LAND-SUBSIDENCE MEASUREMENTS AND AQUIFER-COMPACTION MONITORING IN TUCSON BASIN AND AVRA VALLEY, ARIZONA

By Herbert H. Schumann and S.R. Anderson

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CONVERSION FACTORS

For readers who prefer to use International System (SI) units, conversion factors for the terms in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
square mile (mi^2)	2.590	square kilometer (km^2)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

A vertical-control network and a vertical-extensometer network have been established for measuring land subsidence and for monitoring aquifer compaction caused by ground-water depletion in Tucson basin and Avra Valley in southeastern Arizona. Land subsidence and resultant earth fissures have damaged a variety of engineering structures and present geologic hazards in many parts of southern Arizona.

Ground-water depletion has lowered water levels in wells more than 150 feet in Tucson basin and more than 200 feet in Avra Valley. Conventional first-order leveling surveys indicate that ground-water depletion has caused nearly 0.5 foot of land subsidence in Tucson basin between 1952 and 1980 and as much as 1.1 feet in the northwestern part of Avra Valley between 1948 and 1980.

During the spring of 1987, the Global Positioning System (GPS) was used to make a series of vertical and horizontal measurements at bench marks at 43 key sites to establish the land-subsidence monitoring network. Future satellite observations and conventional first-order leveling surveys of this network will provide information on amounts and areal distribution of land subsidence. Land-subsidence measurements at 14 vertical-extensometer sites will be used to document the relation between aquifer compaction, water-level change, and land subsidence. The relations will be used in refining predictions of land subsidence.

INTRODUCTION

Tucson basin and Avra Valley are large north-trending alluvial basins that occupy about 1,000 and 500 mi^2, respectively, in Pima and Pinal Counties of southeastern Arizona (fig. 1). Tucson basin is becoming heavily urbanized and, like Avra Valley, is totally dependent on ground water for agricultural, industrial, and municipal water supplies. Pumpage of ground water has exceeded natural recharge for several decades, and water levels in wells have declined throughout both areas (Schumann and Genualdi, 1986; Cuff and Anderson, 1987; Babcock and Hix, 1982).

Earth fissures that result from differential land subsidence have been observed in parts of Avra Valley (Caito and Sogge, 1982;

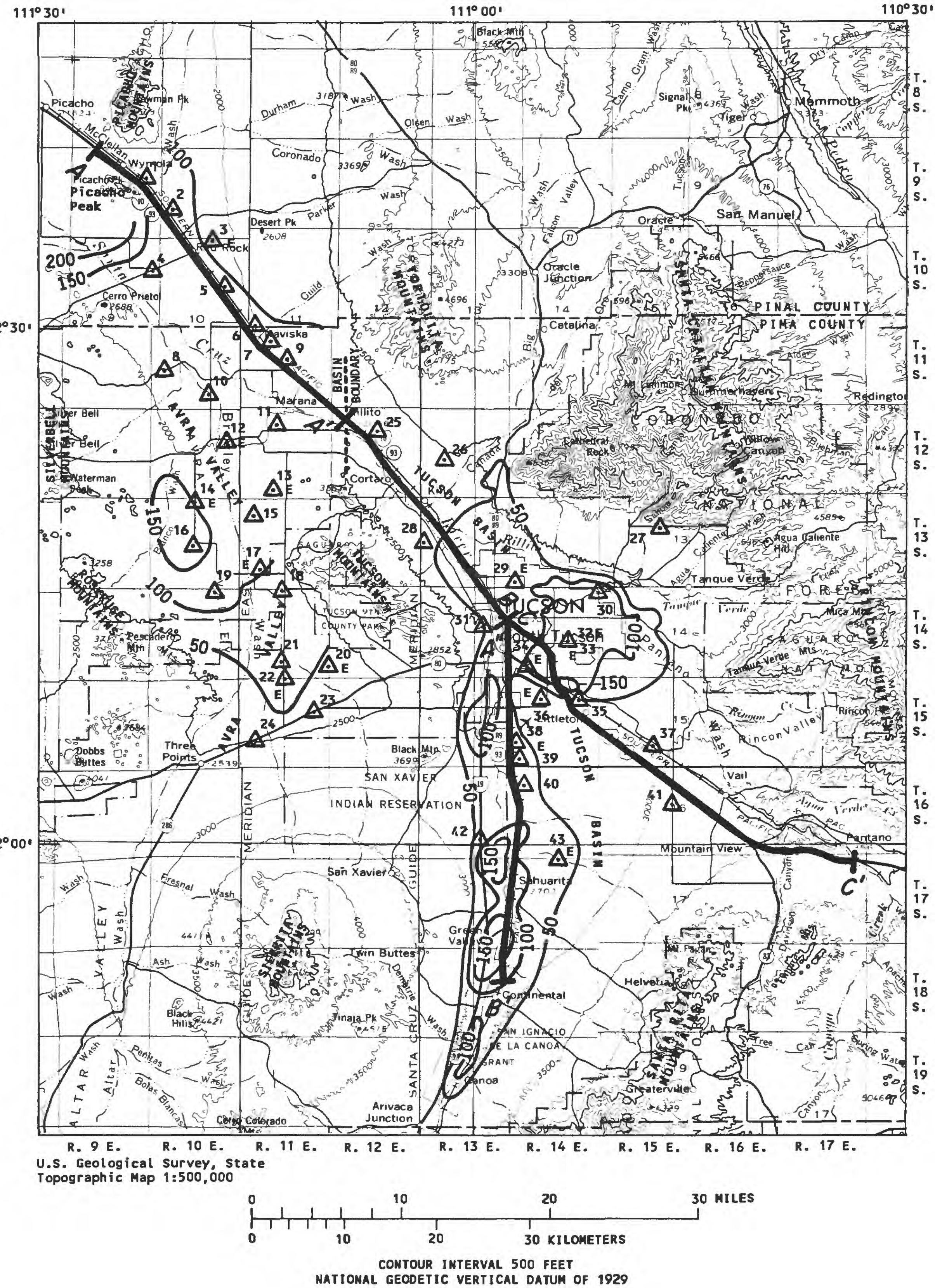

Figure 1.--Location of bench marks and water-level declines in Tucson basin and Avra Valley.

INDEX MAP SHOWING AREA
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EXPLANATION

$\triangle^{15}_{E}$	BENCH MARK—Location of bench mark used in 1987 satellite survey. Station number, 15, is keyed to table 1. Letter, E, denotes vertical-extensometer installation
——— 50 ———	LINE OF EQUAL WATER-LEVEL DECLINE—Interval, 50 feet. Declines in Tucson basin are from 1947 to 1981. Declines in Avra Valley are from 1940 to 1985
A ——— A′	LEVEL LINE—National Geodetic Survey

Figure 1.

Schumann and Genualdi, 1986; and Anderson, 1988). However, similar earth fissures have not been detected in Tucson basin. Land subsidence and earth fissures that result from ground-water depletion have damaged a variety of engineering structures and present geologic hazards in many parts of southern Arizona (Schumann and Genualdi, 1986).

In 1979, the U.S. Geological Survey, in cooperation with the City of Tucson, began an investigation to determine the potential for aquifer compaction, land subsidence, and earth fissures in Tucson basin. The study was expanded in 1983 to include Avra Valley (Anderson, 1988). In 1983, the U.S. Geological Survey, in cooperation with the U.S. Bureau of Reclamation, began a similar investigation to determine land subsidence and earth-fissure hazards in Avra Valley along the alignment of the Tucson aqueduct of the Central Arizona Project (Wrege and others, 1985).

In the fall of 1986, the U.S. Geological Survey, in cooperation with the City of Tucson and the National Geodetic Survey, began work on the design and implementation of a special vertical-control network to determine the amount and distribution of land subsidence in Tucson basin and Avra Valley. A program of satellite measurements was planned to establish the land-subsidence monitoring network. The purpose of this report is to document the design of the land-subsidence monitoring network and to present the preliminary results of the initial satellite measurements conducted during the spring of 1987.

WATER-LEVEL DECLINE, AQUIFER COMPACTION, AND LAND SUBSIDENCE

The relation between water-level decline, aquifer compaction, and land subsidence in southern Arizona was first established at a vertical-extensometer site in western Pinal County (Schumann and Poland, 1970). Water-level declines produce an increased effective stress on the deeper parts of the alluvial aquifer causing them to compact. In turn, the aquifer compaction results in a measurable vertical lowering of the land surface defined as land subsidence (Poland and others, 1972). Water-level declines in excess of 100 ft produced measurable amounts of land subsidence in western Pinal County (Schumann and Poland, 1970). In general, areas of maximum land subsidence correspond to areas of maximum water-level decline (Schumann and Genualdi, 1986).

AQUIFER-COMPACTION MONITORING

A network of 14 vertical extensometers has been established to monitor the rates and magnitude of aquifer compaction and water-level change at selected sites in Tucson basin and Avra Valley. Seven extensometers are in Tucson basin and seven are in Avra Valley (fig. 1). Aquifer compaction is being measured at vertical-extensometer pipes that extend from the land surface to the bottom of cased wells or test holes (fig. 2). The extensometer pipes are isolated from the well casings and are jetted into the formation or are set on concrete plugs placed at the bottom of the well. As the aquifer materials compact, the land surface moves downward in relation to the top of the extensometer pipe.

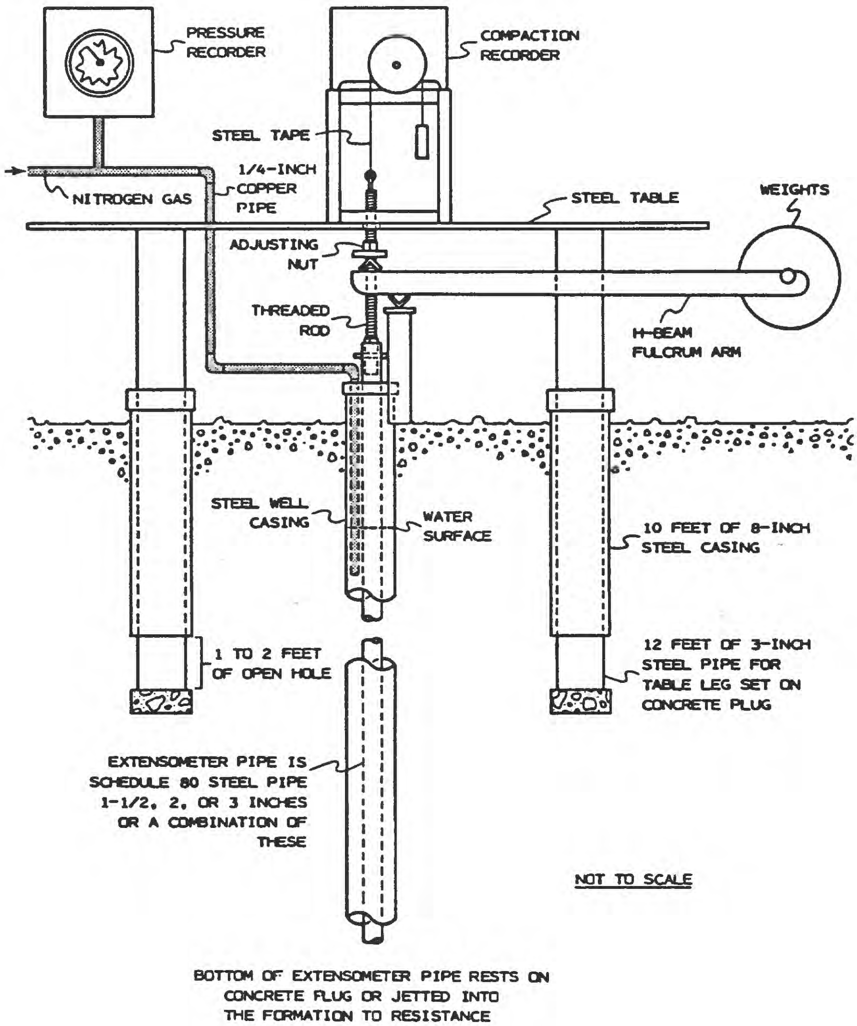

Figure 2.--Diagrammatic sketch of a vertical extensometer.

Records of this movement provide a continuous record of aquifer compaction for the part of the aquifer penetrated by the well. Depths of the extensometer wells range from 485 to 1,410 ft below land surface (Anderson and others, 1982; Wrege and others, 1985). The design and operation of vertical extensometers were described in detail by Schumann (1986) and Anderson and others (1982).

Aquifer compaction and water-level change measured by a vertical extensometer in the southern part of Tucson basin is shown in figure 3. Land-subsidence measurements at the 14 vertical-extensometer sites will be used to document the relation between aquifer compaction, water-level change, and land subsidence. Documentation of these relations should permit refined predictions of land subsidence.

LAND-SUBSIDENCE MEASUREMENTS

Traditionally, land subsidence has been measured by repeated conventional first-order leveling surveys that cross entire ground-water basins. These surveys are tied to stable bench marks set on bedrock or to tidal gages to determine changes in land-surface elevations. The repeated conventional first-order surveys are labor intensive and costly. A cost-effective means of measuring land subsidence over large areas is needed for hazard identification and risk assessment related to land subsidence.

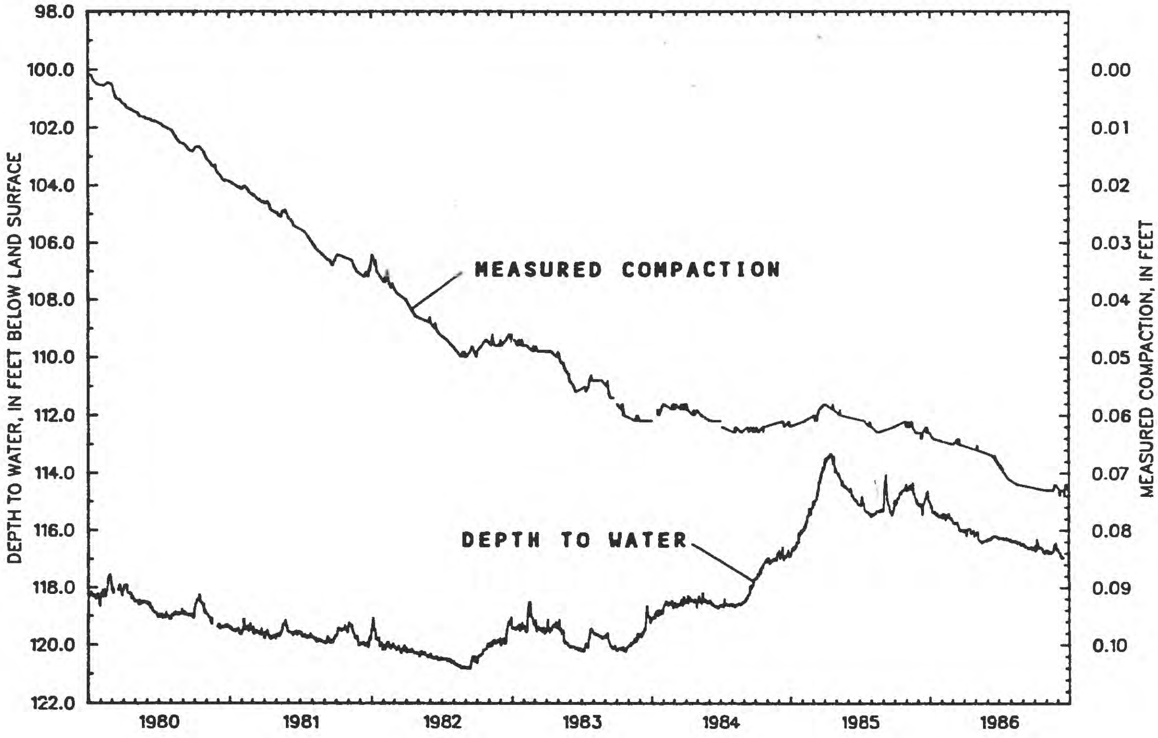

Figure 3.--Depth to water and measured compaction at well in section 30, T. 15 S., R. 14 E. (Babcock and others, 1986).

Conventional First-Order Leveling Measurements

National Geodetic Survey first-order level lines pass diagonally across parts of Tucson basin and Avra Valley (fig. 1). An evaluation of repeated conventional first-order leveling surveys along these lines indicates that nearly 0.5 ft of land subsidence occurred in the north-central part of Tucson basin between 1952 and 1980 (fig. 4) and that as much as 1.1 ft of land subsidence occurred in the northwestern part of Avra Valley between 1948 and 1980 (Strange, 1983). Water levels in wells have declined as much as 200 ft in the northwestern part of Avra Valley and more than 150 ft in the north-central part of Tucson basin (Anderson, 1988).

Satellite Measurements

In the spring of 1987, the Global Positioning System (GPS) was used to measure horizontal and vertical positions for bench marks at 43 key sites to establish a network for monitoring land subsidence in Tucson basin and Avra Valley. The GPS is a satellite-based Department of Defense global radio-navigation system that is used to provide positions of ships, aircraft, tanks, and even soldiers on the ground in real time (fig. 5). The GPS can be divided into three main parts—the space segment, the control segment, and the user segment.

The space segment of the GPS includes the Department of Defense global radio Navigation System With Timing And Ranging (NAVSTAR) earth-orbiting satellites. These satellites transmit radio signals that include time breaks, a predicted satellite ephemeris, and information on the satellite status on two different carrier frequencies. The satellites are tracked, updated, and controlled by the control segment of the GPS that includes a system of tracking stations at various places around the globe (fig. 5).

In 1987, seven NAVSTAR test satellites were in orbit in three different orbital planes with an inclination of 63°. This satellite configuration provided four satellites that could be observed simultaneously during 4 to 5 hours per day in Arizona. Orbits for these satellites were chosen to provide the most favorable coverage for testing the system over the southwestern United States. When the system is fully implemented in 1991, it will include a group of 18 NAVSTAR satellites placed in six equally spaced orbital planes at an inclination of 55°. These satellites will orbit the earth every 12 hours at an altitude of about 12,600 mi and will allow simultaneous visibility of at least four satellites at any time of the day or night from almost any point in the world (Remondi, 1985).

The user segment of the GPS consists of receiver and antenna units that simultaneously receive, identify, and lock on to radio signals from four or more satellites. The incoming satellite signals are processed by a microprocessor unit within or attached to the receiver. For surveying applications, the data from the satellites are recorded on magnetic tape or disk for post processing.

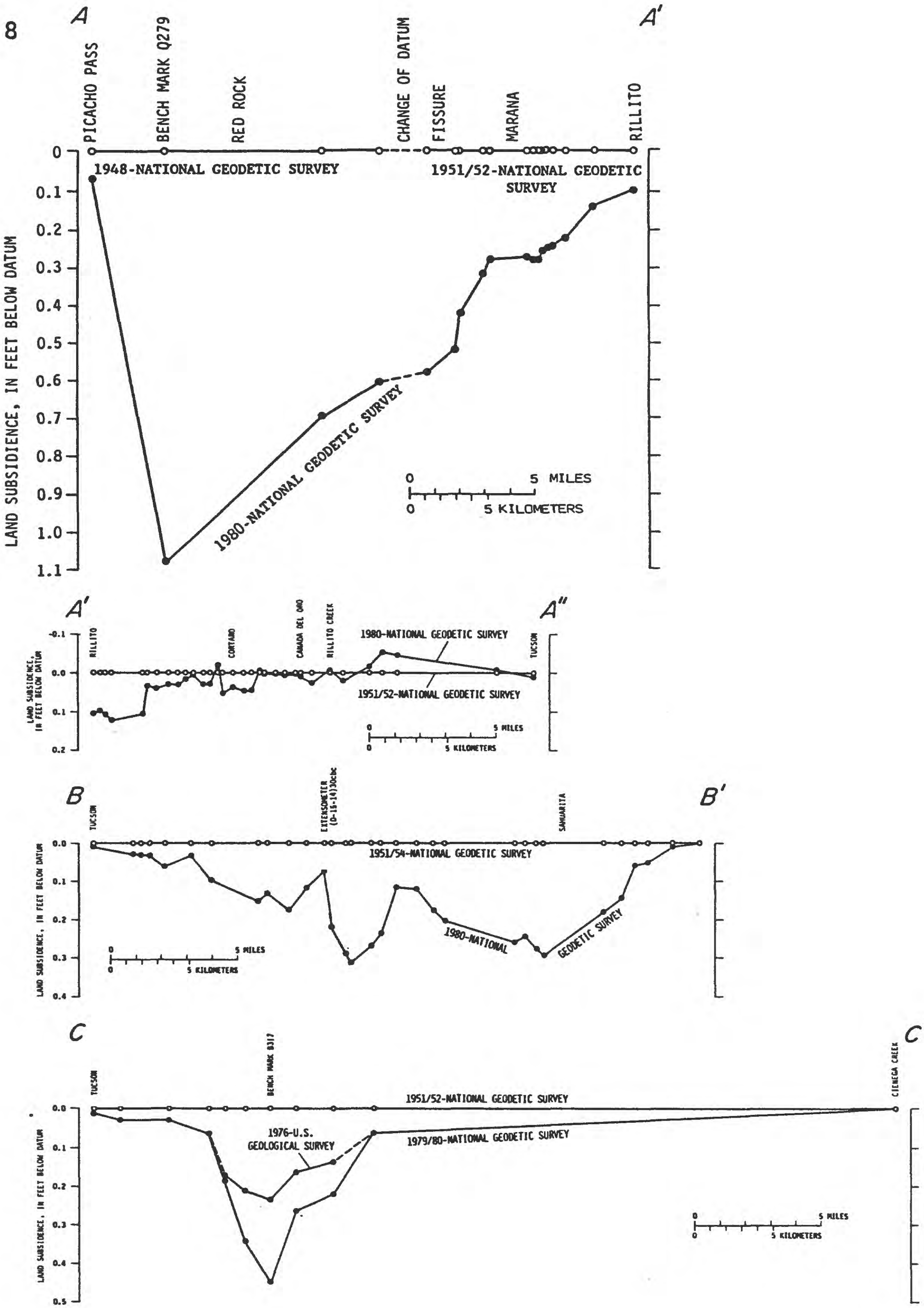

Figure 4.--Land subsidence in Tucson basin and Avra Valley (Anderson, 1987, 1988).

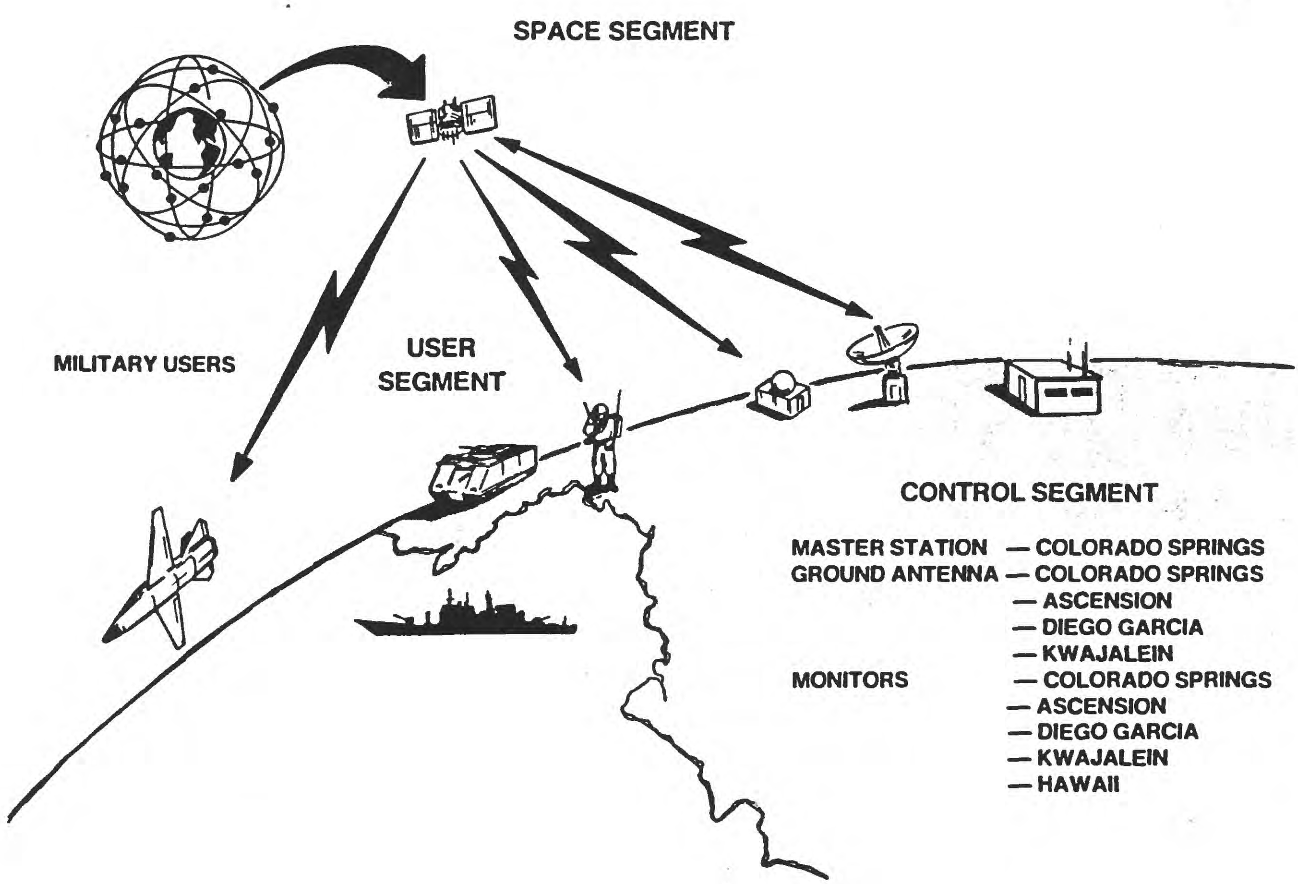

Figure 5.--Global Positioning System (GPS). Illustration courtesy of Motorola, Inc., Government Electronics Group.

When the receiver is in a navigation mode, three-dimensional positions for the antenna are calculated in real time. The actual navigation signal is a code that is modulated on the carrier and provides the information needed to determine the instantaneous ranges between the satellites and the receiver unit. These data are computer processed to provide positions that are accurate to about 80 ft.

Geodetic surveys that require accuracies of a few tenths of a foot (decimeter level) or better are performed using relative-positioning techniques (Goad and Remondi, 1984). Relative-positioning techniques involve operating two or more GPS receiver units simultaneously. One unit is placed at a known position, such as a bench mark, for which the latitude, longitude, and elevation are precisely known. The second unit is placed at the point for which the position is to be determined. The units are operated simultaneously and receive signals from the same satellites (fig. 6). Observations of 1 to 5 hours duration usually are collected to assure geodetic accuracy. The length of observations needed depends on satellite positions and the accuracy required.

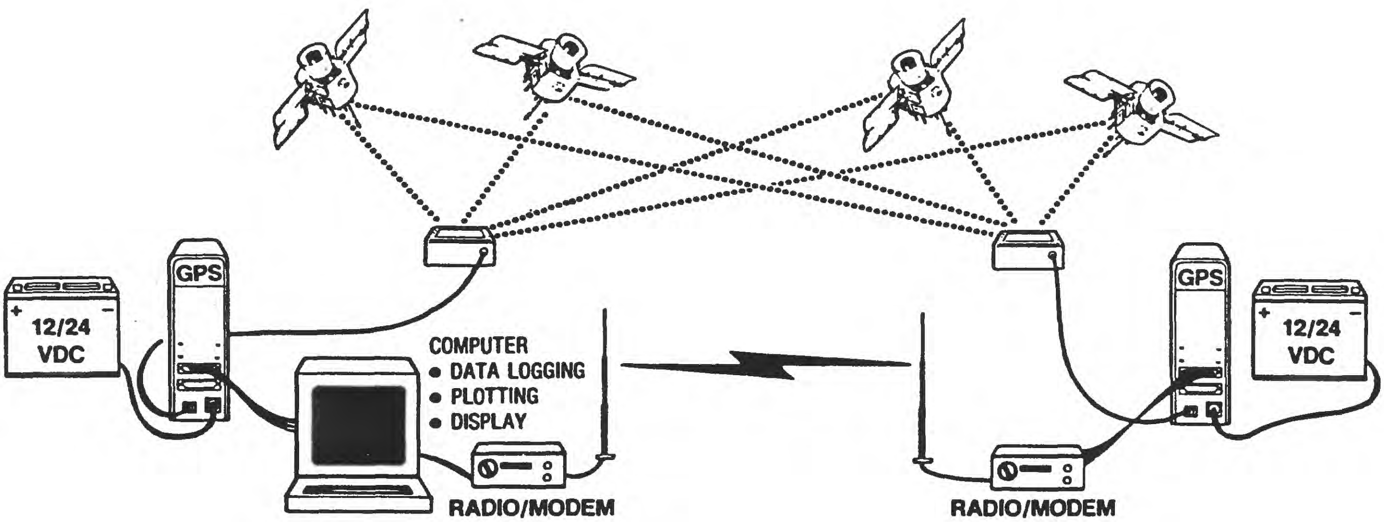

Figure 6.--Operation of dual satellite receivers. Illustration courtesy of Motorola, Inc., Government Electronics Group.

Differential positions between the known point and the points to be determined are obtained by analyzing the carrier-phase data. Relative-positioning accuracies of one part per million (ppm) or less over distances of hundreds of miles are possible (Strange, 1985). Goad and Remondi (1984) and Remondi (1985) presented detailed descriptions of the GPS and its use in geodesy.

During the spring of 1984, a field test in the Eloy basin in central Arizona evaluated the feasibility of using the GPS to make measurements of land subsidence (W.E. Strange, National Geodetic Survey, written commun., 1988). During this test, GPS measurements were repeated at selected sites with an accuracy of about 0.05 ft. These measurements indicated that changes in land-surface elevations could be determined by successive GPS measurements to a precision equivalent to conventional first-order leveling (Strange, 1985). Accuracies of conventional first-order leveling surveys are a direct function of the square root of the length of the survey line. The accuracy of GPS-determined positions, however, generally is uniform and independent of the length of most survey lines.

Elevations and Satellite-Height Measurements

The GPS satellite-height measurements and the height measurements from conventional first-order leveling are referenced to different datums. Conventional first-order leveling data are expressed in terms of elevations above or below a sea level datum. In geodetic terms, the equipotential surface that corresponds to sea level is called the geoid, and leveling heights measured relative to that surface are called orthometric heights (fig. 7).

Observations from the GPS are processed to determine station positions in Cartesian coordinates (X, Y, Z) that can be converted by a simple transformation to geodetic coordinates (latitude, longitude, and height-above-reference ellipsoid). The ellipsoid to which the GPS measurements are referenced is a three-dimensional mathematical depiction of the Earth's shape. The ellipsoid heights measured by the GPS are expressed as vertical heights above the reference ellipsoid. The difference between ellipsoidal heights (h) and orthometric heights (H) are called geoidal heights (N) and represent the vertical separation between the geoid and the ellipsoid (fig. 7).

Ellipsoidal heights must be converted to orthometric heights (elevations above mean sea level) to compare them to elevations obtained from conventional first-order leveling surveys. To convert ellipsoidal heights to orthometric heights, it is necessary to know or to calculate the geoidal heights.

During the test in the Eloy basin, geoidal heights were computed using gravity data. The computed geoidal heights then were used to convert GPS ellipsoidal heights to orthometric heights. An average difference of about 0.15 ft was obtained when the calculated orthometric heights were compared to conventional first-order leveling surveys for the same bench marks (W.E. Strange, National Geodetic Survey, written commun., 1988). The results of the Eloy test indicate a comparison of orthometric heights calculated from GPS results with previously established elevation data from conventional first-order leveling may be used to determine moderate amounts of land subsidence in excess of about 0.3 ft. Successively determined GPS ellipsoidal heights should allow the detection of land-subsidence amounts as small as 0.1 ft between sets of GPS measurements.

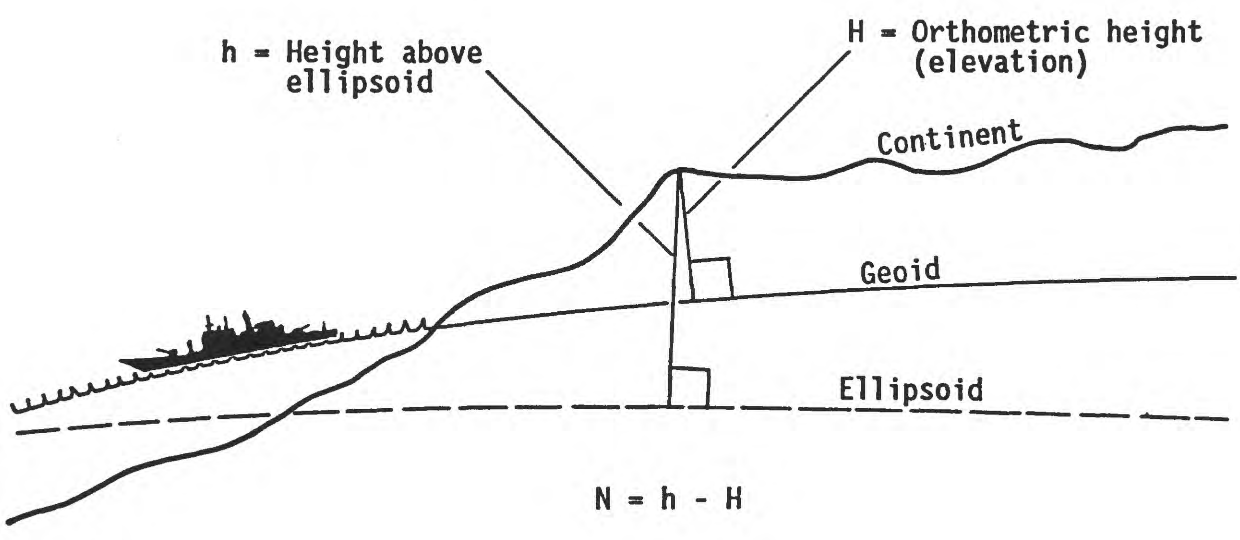

Figure 7.--Relation between ellipsoidal heights (h), orthometric heights (H), and geoidal heights (N).

LAND-SUBSIDENCE MONITORING NETWORK DESIGN

A network of 43 bench marks was established at key locations in Tucson basin and Avra Valley (fig. 1). The bench-mark locations were selected on the basis of historic water-level declines, future water-level changes predicted by ground-water flow models, available vertical-control data, and subsurface geologic conditions. The network was designed to provide a basinwide framework for making determinations of land subsidence in both areas.

During the spring of 1987, a field reconnaissance of the area was done, and special bench marks were installed at selected sites. To initiate the network, a first-epoch series of GPS satellite observations were made in March and April of 1987. The locations and the preliminary ellipsoid heights for the bench marks that comprise the subsidence-monitoring network are listed in table 1. Repeat satellite observations or conventional first-order leveling surveys of the network will provide information on amounts and distributions of land subsidence.

Measurements at seven aquifer-compaction monitoring sites in Tucson basin and at seven sites in Avra Valley were included in the initial network (fig. 1; table 1). Measurements of land subsidence at these sites will aid in documenting the relation between water-level change, aquifer compaction, and land subsidence.

SUMMARY

Ground-water depletion caused nearly 0.5 ft of land subsidence in Tucson basin between 1952 and 1980 and as much as 1.1 ft in the northwestern part of Avra Valley between 1948 and 1980. Land subsidence and resultant earth fissures have damaged a variety of engineering structures and present geologic hazards in adjacent areas and in other parts of southern Arizona.

During the spring of 1987, the GPS system was used to make a series of horizontal and vertical measurements at 43 bench marks to establish a monitoring network. These 43 key sites were selected on the basis of historic water-level declines, future water-level changes predicted by digital ground-water models, available vertical-control data, and subsurface geologic conditions.

The areal distribution of the vertical-control bench marks was designed to provide a land-subsidence monitoring network in Tucson basin and Avra Valley. Repeat satellite observations and (or) conventional first-order leveling surveys of the network will provide information on the amount of land subsidence at each bench mark. Land-subsidence measurements at the 14 vertical-extensometer sites will aid in documenting the relation between aquifer compaction, water-level change, and land subsidence.

Table 1.--Locations and ellipsoid heights of stations in Tucson basin and Avra Valley

Station number	Station name	Latitude	Longitude	Ellipsoid height, in meters[1]
1	M 279[2]	32°38'41.76467"	111°23'11.90762"	516.846
2	Q 279	32°36'49.76497"	111°21'21.41921"	523.240
3[3]	GPS 13	32°35' 9.41662"	111°18'10.05468"	555.938
4	6 WBC USGS	32°33'31.14427"	111°22' 6.33304"	526.239
5	1899 USGS	32°32'28.68393"	111°17'43.15553"	552.164
6	NAVISKA 2	32°30' 9.85369"	111°15'48.43957"	563.515
7	F 424	32°29' 4.00136"	111°14'48.69434"	562.680
8	L 94	32°27'43.04924"	111°21'12.80656"	553.337
9	171+82 AZHD	32°28' 5.0146"	111°13'25.06206"	570.232
10	F 294	32°26'20.59671"	111°18'15.39080"	557.454
11	Q 94	32°24'32.32246"	111°13'35.16224"	583.050
12[3]	AF 14	32°23'38.06025"	111°16'58.70339"	577.751
13[3]	GPS 32[4]	32°20'56.00120"	111°13'52.86041"	610.766
14[3]	AF 17	32°20' 7.76537"	111°19'18.00651"	600.259
15	H 292	32°19'15.17496"	111°15' 7.26185"	613.681
16	SA 105	32°17'29.97832"	111°19'17.17949"	623.268
17[3]	GPS 33	32°15'46.41962"	111°14'41.04307"	638.739
18	USBR 938+0.00	32°14'54.44331"	111°13'13.07609"	676.172
19	H 301	32°14'47.85933"	111°17'45.18841"	646.033
20[3]	GPS 44	32°10'29.85870"	111°10' 8.30075"	694.952
21	SA 109	32°10'20.19124"	111°13' 3.45897"	674.224
22[3]	AV 25	32° 9'45.11632"	111°13' 0.05070"	678.056
23	D 296	32° 7'46.89479"	111°10'59.80533"	709.088
24	MISS AZDT	32° 6' 7.50123"	111°15' 0.06314"	730.489
25	H 140	32°23'45.85454"	111° 7'24.17037"	606.691
26	PARK	32°22'25.84426"	111° 2' 1.60196"	715.408
27	TUCSON	32°18'34.60861"	110°47' 4.64039"	873.679
28	FD 62	32°17'38.02722"	111° 3'21.06905"	683.972
29[3]	W 52 USGS	32°15'20.12050"	110°57'17.73264"	699.786
30	SUNNY	32°14'50.13896"	110°51'27.85082"	729.316
31	N 419	32°12'48.50861"	110°59'17.52940"	694.260
32[3]	C 45 USGS	32°12' 9.09561"	110°53'47.09022"	748.297
33[3]	D 61 USGS	32°11'57.97680"	110°53'16.02794"	756.110
34[3]	X 419	32°10'55.93460"	110°56'35.60810"	732.269
35	C 317	32° 8'44.70897"	110°53' 9.90766"	783.159
36[3]	WR53 USGS	32° 8'43.40275"	110°55'15.75124"	762.791
37	5DOR USGS	32° 5'41.45432"	110°47'45.33871"	868.627
38[3]	XAVIER 1935	32° 5'38.54763"	110°57'34.67629"	758.408
39	X 333	32° 4'47.35386"	110°57'29.95588"	759.138
40	L 75	32° 3'19.51300"	110°57'13.38595"	763.189
41	GPS SA115	32° 2'29.54441"	110°46'26.02311"	908.816
42	PA4 1959	32° 0' 5.22269"	110°59'40.43942"	822.089
43[3]	SC-30 USGS	31°59'12.21891"	110°54' 7.57404"	805.151

[1]Data from National Geodetic Survey were reported in meters.
[2]Position held fixed to the World Geodetic System of 1972.
[3]Vertical-extensometer installation.

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