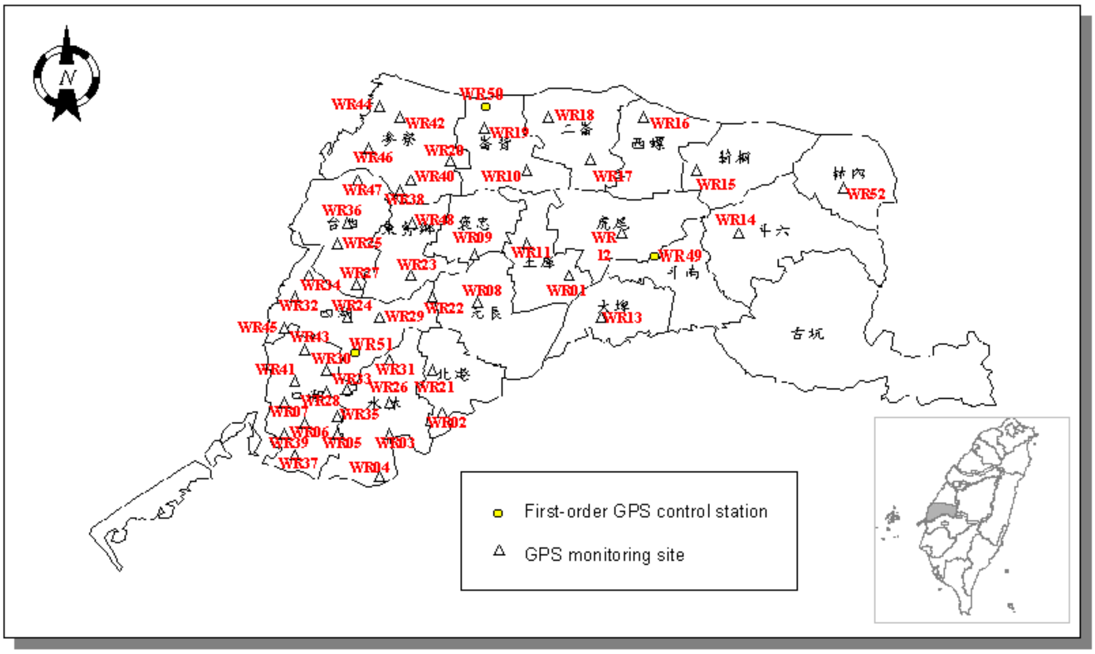

Figure 1 GPS monitoring stations in Yunlin County

It is believed that a GPS campaign with more observations, i.e. more days and longer observation sessions, will provide more reliable results. For logistical and financial reasons, however, the observation session of 2 hours was carried out for the GPS monitoring campaign. Around 70% of the sites were re-observed on different days or at different time during the campaign. A summary of the observation specifications, used by the campaign and based on the guidelines for the second-order GPS control survey [Ministry of Interior, 1994], is given in Table 1.

Table 1 Specifications for observation used in GPS monitoring campaign

Specification	Second Order GPS Control Survey	GPS Monitoring Campaign
Observation Session (hour)	≥ 2	2
Simultaneous Observation (hour)	≥ 1	2
Receiver Occupied	≥ 3	10
Epoch Interval(second)	≥ 15	15
Cut-off Angle(degree)	≤ 30	15
Dilution of Precision	≤ 10	≤ 10
Reference Station	≥ 3	≥ 3

Ten dual frequency P-code receivers, consisting of three Trimble 4000 SSI, two Ashtech Z-XII, and five Leica SR9500, were simultaneous used in each sub-network. The three first-order GPS control stations in this region were occupied with 8-hour daily observations, using Trimble receivers. GPS monitoring campaign was carried out over four consecutive days, from February 4 to February 7 1998, with totally twelve 2-hour sessions.

It was found during the reconnaissance that most of the benchmarks in the study area, whose heights were measured by leveling on a long term basis and expected to be used with the first epoch GPS data set for the estimation of subsidence, were not suitable for GPS signal reception. Twenty-seven of those GPS monitoring stations were, therefore, actually established within 200 m of such historic benchmarks. A local leveling link measurement was followed, so that the height of GPS monitoring station can be connected to the benchmark and used for the estimation of ground subsidence.

A second GPS campaign was also performed from June 14 to June 16 1998, separated by an interval of around six months from the first GPS monitoring campaign. The aim of this campaign is to obtain the second epoch GPS data set and to test the height variations based on the GPS solutions. The estimates of ground subsidence decided by using the first epoch GPS data and historic leveling data can then be assessed with the GPS-based estimates. A smaller number of monitoring stations was measured in this test campaign (see Figure 2). However, only nineteen stations were practically used in the estimation as one receiver was found to have bad GPS signal during the data processing.

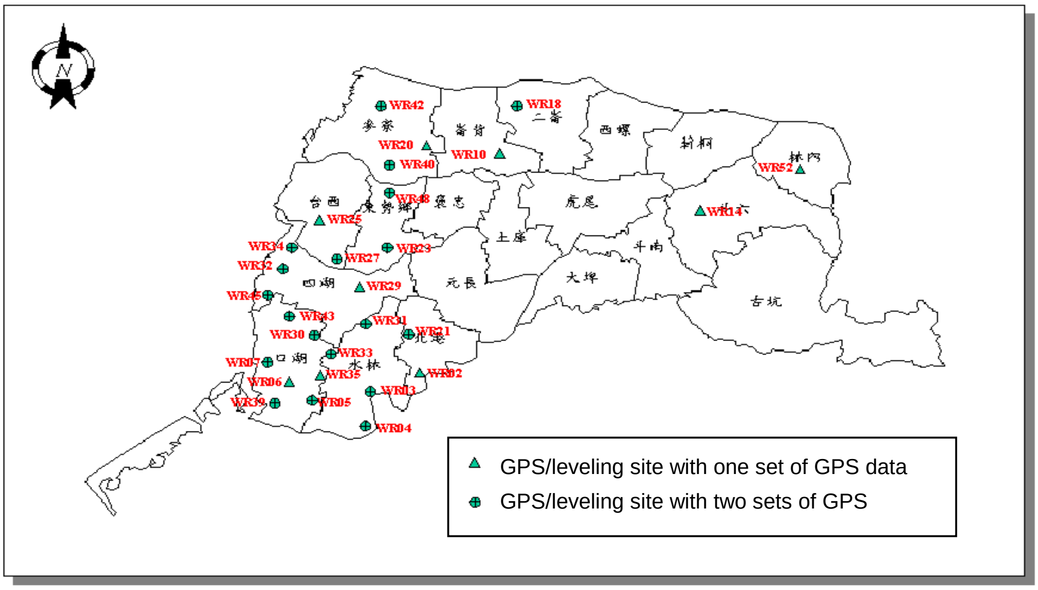

Figure 2 Monitoring stations observed in the second GPS campaign

GPS Network Adjustment

The data processing for GPS campaigns was mainly carried out by using commercial software of AOSS (Ashtech Office Suite for Survey) [Ashtech Inc., 1997]. As an identical type of antenna was not applied for the observation, the antenna height and offset were processed carefully during the GPS data processing. A summary of the processing options used during the GPS network adjustment is listed in Table 2.

Table 2 Processing options for the network adjustment

Reference Frame Definition	
Reference Stations:	First-order GPS Control Station or Tracking Station
Coordinate Source:	TWD97 [Chang and Tseng, 1998]
Reference Frame:	ITRF94 [Boucher et al., 1996]
Reference Epoch:	1997.00
Models Applied	
Ionospheric Delay:	L1/L2 Frequency Combination
Tropospheric Delay:	Modified Hopfield Model, with a Standard Atmosphere
Antenna Phase Center:	Offset Corrections
Adjusted Parameters	
Stations:	Position (X,Y,Z) and (φ,λ,h)of Monitoring Stations
Satellite:	Fixed to IGS Precise Ephemeris
Ambiguities:	Integer Fixed

In order to achieve the best solution from the GPS network adjustment, the GPS data sets were tested with different selections of reference station and adjustment mode in the network adjustment. The reference stations selected from either the first-order GPS control stations nearby the monitoring area or the GPS tracking stations distributed over the Taiwan area (see Figure 3), and their coordinates held fixed or free during the network adjustment were all tested. The models tested are listed in Table 3.

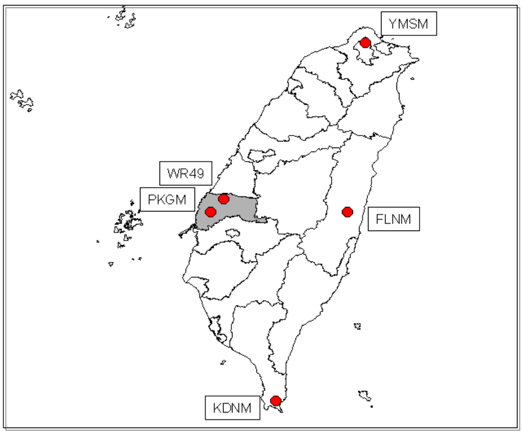

Figure 3 Distribution of reference stations

Table 3 Test models for the GPS network adjustment

Model	Reference Station	Adjustment Mode
1	WR49	Fixed
2	WR49	Free
3	PKGM	Fixed
4	PKGM	Free
5	YMSM, FLNM, KDNM	Fixed
6	YMSM, FLNM, KDNM	Free
7	YMSM, FLNM, KDNM, PKGM	Fixed
8	YMSM, FLNM, KDNM, PKGM	Free

Three leveling sections, i.e. WR33-WR35 (1.22 km in length), WR40-WR38 (3.67 km in length) and WR29-WR27 (4.28 km in length), were measured by precise leveling with Leica NA3003 digital level and GPCL3 invar bar code staffs. The height differences measured by precise leveling would be used to assess the external accuracy of the GPS network solution, based on each test model. These two sets of height difference are based on the different datums, but in practice the differences in ellipsoidal height can be regarded as differences in orthometric height, if the local geoid is assumed to be effectively constant over the short distance between the two ends of the line. The measurements of precise leveling were then treated as the 'standard' values for the comparison of height difference. The discrepancies between the GPS network solutions and the standard values are shown in Table 4. The RMS (Root Mean Square) agreements are also listed for each test model.

Table 4 Agreements of height difference for GPS and leveling measurements
(Values shown are GPS solutions minus leveling measurements, unit: cm)

Model	WR33-WR35	WR40-WR38	WR29-WR27	RMS
1	0.5	0.7	-7.2	4.2
2	0.4	-1.2	-6.5	3.8
3	0.7	1.1	-7.6	4.5
4	0.7	1.0	-7.5	4.4
5	1.1	1.7	-8.0	4.8
6	0.6	1.7	-7.6	4.5
7	1.2	2.5	-8.5	5.2
8	1.2	2.0	-8.0	4.8

The GPS network solution based on each test model demonstrates that the height differences differ from those leveling measurements by a RMS agreement of 3.8 cm to 5.2 cm. It can be assumed that the accuracy of height difference derived from different sets of GPS solution can be varied by 1.4 cm. The model 2, using first-order GPS control station nearby the monitoring area as the reference station and holding its coordinates free during the network adjustment, is seen to have a slightly better agreement.

The comparisons between the two sets of height difference, shown in Table 4, also indicate a systematic trend that the agreements are generally correlated with the length of the section. It is likely caused by the neglect of the geoidal height, which is used to connect the two different height systems. When the geoidal height, provided from an in-house developed geoid model, is applied to the section of WR29-WR27, the RMS agreement based on the solution of model 2 can be effectively reduced from 3.8 cm to 2.9 cm. However, this level of improvement is not appeared to the other shorter length of sections. It seems to be important to investigate the effects of height-dependent errors, such as the errors in geoid model, in order to improve the accuracy of GPS-derived height difference and its consistency with the leveling height difference [Satalich, 1996].

The first epoch GPS data set for the monitoring of ground subsidence in Yunlin County is proved to be accurate in an order of 3 cm, based on the GPS network solutions. This level of accuracy implies that the GPS campaign carried out by this project is capable of detecting the annual subsidence of 6 cm occurred in this monitoring area over a time scale of one year.

Estimation of Subsidence

In conventional geodesy, the orthometric height has been measured by the technique of leveling, where the reference surface is identified as the geoid, an equipotential surface that approximates to the local mean sea level. With the recent development of GPS, the ellipsoidal height referred to a reference ellipsoid, e.g. WGS84, is normally introduced. When GPS is used to monitor ground subsidence at sites, the ellipsoidal heights of the GPS monitoring stations are determined. If two sets of GPS height data measured at the same station, but observed at different times, are compared, changes in ellipsoidal height, regarded as changes in orthometric height, can be basically used to realize the vertical ground movement. However, the integrated models combining both GPS and leveling heights to estimate the rate of subsidence are still required when one set of GPS height is only provided.

Integrated Models

The combination of leveling and GPS heights involves problem of different height systems. The difference between the ellipsoidal height (h) and the orthometric height (H) is called the geoidal height or geoidal undulation (N). Their relationship is well-known by

$$H = h - N \qquad (1)$$

From the GPS point of view, once the geoidal heights are determined with sufficient accuracy, measuring ellipsoidal heights with GPS can be effectively converted into orthometric heights.

When one set of GPS heights (h_2), measured at epoch 2, combines with leveling heights (H_1), measured at epoch 1, to estimate the ground subsidence (dH_{12}) at the monitoring sites, a so-called absolute model, using height-related data from site itself, can be modified from equation (1) and expressed by

$$dH_{12} = (h_2 - N) - H_1 \qquad (2)$$

A differential mode, aimed at mitigating the uncertainties of geoidal heights, can also be introduced to get more accurate value between two sites with short distance, i.e.

$$\Delta H = \Delta h - \Delta N \qquad (3)$$

In practice, one benefit is achieved as GPS-derived ellipsoidal height differences over long distances are more precise than leveling-derived orthometric height differences over the same length. Moreover, the errors presented in the determination of N, computed from a gravimetric geoid model, can be effectively reduced by intorducing the difference of geoidal heights between two sites (ΔN). Hence, the estimates of ground subsidence based on the differential mode can be derived more accurately than those estimated using the absolute mode.

The GPS and leveling height differences can be combined on the basis of differential mode to estimate the relative subsidence (dH_{AB}) if the stations A and B are close to each other. A so-called relative model can then be expressed by

$$dH_{AB} = (\Delta h_{AB} - \Delta N_{AB}) - \Delta H_{AB} \qquad (4)$$

When the relative model is used, an initial station, such as station A, is require by knowing its subsidence value (dH_A) to a certain order of accuracy. The subsidence value (dH_B) of station B can then be estimated through the following relationship:

$$dH_B = dH_A + dH_{AB} \qquad (5)$$

where, dH_{AB} is determined by equation (4).

Estimates

Using absolute model. The subsidence values estimated using equation (2), based on the absolute model, are given in Table 5 and shown in Figure 4 for part of monitoring stations whose historic leveling heights were collected and the ellipsoidal heights were measured by the GPS campaign. The heights referred to different datums are also listed, along with the average annual subsidence rate estimated for the sixteen-month interval from October 1996 to February 1998.

Table 5 The estimation of subsidence based on the absolute model

Site	GPS-derived Ellipsoidal Height (m) <Feb/1998>	Gravimetric Geoidal Height (m) <Feb/1998>	GPS-derived Orthometric Height (m) <Feb/1998>	Leveling-derived Orthometric Height (m) <Oct/1996>	Subsidence (m)	Annual Subsidence Rate (cm/year)
WR02	26.937	20.300	6.637	8.1260	1.482	111.2*
WR03	23.326	20.133	3.193	3.6046	0.412	30.9
WR04	22.417	20.146	2.271	2.6771	0.406	30.7
WR05	19.668	19.967	-0.299	0.1011	0.400	30.0
WR06	20.320	19.883	0.437	0.8201	0.383	28.7
WR07	20.062	19.802	0.260	0.6371	0.377	28.2
WR10	34.650	19.927	14.723	15.1986	0.476	35.7
WR14	77.654	21.466	56.188	57.0235	0.836	62.7*
WR18	37.380	19.944	17.436	17.8905	0.455	34.1
WR20	29.102	19.821	9.281	9.7763	0.495	37.1
WR21	27.773	20.199	7.574	8.0965	0.523	39.2
WR23	25.550	19.927	5.623	6.0852	0.462	34.6
WR25	20.117	19.693	0.424	0.8275	0.404	30.3
WR27	22.697	19.831	2.866	3.2619	0.396	29.7
WR29	23.533	19.945	3.588	4.0762	0.488	36.6
WR30	20.656	19.857	0.799	1.1866	0.388	29.1
WR31	24.663	20.031	4.632	5.1005	0.468	35.1
WR32	20.718	19.683	1.035	1.3791	0.344	25.8
WR33	22.181	19.942	2.239	2.6281	0.389	29.1
WR34	21.389	19.723	1.666	2.0656	0.400	30.0
WR35	20.328	19.951	0.377	0.7761	0.399	29.9
WR39	25.070	19.797	5.273	5.6336	0.361	27.1
WR40	25.038	19.717	5.321	5.7932	0.483	36.2
WR42	21.733	19.558	2.175	2.6688	0.494	37.0
WR43	20.288	19.786	0.502	0.8611	0.359	26.9
WR45	20.434	19.721	0.713	1.0596	0.347	25.9
WR48	25.097	19.823	5.274	5.7326	0.459	34.4
Average						31.3

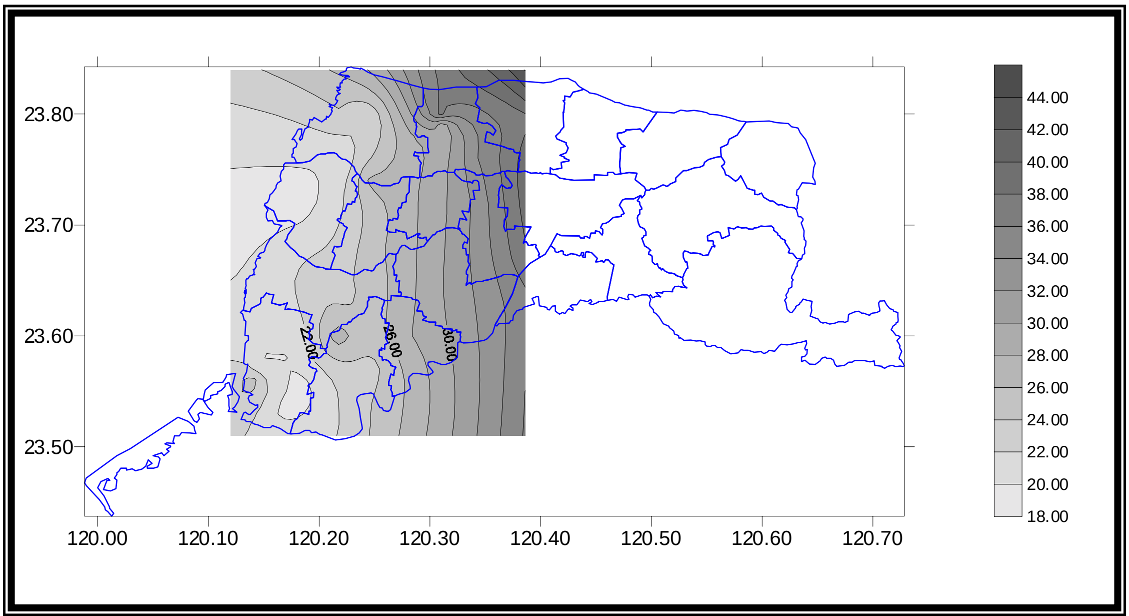

Figure 4 Annual subsidence rate estimated using the absolute model (unit: cm/year)

The estimates of subsidence shown with the asterisk in Table 5 indicate that the values are much higher than the average. This level of value is most likely to be due to the possible presence of two independent benchmarks at one GPS monitoring site. The one which was used as the bench mark with the historic leveling data is not exactly the one which was used in the leveling link surveys to the GPS site. The estimates of these two sites are then not used for analysis. However, it is still a difficult task to analyze this level of average subsidence and interpret the trend of subsidence shown in Figure 4. This is because the serious subsidence rate is well known to occur along the southwestern coast of Yunlin County, whereas the subsidence rate estimated is shown to be low around this area. The absolute model, hence, has not been proved effective in estimating the subsidence using GPS and leveling heights associated with the geoidal heights at sites.

Using relative model. Equation (4), based on a differential mode of estimation, is expected to reduce the uncertainties of geoidal heights to improve the accuracy of estimate using GPS and leveling heights. The sections with the shortest distance between the two neighboring sites were selected. The initial site, required by equation (5) to estimate the subsidence for the next site, was determined by using WR21, whose 6 cm annual subsidence was derived from the GPS tracking data observed at PKGM from 1995 to 1997. The estimates of subsidence based on using the relative model is now listed in Table 6 and shown in Figure 5.

Table 6 The estimation of subsidence based on the relative model (period: Oct/1996-Feb/1998)

Site	Section Length (km)	Subsidence (m)	Annual Subsidence Rate (cm/year)
WR21	---	0.080	6.0
WR31	4.38	0.134	10.0
WR33	5.70	0.214	16.1
WR35	1.11	0.203	15.2
WR03	5.14	0.191	14.3
WR04	3.37	0.193	14.5
WR05	5.34	0.202	15.2
WR06	2.55	0.219	16.5
WR39	2.68	0.242	18.1
WR07	1.95	0.226	17.0
WR30	4.47	0.215	16.1
WR43	2.08	0.243	18.2
WR45	1.95	0.257	19.3
WR32	2.45	0.258	19.4
WR34	2.94	0.203	15.2
WR27	3.26	0.207	15.5
WR29	4.04	0.114	8.6
WR23	5.45	0.140	10.5
WR25	6.99	0.199	14.9
WR48	6.49	0.144	10.8
WR40	4.27	0.130	9.8
WR42	4.94	0.110	8.2
WR20	7.69	0.107	8.0
WR10	3.74	0.127	9.5
WR18	5.25	0.148	11.1
Average			13.9

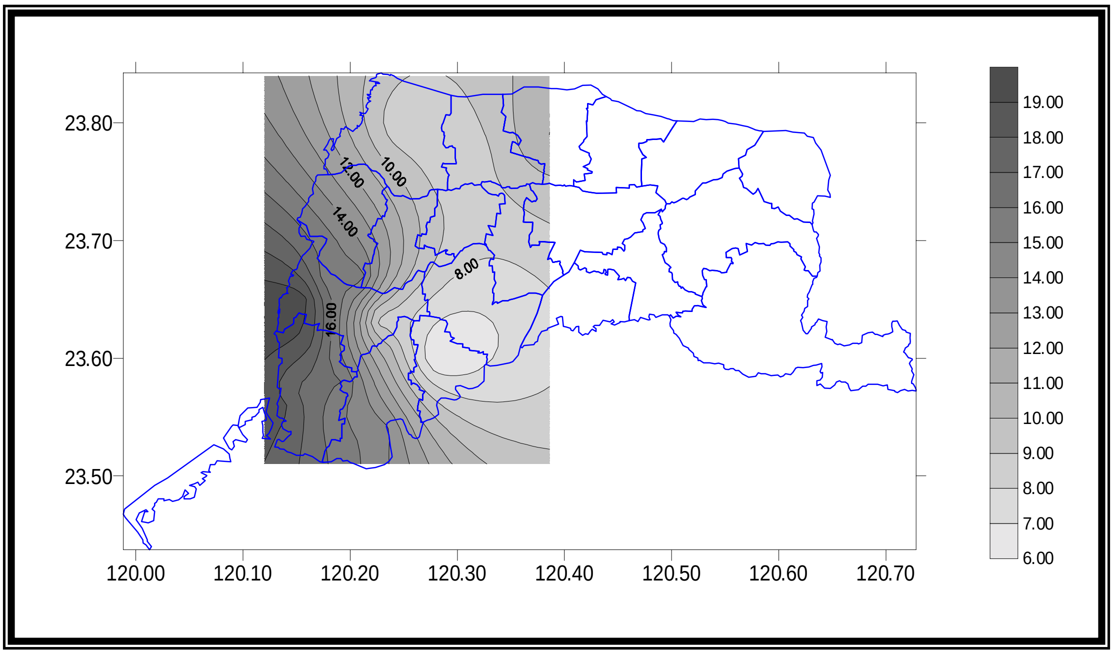

Figure 5 Annual subsidence rate estimated using the relative model (unit: cm/year)

It is clear to see from Table 6 that the average subsidence of 14 cm per year, estimated by using the relative model, is much lower than the average value of 31 cm shown in Table 5, based on the absolute model. This significant level of difference indicate that the integrated models play an important role on the estimation of subsidence using GPS and leveling combined data in this study area. Furthermore, the contour lines showing the subsidence rate in Figure 5 are more coincided with those determined by the historic leveling data sets, comparing to the values appeared in Figure 4.

Analysis of Estimates

As a second GPS campaign, which was six months following the first GPS campaign, was implemented for part of the monitoring stations. It can be noted that the aim of this campaign was to repeat some observations carried out in the first campaign, in order to obtain an independent GPS test data set. The changes in GPS-derived ellipsoidal heights between the two sets of solutions can be treated as changes in orthometric heights, if the local geoid is assumed to be effectively constant over the time period between the GPS observations. Hence, GPS ellipsoidal heights can be used to estimate the ground subsidence at monitoring sites without requiring any geoidal height information. The subsidence values determined using two sets of GPS solutions can then be considered as more 'accurate' and 'consistent' results to assess those estimated using GPS and leveling combined data.

Estimates from GPS Solutions

The estimation of subsidence using the data based on the same height system is summarized in Table 7 and shown in Figure 6 for the nineteen monitoring sites, which were measured by both the first and the second GPS campaign.

Table 7 The estimation of subsidence using two sets of GPS solutions

Site	GPS-derived Ellipsoidal Height (m) <Jul/1998>	GPS-derived Ellipsoidal Height (m) <Feb/1998>	Subsidence (m)	Annual Subsidence Rate (cm/year)
WR03	23.226	23.326	0.100	22.8
WR04	22.339	22.414	0.075	17.1
WR05	19.588	19.668	0.080	18.2
WR07	19.997	20.063	0.066	15.1
WR18	37.363	37.380	0.017	3.9
WR21	27.744	27.773	0.029	6.6
WR23	25.499	25.550	0.051	11.6
WR27	22.592	22.697	0.105	24.0
WR30	20.598	20.656	0.058	13.2
WR31	24.589	24.663	0.074	16.9
WR32	20.611	20.718	0.107	24.4
WR33	22.078	22.182	0.104	23.7
WR34	21.323	21.389	0.066	15.1
WR39	24.969	25.070	0.101	23.0
WR40	24.989	25.038	0.049	11.2
WR42	21.705	21.734	0.029	6.6
WR43	20.209	20.288	0.079	18.0
WR45	20.369	20.435	0.066	15.1
WR48	25.052	25.097	0.045	10.3
Average				15.6

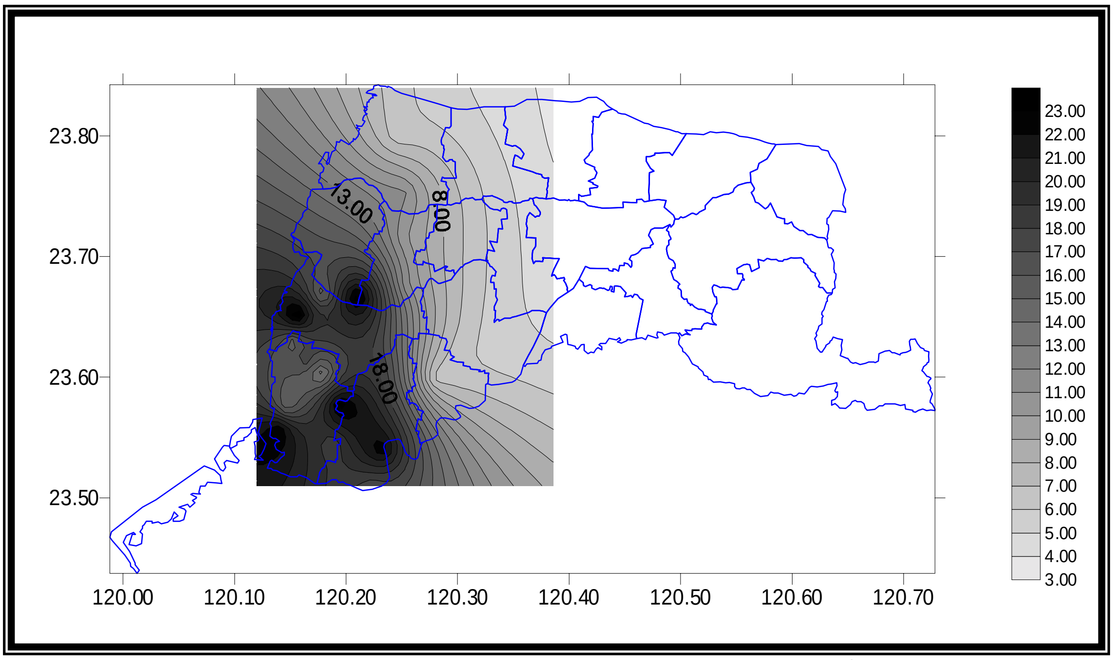

Figure 6 Annual subsidence rate estimated using two sets of GPS solutions (unit: cm/year)

Assessment of Estimates

The subsidence values estimated from GPS-derived height variations are also helpful to investigate the agreements for estimates based on the absolute and relative modes of integrated models, which use GPS and leveling combined data. The individual differences between the subsidence rates estimated using GPS/leveling combined data and GPS/GPS data are now listed in Table 8 for those common sites. The RMS differences, based on using the estimates from GPS/GPS data as the standard values, are also given in Table 8.

Table 8 Comparisons of estimates based on the different data sets
（Difference values shown are GPS/leveling minus GPS/GPS)

Site	GPS/GPS data <Feb/1998-Jul/1998>	GPS/Leveling Data <Oct/1996-Feb/1998>			
	Annual Subsidence Rate (cm/year)	Absolute Model (cm/year)	Difference (cm/year)	Relative Model (cm/year)	Difference (cm/year)
WR03	22.8	30.9	8.1	13.4	-9.4
WR04	17.1	30.7	13.6	14.5	-2.6
WR05	18.2	30.0	11.8	15.2	-3.1
WR07	15.1	28.2	13.1	17.0	1.9
WR18	3.9	34.1	30.2	11.1	7.2
WR21	6.6	39.2	32.6	6.0	-0.6
WR23	11.6	34.6	23.0	10.5	-1.1
WR27	24.0	29.7	5.7	15.5	-8.5
WR30	13.2	29.1	15.9	16.1	2.9
WR31	16.9	35.1	18.2	10.0	-6.9
WR32	24.4	25.8	1.4	19.4	-5.0
WR33	23.7	29.1	5.4	16.1	-7.6
WR34	15.1	30.0	14.9	15.2	0.1
WR39	23.0	27.1	4.1	18.1	-4.9
WR40	11.2	36.2	25.0	9.8	-1.4
WR42	6.6	37.0	30.4	8.2	1.6
WR43	18.0	26.9	8.9	18.2	0.2
WR45	15.1	25.9	10.8	19.3	4.2
WR48	10.3	34.4	24.1	10.8	0.5
Average	15.6	31.3	—	13.9	—
RMS	—	—	18.2	—	4.7

As can be seen from Table 8, the individual differences show that the annual subsidence rates estimated using GPS and leveling combined data, based on absolute model, are systematically higher than those estimated using two sets of GPS solutions. The same case is not shown for the estimates based on the relative model, as those individual differences are varied in a random. Moreover, it can also be found from the RMS differences that the estimates based on the relative model are generally in good agreement with the estimates obtained by using two sets of GPS solutions. The

RMS differences show quite an impressive enhancement from the estimates based on the absolute model to those based on the relative model, where the value is lowered from 18 mm to 5 mm. This basically shows the effectiveness of the use of relative model, as opposed to an absolute model.

As the large differences, shown in Table 8, are likely due to the insufficient accuracy of geoidal heights provided by the in-house developed geoid model, the assessment of geoidal heights has been made for a test line crossing the study area [Tsuei et al., 1996]. The test line is composed of 26 points with a total length of 170 km, whose high accuracy leveling heights and GPS heights were both measured at the same time. The geoidal heights computed using the geometric relationship and gravimetric geoid model, respectively, are compared. The comparisons show that the absolute and relative modes of gravimetric geoidal heights have the RMS differences of 9 cm and 6 cm, respectively, with the geometric geoid values.

Errors in the subsidence values estimated from GPS and leveling combined data can be attributed to a sum of the errors in the GPS ellipsoidal heights, errors in the leveling measurements, and errors in the gravimetric geoid computation. In general, an error budget of around 10 cm and 7 cm for the estimates of subsidence values based on using absolute and relative models, respectively, can be assumed. The error of the subsidence value obtained using two sets of GPS solutions, however, is evaluated to be around 3 cm based on the error propagation of the estimation model.

Therefore, a hypothesis test assuming that the average difference between the subsidence rates estimated using GPS/GPS data and GPS/leveling data, based on the relative model, is not significant has been accepted at an α=0.05 significance level. In other words, two sets of estimates, using GPS/GPS data and the relative model of GPS/leveling data, can be assumed to be consistent, under the error budgets.

Conclusions and Suggestions

An overall summary of the research on the main subject of estimating ground subsidence using GPS and leveling combined data is now given as follows:

(1) The use of GPS measurements at monitoring sites offers a level of accuracy, which enables the ground subsidence to be effectively determined. Moreover, the GPS technique has more advantages than those of leveling measurements, such as connecting the monitoring sites to any reference frame selected, easily extending the working scale for monitoring area, and less constrains to the selection of reference sites for the coordinate referred.

(2) The changes in GPS-derived ellipsoidal heights between the two sets of solutions can be treated as changes in ground subsidence, without requiring any geoidal height information over a shorter period of time. However, the estimation of subsidence using GPS and leveling combined data is also required, particularly for those monitoring areas where the leveling data have been long-term monitored and the first set of GPS heights are just measured.

(3) The GPS height solutions used for the estimation of subsidence showed a RMS agreement of better than 3 cm with the height differences measured by precise leveling for three test sections. However, this level of GPS heighting accuracy is still expected to be improved by investigating more effects of height-dependent errors and establishing the observation and processing specifications for GPS monitoring, such as the guideline recently proposed by the NGS [Parks, 1998].

(4) The results from using GPS and leveling combined data showed that the

differential mode of relative model has a more significant effect on the estimates of subsidence, as opposed to an absolute model. A RMS difference of around 13 cm was found in the estimates of subsidence between an absolute and a relative model applied. However, the resolution of geoidal heights computed from the gravimetric geoid model is still expected to be improved to obtain more reliable and consistent estimates for the monitoring of subsidence.

(5) The subsidence values determined using two sets of GPS solutions were used to assess those estimated from GPS and leveling combined data. The comparisons showed that the average differences were significantly reduced from 16 cm for the solutions based on an absolute model to 2 cm for the solutions based on a relative model. The RMS differences were also assessed to be 18 cm and 5 cm for the estimates based on the absolute and relative models, respectively.

(6) The results basically indicated that the significant subsidence has occurred in the monitoring area. However, it is still insufficient to clearly give a picture showing the subsidence rate estimated using more periods of GPS observations. A longer time series of monitoring, using repeat GPS surveys, would be very useful.

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