The Harris-Galveston Coastal Subsidence District/ National Geodetic Survey Automated Global Positioning System Subsidence Monitoring Project

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Abstract

Subsidence can severely damage property and infrastructure in a developed area. Typically when subsidence is human-induced, its mitigation can be very costly. For example, when the subsidence is caused by the compaction of susceptible aquifer systems related to ground-water pumping and the accompanying ground-water-level declines, water-resource managers might choose to reduce use of the ground-water resource, which often entails some effort to convert from ground-water to surface-water supplies. Accurate monitoring of subsidence over time is vital to providing calibration data for modeling and prediction purposes. The method of geodetic differential leveling used previously to measure subsidence was satisfactory but very costly. A cooperative study by the Harris-Galveston Coastal Subsidence District (HGCSD) and the National Geodetic Survey (NGS) is using Global Positioning System (GPS) methods to measure subsidence at a fraction of the cost of the previous leveling method. Because of the broad extent of subsidence in the Houston-Galveston region, no stable benchmarks are in the area. Therefore, relatively stable borehole extensometers were equipped with GPS antennas to provide a reference frame to measure subsidence at other stations in the area. These stations are known as local GPS Continuously Operating Reference Stations (CORS). In support of the project, it was also necessary to design and construct portable GPS measuring stations called Port-A-Measure (PAM) units.

The project uses dual-frequency, full-wavelength GPS instruments with geodetic antennas. Data are collected at 30-second intervals and averaged over 24 hours. The goal is to yield differential accuracy of less than 1 centimeter vertically in an automated mode operated by HGCSD personnel. Data have now been collected from three CORS and four PAM units for more than 4 years in the Houston-Galveston region. Results between CORS and PAM units indicate that some monuments are subsiding at rates of 7 centimeters per year and correlate well with extensometer data.

In addition to the GPS CORS and PAM units, NGS and HGCSD also performed two GPS network surveys to estimate subsidence in the area—one survey in 1995 and another in 2000. This report presents a brief summary of the CORS and PAM units results and discusses the use of GPS for estimating subsidence in the Houston-Galveston region of Texas.

INTRODUCTION

For several decades, parts of the upper Gulf Coast region of Texas have subsided. Land subsidence is the lowering (sinking) of the land surface in response to the removal of subsurface support. Compaction of subsurface clay layers owing to withdrawal of ground water is the primary cause of subsidence in the Houston-Galveston region. Subsidence can lead to costly damage in coastal regions because of the relative rise of sea level, the associated landward shift of the shoreline, and the increased risk of flooding from storm surges. In inland regions subsidence causes several

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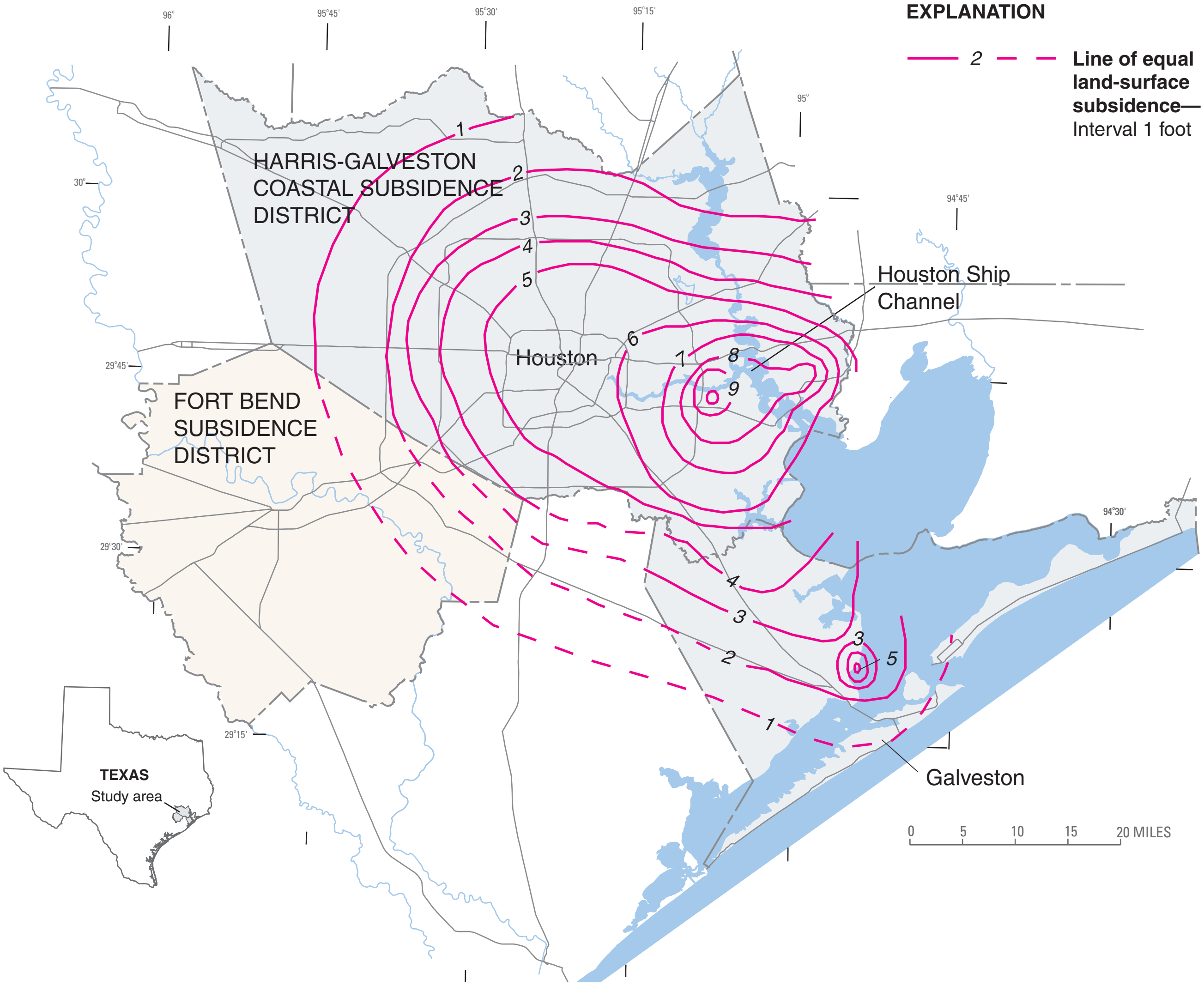


Figure 1. Subsidence occurring between 1906 and 1987 in the Houston-Galveston region, Texas.

problems, including modifying stream gradients and changing the geomorphology of flood plains. In 1975 the Texas Legislature created the Harris-Galveston Coastal Subsidence District (HGCSD) to mitigate the subsidence problem in Harris and Galveston Counties through regulation and management of the groundwater resource. In 1989, the Texas Legislature created the Fort Bend Subsidence District (FBSD) to manage subsidence in Fort Bend County. FBSD, a separate district with its own Board of Directors, has adopted an inter-local agreement with HGCSD to provide staff for its operation. FBSD is a partner in the GPS project. Figure 1 is a map of HGCSD and FBSD showing subsidence occurring between 1906 and 1987. Subsidence has occurred throughout most of the two districts, with the greatest amount of subsidence occurring near the Houston Ship Channel.

In the past, the National Geodetic Survey (NGS), a program office of the National Ocean Service, National Oceanic and Atmospheric Administration (NOAA), and HGCSD have used two methods to measure subsidence. The first method, releveling, used conventional differential leveling. More than 2,500 benchmarks are in the area. Some of these were established as early as 1906. Simple algebraic subtraction along level lines yielded the subsidence that occurred between any two releveling epochs. This method gives excellent spatial subsidence data. The cost of the relev-

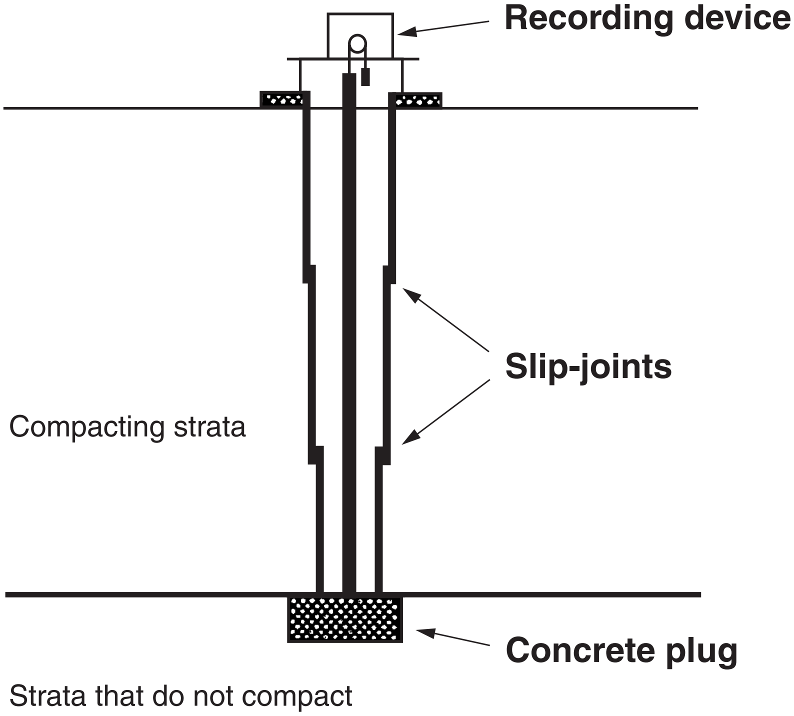


Figure 2. Extensometer used by HGCSD.

eling procedure, about $1,170,000 (2001 dollars) for a single epoch of leveling, prohibits frequent releveling. The development of the GPS in the late 1980s resulted in an affordable alternate method to accurately measure land-surface datums.

The second method of measuring subsidence used deep borehole extensometers, established as deeply-anchored benchmarks. The U.S. Geological Survey (USGS) designed and installed the first of these extensometers in the early 1960s. Figure 2 shows the typical construction of such a benchmark. To construct an extensometer, a hole is drilled to a depth at which the strata are relatively stable. Then, the hole is lined with a steel casing with slip-joints to prevent crumpling as subsidence occurs. An inner pipe rests on a concrete plug at the bottom of the borehole and extends to the top. This inner pipe then transfers the stable elevation below to the surface. A measurement of the distance from the inner pipe to the surrounding land surface gives the amount of subsidence that has occurred. Since many of these extensometers were constructed, the design of borehole extensometers was improved (Riley, 1984) by counter-weighting the inner pipe to reduce frictional forces between the inner and outer pipes and by establishing a more stable surface datum using shallow (15- to 20-ft deep) piers bored in the subsurface. A chart recorder provides a continuous record of subsidence over time. Figure 3 is a typical plot generated from extensometer data for the Addicks extensometer. The six project borehole extensometers in the Houston-Galveston region represent an estimated investment of $800,000 each (in 2001 dollars). Borehole extensometers provide excellent subsidence data, but their cost prohibits their use in sufficient numbers to provide adequate information for the entire area of HGCSD and FBSD.

THE PROPOSED GPS SOLUTION

In late 1993, HGCSD and NGS signed a cooperative agreement to jointly pursue improved, less expensive methods of monitoring land subsidence in the Houston metropolitan area. The agreement between HGCSD and NGS resulted in an experimental study to use GPS to measure subsidence. The project used dual-frequency, full-wavelength GPS instruments and geodetic antennas. Data were collected at 30-second intervals and averaged over 24 hours. The goal was to yield a differential vertical accuracy of less than 1 cm in an automated mode. The collection, processing,

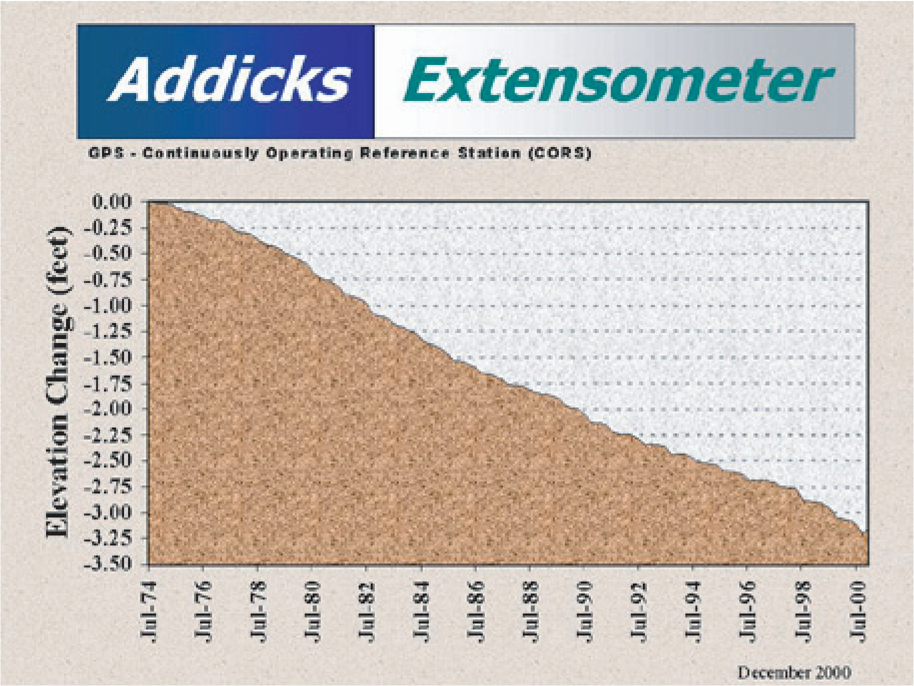


Figure 3. Addicks extensometer data, July 1974–July 2000.

and analysis of the observed GPS data are accomplished automatically using computer software. This report describes the results of the data collection and processing.

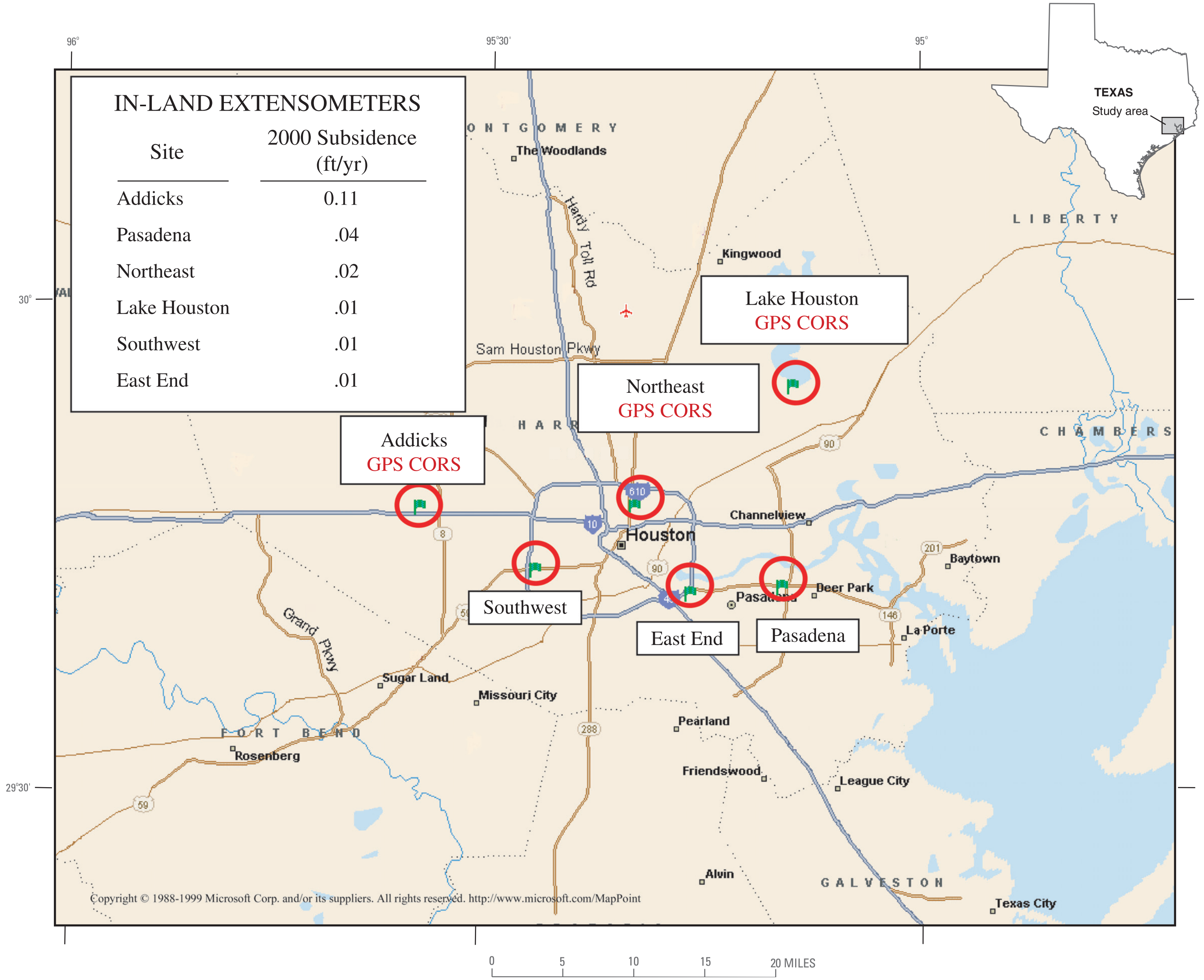
No stable benchmarks except for a few extensometers are in the Houston-Galveston region. Therefore, only the extensometers would be available as a reference to measure other stations. The borehole extensometers, which are not typical benchmarks, are relatively stable and provide the location for the project's three GPS Continuously Operating Reference Stations (CORS) (fig. 4). The CORS are Lake Houston, Northeast, and Addicks. Figure 5 is a photograph of the Northeast station, which also is part of the NOAA national CORS system.

It was recognized that any additional GPS receivers used to expand the network would need to be portable. Portability provides flexibility in long-term relocation or, as planned for this project, short-term relocation. Trailers provide the ability to move the equipment from point to point and also provide adequate housing and protection. Port-A-Measure (PAM) units are required to stay in one location for a sufficient time to provide a statistically valid difference in height relative to the three stable CORS.

Design of CORS and PAM Units

The three CORS are colocated on borehole extensometers. These three CORS are considered fixed locations relative to one another. Shelters housing the CORS measure about 6 by 7 ft (fig. 5). These shelters house the borehole extensometers, GPS receivers, and related monitoring equipment. The pipe extending through the roof of the shelter holds the GPS antenna and is an extension of the inner pipe of the borehole extensometer. AC power and a conventional telephone line serve each CORS. A personal computer (PC) receives and stores the data from the GPS receiver. A modem is used to download data from the PC at any time. The capacity of the hard disk on the PC is 300 MB, which is sufficient to store several months of data. An uninterruptable power supply manages the electricity to the GPS receiver, PC, and modem.

Each of the PAM trailers would occupy one reference site for 1 week and then rotate among three other PAM sites, thereby providing measurements of land-surface height changes from the four sites on a monthly basis. A small trailer was selected to house each PAM unit (fig. 6). Each PAM trailer is truly portable with its own power supply and cellular phone. Each site has its own benchmark that the GPS antenna is mounted upon.



IN-LAND EXTENSOMETERS

Site	2000 Subsidence (ft/yr)
Addicks	0.11
Pasadena	.04
Northeast	.02
Lake Houston	.01
Southwest	.01
East End	.01

Figure 4. Locations of the three GPS CORS colocated with borehole extensometers, locations of other project borehole extensometers, and rates of subsidence in six extensometers in the Houston-Galveston region, Texas.

Figure 5. Northeast GPS CORS.

Figure 6. Trailer at PAM site.

The PAM trailer is connected to the antenna and relies on its own power and communication devices to transmit data to the office. The cellular antenna and other equipment also can be stored inside. Three 50-watt solar panels routed through a charge controller to four 80-Ah gel cell batteries provide the power supply. A 12-V DC power bus supplies current to the remainder of the equipment. The receiver is powered continuously and draws directly from the 12-V power bus. In the beginning of the project, a timer turned on the power for the modem and cellular phone for 1 hour each day to transmit data to the office, but this proved unreliable. Owing to problems with transmitting data via cellular telephone and modem, the data were subsequently downloaded from the receivers on a weekly basis when the PAM trailers were moved to a new site.

Monumentation of PAM Sites

Clay-rich soils with a high shrink-swell potential (vertisols) are widespread in the HGCSD area. The soil-moisture active zone, the depth at which large variations in soil moisture cause shrink-swell behavior, can extend 4 to 6 m (15 to 20 ft) below the surface. Measurements show that as much as 6 to 9 cm (0.2 to 0.3 ft) of vertical movement can occur in a few days, as expansive clay soils respond to seasonal variations in rainfall and temperature. The reference mark devised for the PAM sites (fig. 7) minimizes this movement.

During 2001, five PAM trailers and 20 PAM sites were operated cooperatively by the City of Houston, Harris County, Fort Bend County, Texas Gas Co., Houston Pipeline, and West Houston Airport. The first of the three CORS (fig. 4) started collecting data in 1993, and all three have been operational since 1996. The first of the five PAM units began collecting data in January 1994, and the fifth PAM trailer was deployed on January 15, 1999. The locations of the 20 sites that the five PAM trailers are moved to on a weekly basis are shown in figure 8.

Stability of Local CORS

The Lake Houston GPS CORS is part of the NOAA National CORS, and its coordinates are monitored daily by the NGS CORS project team. Plots of Lake Houston CORS data are available on the NGS Web site at http://www.ngs.noaa.gov/CORS/Texas/texas_lkhu.html.

Coordinates for the Lake Houston CORS are held fixed when the other two CORS coordinates, tropospheric delays, and phase bias values are determined. The daily coordinates at the other two CORS, Addicks and Northeast, determined using 24-hour datasets, were compared for 1996–2001 to ensure that the system was working properly. These stations are on relatively stable platforms, deep borehole extensometers, and should not be moving provided the anchored depths of the extensometers are below the zones in the aquifer system affected by aquifer-system compaction. Figures 9 and 10 depict the difference in estimates of ellipsoid heights for 5 years (1996–2001) between the

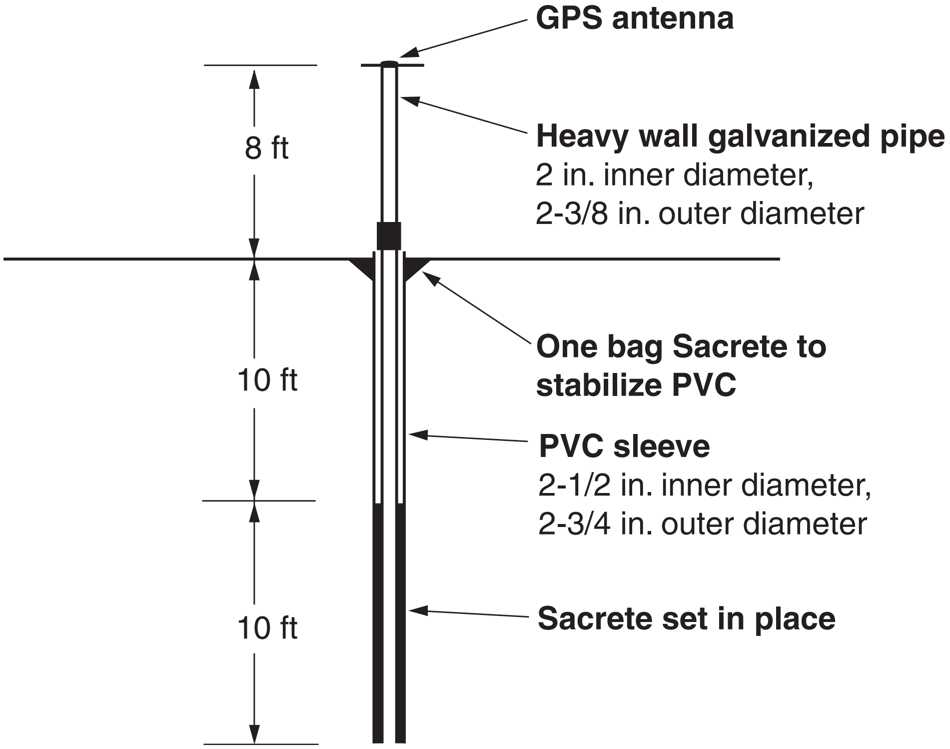


Figure 7. Design of PAM monuments.

other two CORS and the Lake Houston CORS. The GPS solutions were computed using NGS automated data editing and reduction software, PAGES (Schenewerk and others, 1999). The vertical components computed by PAGES were plotted and all outliers were removed manually.

The slope of the line between Northeast GPS CORS and Lake Houston GPS CORS is 0.06 cm/yr, well within the noise of the measurement techniques. This was expected because on the basis of other hydrogeologic and geodetic information, these two stations should not be moving. The slope of the line between Addicks GPS CORS and Lake Houston GPS CORS is 0.13 cm/yr. A slope of 0.13 cm/yr is small, but the fact that the slope between the two control stations is greater than 0.1 cm/yr is notable. Other hydrogeologic and geodetic data indicate that the Addicks site is not subsiding, but it is located near a region, centered on Jersey Village, that is subsiding (Stork and Sneed, 2002). The PAM 07 site is located in Jersey Village (fig. 8). The GPS data from 2001 currently are being investigated.

A major goal of the HGCSD project is to determine GPS-derived ellipsoid height differences at the 1-centimeter accuracy level at designated PAM sites using an automated approach. Some of the results indicated that a few of the residuals were larger than 1 cm but typically less than 3 cm. NGS is analyzing the GPS data to reduce the noise level of the results. Future studies include correlating ellipsoid height differences with atmospheric conditions and changes in temperature. Preliminary analyses indicate that larger differences in ellipsoid heights occur during the summer months when the Houston region weather is hot, humid, and stormy.

Estimation of Height Changes at PAM Sites

Coordinates of the CORS are held fixed when coordinates, tropospheric delays, and carrier-phase ambiguities of the four PAM sites are determined. Therefore, each PAM site has three vectors associated with it every day it is occupied—one relative to Addicks CORS, one to Northeast CORS, and one to Lake Houston CORS. Each month, a PAM trailer collects data at a site for 1 week so the site has 21 vectors associated with it each week. Once a week for 4 weeks, each PAM trailer is moved to another site for a week,

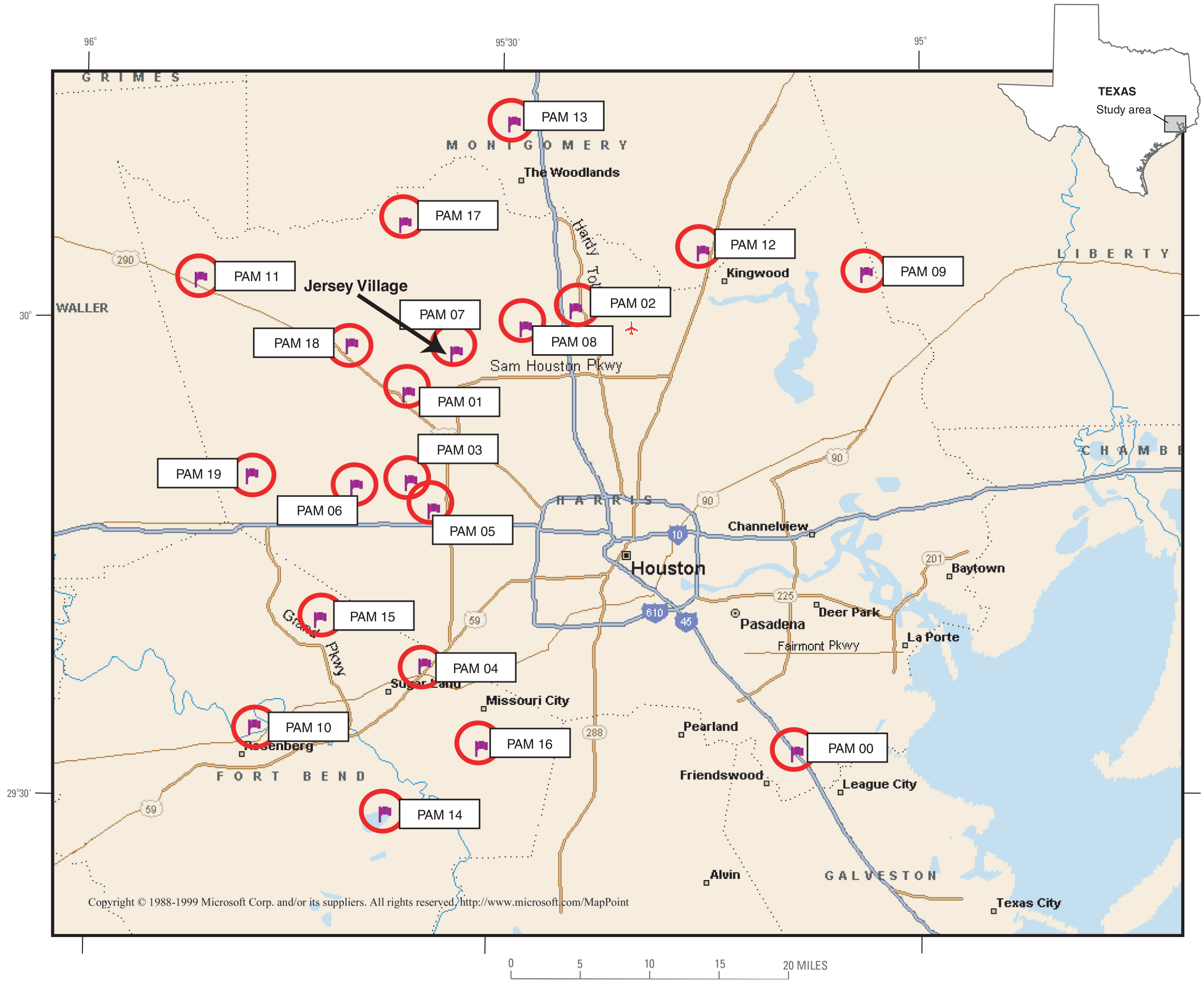


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Figure 8. Locations of 20 PAM sites in the Houston-Galveston region, Texas.

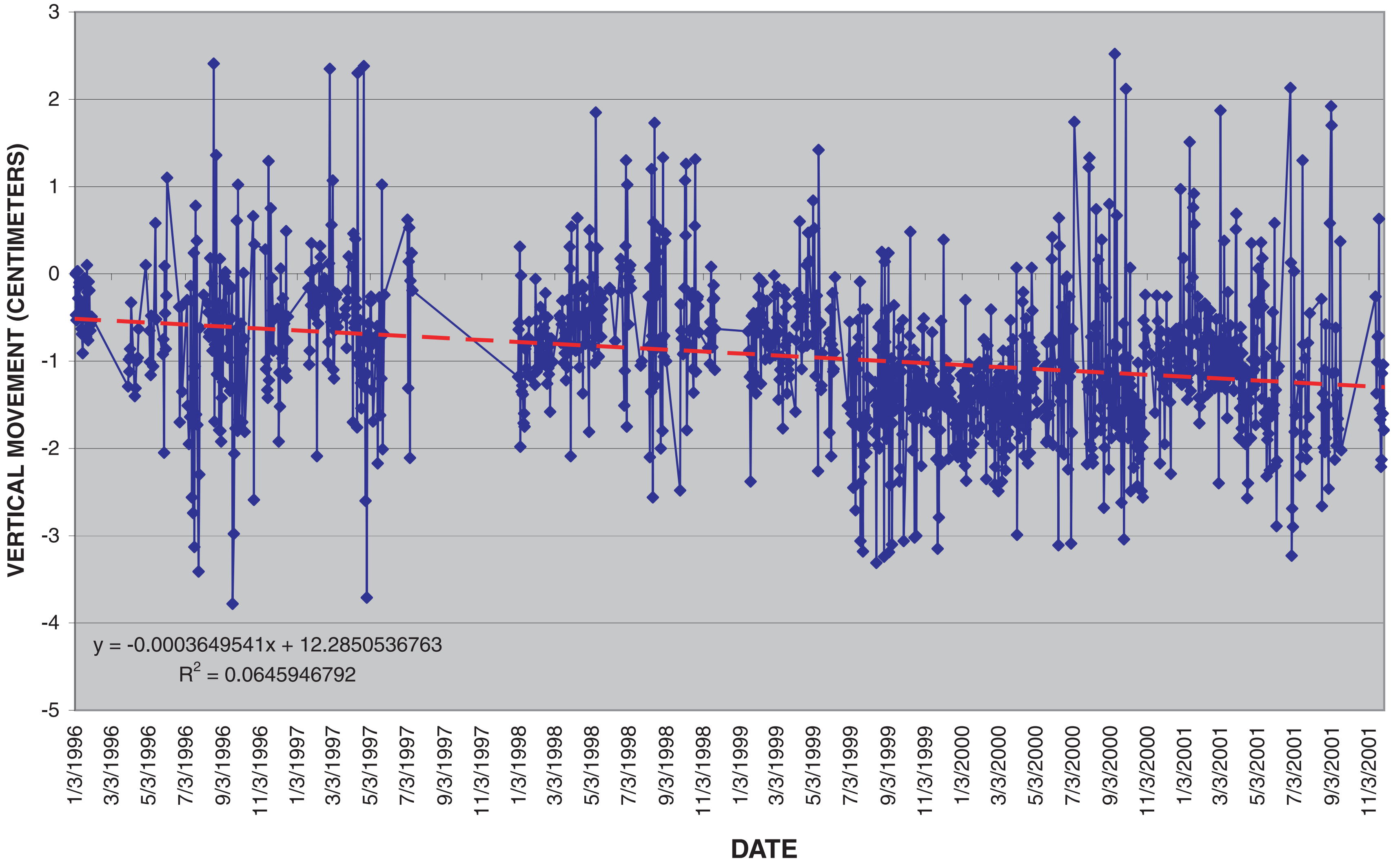

Figure 9. Ellipsoid height differences between Lake Houston CORS and Addicks CORS.

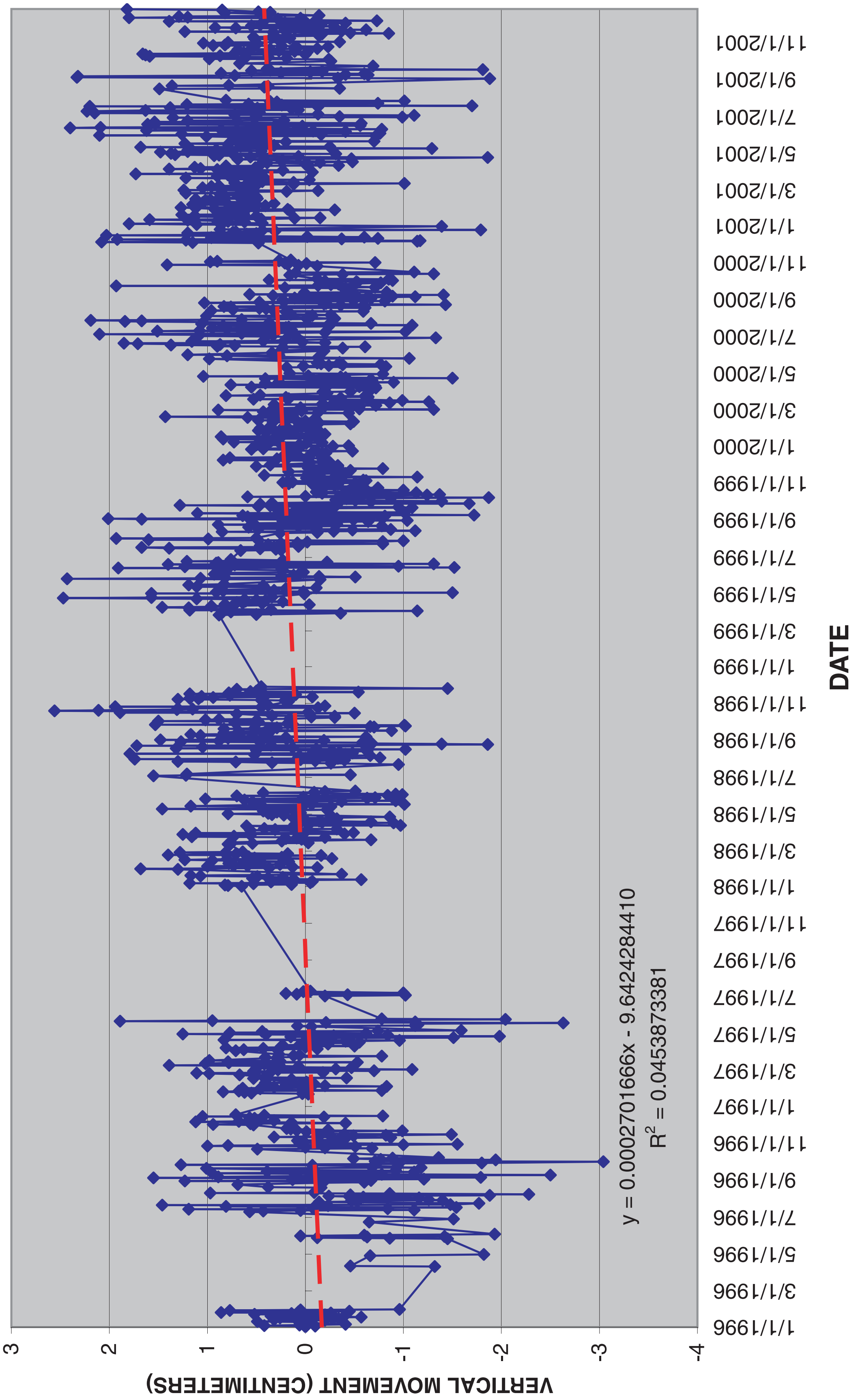

Figure 10. Ellipsoid height differences between Lake Houston CORS and Northeast CORS.

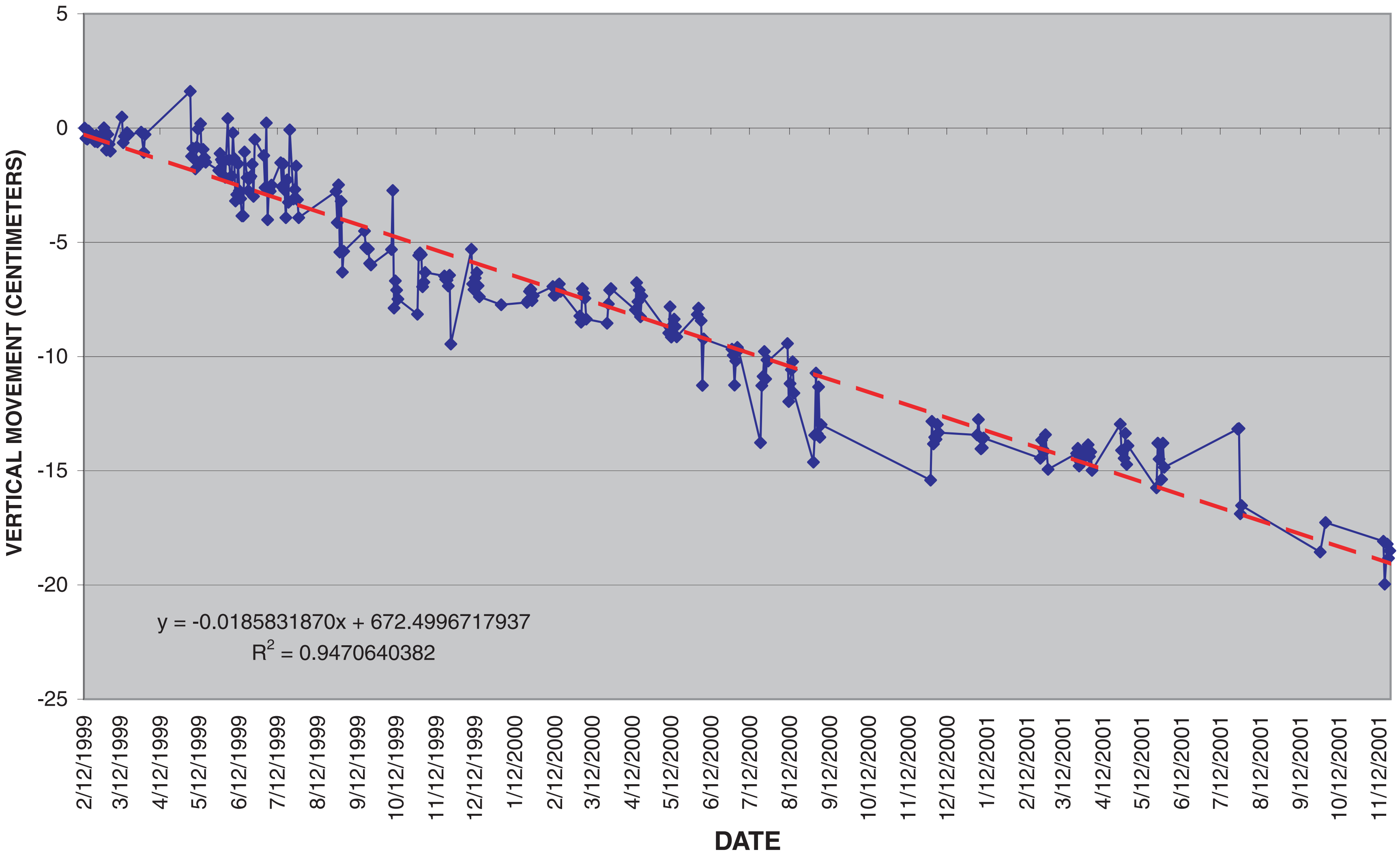

Figure 11. Ellipsoid height differences between Lake Houston CORS and PAM 07 site.

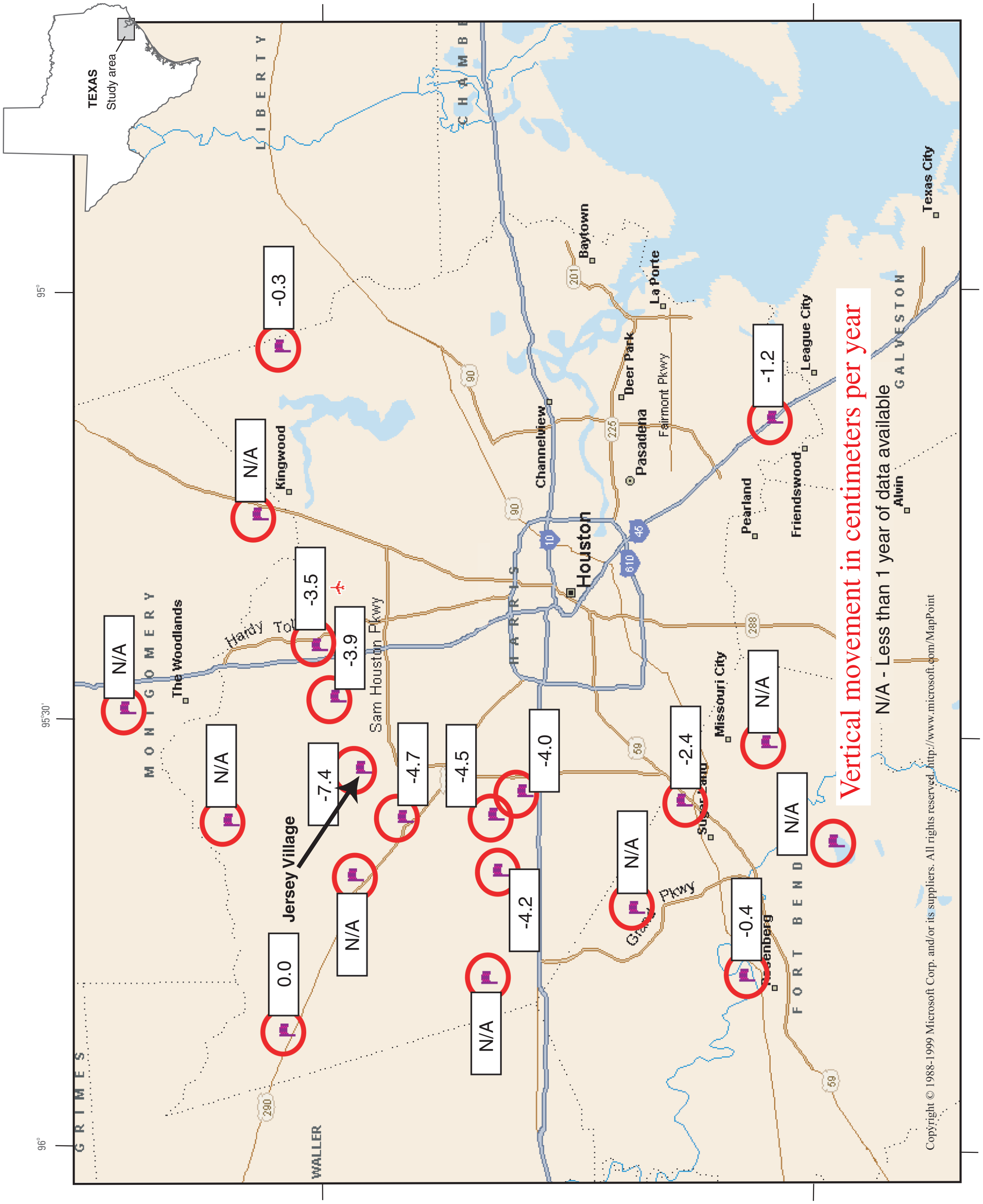

Figure 12. Weighted mean subsidence rates for PAM sites in the Houston-Galveston region, Texas.

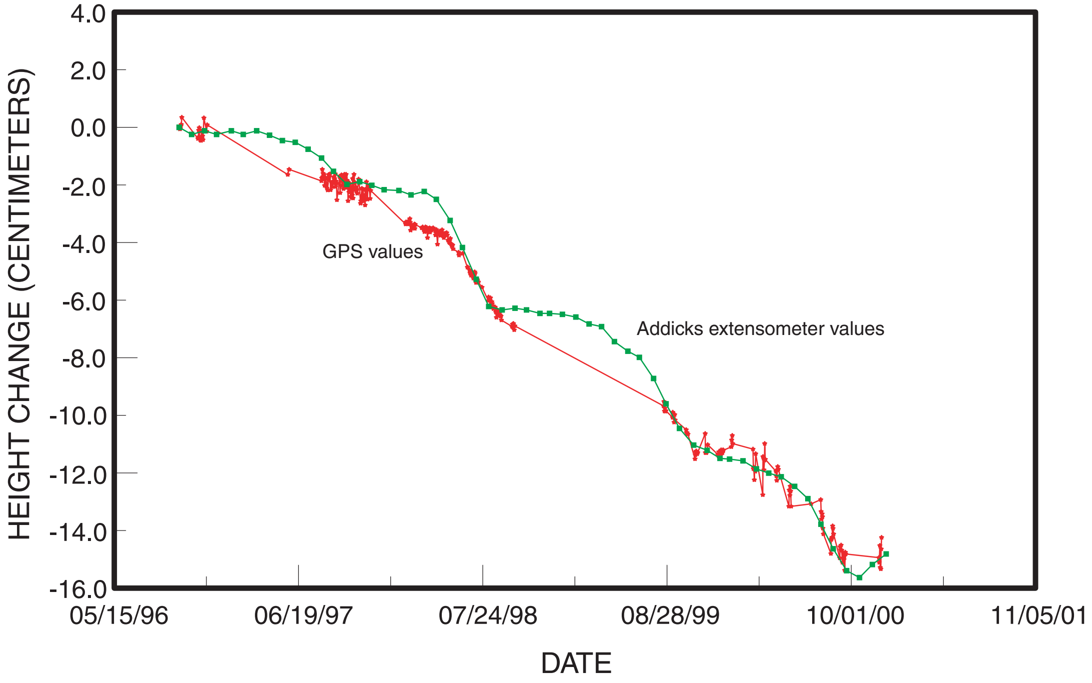

Figure 13. Comparison of techniques to estimate subsidence—Addicks extensometer values versus PAM 05 GPS ellipsoid height values.

returning to the original site every fifth week of the rotation. Thus, every site is occupied 12 different times a year and 7 days of GPS data are collected during each occupation. Some weeks data are missing because of equipment malfunction and alternate use of PAM units during special GPS surveys.

GPS data from the PAM sites are compiled and processed weekly, the height differences are plotted monthly, and individual and weighted average subsidence rates are computed and analyzed quarterly. NGS then provides the results to HGCSD for their review and dissemination. In the near future, the results will be placed on the NGS Web site for others to use.

Figure 11 depicts the estimates of ellipsoid heights for PAM 07 site relative to the Lake Houston CORS. This is the largest subsidence rate reported by the PAM units, nearly 7 cm/yr as of December 2001. PAM sites are located in areas of known subsidence, as well as in areas where subsidence rates are not known, to assess subsidence in the area.

As previously mentioned, each day that a PAM site is occupied, it has three vectors associated with it, one relative to each GPS CORS. Each vector is computed using 24 hours of GPS data, sampled at 30-second intervals. The vector is used to compute an ellipsoid height value. Therefore, three ellipsoid height values are estimated for each day that a PAM site is occupied. An initial ellipsoid height was determined for each PAM site from an average of seven 24-hour solutions; this is considered the reference ellipsoid height for the PAM site. Subsequently, each ellipsoid height determined at the PAM site is subtracted from the reference ellipsoid height to obtain a change in ellipsoid height. These ellipsoid height changes are tabulated and plotted weekly. Subsidence rates are estimated using a least-squares straight-line fit to the height differences. A standard error of the rate is computed using the statistics from the results of the least-square straight-line fit. The final subsidence rate is computed using a weighted mean of the three rates. The subsidence rates for all PAM sites that have been collecting data for at least 1 year are listed in table 1. The data indicate that the HGCSD/NGS GPS network can accurately measure a 1-cm/yr subsidence rate with 2 to 3 years of data and can potentially detect a smaller rate (for example, 0.5 cm/yr) over the same period.

Figure 12 shows the weighted mean subsidence rates for each PAM site. Sites that have been collecting data for less than 1 year are labeled N/A.

Validation of the PAM Monitoring System

To support the validation of the system, a PAM site was installed near one of the GPS CORS. Addicks CORS was selected because the subsidence rate around this site is known to be about 4 cm/yr. This will provide a large enough signal-to-noise ratio to detect movement over a few years.

Figure 13 depicts subsidence estimates at the Addicks extensometer and PAM 05 site. Because the two stations are only 50 m apart, the subsidence estimates should be approximately equivalent. The subsidence trends are step-like, not linear, and very similar. During fall and winter, subsidence is less than during spring and summer. This cyclic pattern probably is related to seasonal variations in ground-water pumping for irrigation and municipal/industrial water supply. As indicated in figure 13, this pattern also is evident in the GPS data. This site provides HGCSD and NGS with assurance that the automated system is functioning properly.

SUMMARY AND CONCLUSIONS

The joint HGCSD/NGS automated GPS subsidence cooperative project was initiated in late 1993. Since 1996, data have been routinely collected from three CORS in the Houston-Galveston region. Five portable GPS measuring stations, called PAM units, have been built and are successfully providing data for estimating subsidence at 20 additional sites in the Houston-Galveston region. Data have currently (2003) been collected from PAMs for more than 6 years in the Houston-Galveston region. Results indicate that some monuments northwest of downtown Houston are subsiding at rates of 7 cm/yr and correlate well with extensometer and PAM unit data.

The data collected by the GPS stations should prove useful to the commercial sector. Several meetings with local surveyors using GPS equipment in the area have indicated that there is a need for data from stable base stations in the Houston-Galveston region. An Internet connection allows local surveyors to download data from stations applicable to their particular needs and time periods. This system provides a common vertical and horizontal reference upon which all future GPS surveying can be referenced.

ACKNOWLEDGMENTS

Several people contributed to the progress of this cooperative project. Most helpful were Miranda Chin, Ross Mackay, Gerald Mader, and Neil Weston (NGS Geosciences Division), and Mark Schenewerk (formerly of NGS) who developed the multi-baseline processing production and CORS data-retrieval software. Without their assistance this project would not have been possible.

The first PAM trailer was designed and equipped by Leo Gittings, retired chief of NGS Instrumentation and Methodologies Branch (IMB). IMB personnel also designed and provided the antenna mounting hardware. Mark Kasmarek, USGS, provided the benchmark data. J.C. “Bud” Holzschuh, formerly of HGCSD, assisted in the engineering and construction of the PAM hardware, including the equipment to make it completely portable. Mr. Holzschuh also developed the data-retrieval software.

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Table 1. Subsidence rates for all PAM sites

[m, meters; cm, centimeters; Std. err, standard error; cm/yr, centimeters per year; ADKS, Addicks; LKHD, Lake Houston; NETP, Northeast]

HGCSD: Analysis of data to Dec. 26, 2001

Site	Years observed	Reference site	Distance (m)	No. observations	Yearly vertical movement (cm)	Std. err (± cm)	Weighted mean (cm/yr)	Model
00	1999–2001	ADKS	50,488	147	-1.5501	0.1234		
		LKHU	41,555	180	-1.2422	.0858	-1.44	Linear
		NETP	33,075	166	-1.5799	.0906		
							±.06	Std. err
01	1996–2001	ADKS	13,717	392	-4.8492	.0405		
		LKHU	45,472	438	-4.9327	.0402	-4.96	Linear
		NETP	30,393	416	-5.0911	.0386		
							±.02	Std. err
02	1996–2001	ADKS	23,489	351	-3.5153	.0316		
		LKHU	27,807	381	-3.5577	.0249	-3.59	Linear
		NETP	24,525	340	-3.7262	.0297		
							±.02	Std. err
03	1999–2001	ADKS	4,212	170	-4.6767	.0969		
		LKHU	46,332	212	-4.7585	.0814	-4.79	Linear
		NETP	27,187	212	-4.9925	.0804		
							±.06	Std. err
04	1996–2001	ADKS	17,828	444	-2.2713	.0454		
		LKHU	53,737	513	-2.3611	.0474	-2.39	Linear
		NETP	31,040	481	-2.5498	.044		
							±.03	Std. err
05	1996–2001	ADKS	55	421	-3.8303	.0296		
		LKHU	44,638	495	-3.8965	.0434	-3.89	Linear
		NETP	24,335	501	-4.0376	.0429		
							±.02	Std. err
06	1997, 1999–2001	ADKS	9,272	248	-4.3257	.0448		
		LKHU	52,517	274	-4.2899	.0364	-4.32	Linear
		NETP	33,332	277	-4.3497	.0441		
							±.02	Std. err
07	1999–2001	ADKS	16,137	203	-6.6237	.1018		
		LKHU	41,684	246	-6.7831	.1027	-6.73	Linear
		NETP	28,416	219	-6.798	.1008		
							±.06	Std. err
08	1999–2001	ADKS	23,468	153	-3.6944	.0998		
		LKHU	32,741	187	-3.7939	.0769	-3.83	Linear
		NETP	25,000	175	-4.1072	.1042		
							±.05	Std. err
09	1999–2001	ADKS	56,775	182	-.2071	.092		
		LKHU	15,568	239	-.0646	.0743	-.24	Linear
		NETP	37,327	220	-.6675	.103		
							±.05	Std. err

Table 1. Subsidence rates for all PAM sites—Continued

HGCSD: Analysis of data to Dec. 26, 2001								
Site	**Years observed**	**Reference site**	**Distance (m)**	**No. observations**	**Yearly vertical movement (cm)**	**Std. err (± cm)**	**Weighted mean (cm/yr)**	**Model**
10	1999–2001	ADKS	32,309	433	-0.316	0.0684		
		LKHU	73,997	481	-.4434	.0622	-0.48	Linear
		NETP	51,442	436	-.721	.081		
							±.04	Std. err
11	1999–2001	ADKS	37,945	178	-.0726	.0821		
		LKHU	70,673	230	.0656	.0717	-.03	Linear[1]
		NETP	57,822	218	-.1062	.0818		
							±.05	Std. err
12	2000–2001	ADKS	43,152	49	-1.268	.7554		
		LKHU	61,081	69	-1.0794	.6682	-1.1	Linear
		NETP	39,168	71	-.9303	.6081		
							±.4	Std. err
13	2000–2001	ADKS	45,722	65	-2.2161	.3022		
		LKHU	45,548	74	-2.3861	.3413	-2.2	Linear
		NETP	47,202	71	-2.0955	.3464		
							±.19	Std. err
14	2000–2001	ADKS	35,614	44	.8048	.3788		
		LKHU	68,577	55	.3248	.3202	.64	Linear
		NETP	46,250	45	.7055	.6926		
							±.26	Std. err
15	2000–2001	ADKS	17,578	54	-.3239	.3541		
		LKHU	61,081	91	-1.5778	.2759	-.95	Linear
		NETP	39,168	102	-1.6318	.2629		
							±.2	Std. err
16	2000–2001	ADKS	27,918	60	.4504	.3251		
		LKHU	55,092	79	-.3298	.2894	-.08	Linear[1]
		NETP	33,119	61	-.4499	.226		
							±.17	Std. err
17	2000–2001	ADKS	33,393	33	.2757	.3702		
		LKHU	49,400	37	-.7859	.3868	-.29	Linear[1]
		NETP	42,922	31	-.5878	.3264		
							±.21	Std. err
18	2000–2001	ADKS	21,226	41	-.0545	.5321		
		LKHU	51,723	44	-.5467	.448	-.43	Linear[1]
		NETP	38,411	47	-.984	.4338		
							±.29	Std. err
19	2000–2001	ADKS	21,881	53	.1319	.3804		
		LKHU	64,221	81	-1.2981	.2262	-.64	Linear
		NETP	45,875	63	-.8781	.191		
							±.16	Std. err
ADKS	1996–2001	LKHU	44,692	1,278	-.1332	.0143	-.13	Linear
NETP	1996–2001	LKHU	22,704	1,311	.0986	.0125	.1	Linear

[1] Rate highly uncertain.