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SEASONAL DEFORMATION OF A TWO-MILE STRAIGHT LINE*

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ABSTRACT

Relative motions of parts of the Stanford Linear Accelerator housing were measured and corrected repeatedly between 1966 and 1971. The vertical motion shows a steady decline with time, whereas both vertical and horizontal motions have a periodic component of one cycle per year. Displacement is upward in winter and downward in summer, and is clearly correlated with rainfall and water level in nearby wells. Consequently, the observed displacements must be associated with local soil and rock properties, and are not due to tectonic stress around the San Andreas fault system.

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INTRODUCTION

It has been observed that the alignment of the two-mile-long Stanford Linear Electron Accelerator varies with time. This phenomenon is of interest because it is related to sub-surface soil changes, and because a clear understanding of causes of misalignment may be helpful in scheduling complete re-alignments of the accelerator. This "electron gun" is kept in a straight line, over two miles, to better than the thickness of a dime, that is, ± 1 mm at any time. A deviation from straight of less than 0.1 mm can be detected anywhere along the machine. Four years of data has been carefully collected, showing the movement of 270 points along these 2 miles, where this movement is recorded at least twice a year, and sometimes 4 times a year.

The precision and accuracy of the displacement measurements of this two-mile-long line are unique. The proximity of the machine to the San Andreas fault and the relatively complete knowledge of the local rock and soil properties make the results particularly interesting to geologists and geophysicists, in connection with studies of tectonic strains, associated with the San Andreas fault system.

This paper deals with the most active section of the two miles, and the response of this section to changes in ground water level. Certain divisions within the area will be emphasized more than others.

ALIGNMENT SYSTEM

The SLAC alignment system (2) consists of a laser, some lenses, an image detector and a 10,000-foot-long, 2-foot-diameter aluminum pipe. (Referred to as the alignment pipe.) See Fig. 1. Inside this pipe, very precisely located, are 270 Fresnel diffraction gratings. There is one grating every 40 feet. The gratings act as lenses, working by diffraction (rather than by refraction as do conventional glass lenses). A grating is mounted in the plane of 3 jacks, two of which hold the pipe vertically from the floor. The third jack connects the pipe to the north wall of the accelerator housing, and supports the pipe laterally. To allow bending freedom, the pipe is segmented every 40 feet near each lens, and the segments are connected by two special pins, firmly fixed to one pipe segment, and operating through roller bearings on the adjacent pipe. In every case a metal bellows maintains an air proof seal to the atmosphere, the alignment pipe being evacuated to 10^{-2} torr. The concrete tube around the accelerator, called the accelerator housing, is 30 feet below ground.

The accelerator housing is a monolithic structure in structural engineering terms, and has extensive circumferential re-inforcing. See Fig. 2. But, due to the extreme size and length of the structure, as the ground moves, the accelerator housing moves. Since the alignment pipe is intimately connected to the accelerator housing, the alignment correction corresponds to ground motion. The lenses are spaced 40 feet apart and are, as said, very precisely mounted inside the alignment pipe. These diffraction lenses have an optical center line, established to better than .001 in. They are on hinges and normally are kept hinged up against the top of the inside of the evacuated pipe. But, when required, any one may be swung down, normal to the axis of the pipe, and detented. Only one lens is employed at a time, this being the one located where it is desired to

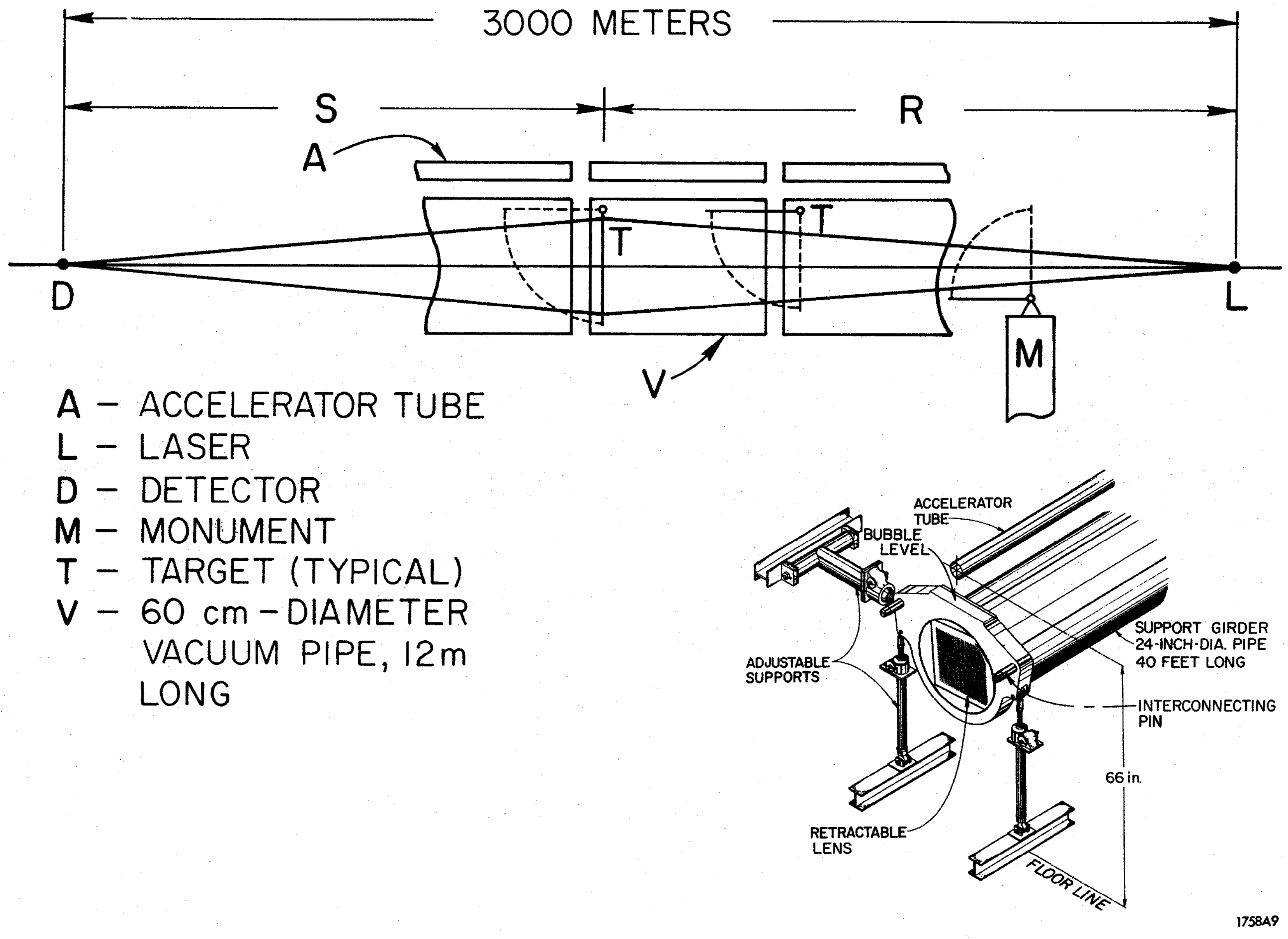

FIG. 1--Alignment system schematic.

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FIG. 2--The SLAC housing under construction. The structure is heavily reinforced with steel.

align. At the east end of this alignment pipe is a source of light, which is a laser giving continuous wave light at 6328 Å. It must be emphasized that this is a point-source of light with a rate of divergence of 8 in. in 50 feet. When a diffraction lens is inserted into the light path the light from this point source is diffracted, and focused onto a focal plane at the west end of the accelerator, where it appears as an image of the point source. The focal length of each lens is determined such that all lenses focus to the same plane. By measuring the position of this image on the focal plane, one can calculate the position of the Fresnel diffraction lens. This position is relative to a straight line defined by the point light source and a predetermined point in the focal plane. So, one knows the alignment of the accelerator light-pipe to better than ± 0.005 in. every 40 feet for two miles, and therefore one knows to a very high accuracy the changes in alignment of the accelerator housing.

The accelerator housing is divided for identification purposes into 30 incidental "sectors" where each sector has 9 girders. Starting from the west end (the accelerator runs N82-1/2°E) the numbers go 1-1, 1-2, to 30-8, 30-9; that is, sector 1, girder 1; sector 1, girder 2; etc. to sector 30, girder 8 and finally sector 30, girder 9. For construction purposes, the accelerator was divided into "100 stations", where each station segment was 100 feet long. The "0" station is right at sector 1-1.

In three places, the housing has a 3-foot-diameter monument hole drilled through the floor. In each hole is a monument pier, 2 feet in diameter, planted in the bedrock below. On these piers are special Fresnel diffraction gratings which indicate the position of the piers, relative to the accelerator housing. This supplies information about shifts in the sub-soil below the accelerator. The piers are about 20 feet deep.

GEOLOGY AND CONSTRUCTION

SLAC is located southeast of San Francisco, and due west of the Palo Alto-Stanford University complex (Fig. 3). The accelerator alignment is east to west, and the San Andreas fault is some 3/4 miles from the west end of the machine. The topography is gently rolling, with foothills toward the west. These hills rise to 2000 feet within 2 miles. One creek traverses the alignment, at sector 15, the middle of the machine. This creek bed was roughly 20 feet below the accelerator grade. The geology of the site is described by Aetron-Blume-Atkinson (1) and Page and Tabor (5). The accelerator was built principally on Miocene rocks (sandstone and mudstone, chert, siliceous mudstone, porcelanite) and Eocene rocks (sandstone and mudstone, with a small percentage of chaotic zones). Under the Eocene stratum are Franciscan rocks (greenstone, chert, graywacke, shale). The Franciscan rocks are most likely fissured regularly parallel to the San Andreas fault. In certain cases, there are masses of Montmorillanite clay.

The accelerator housing floor is 35 feet below finish ground level. The housing inside dimensions are 11 feet wide, 10 feet high and 10,000 feet long. Areas which were low such as the creek, were filled, and hills such as that from sector 19 through 30 were excavated. All sandy fill was compacted to 95% maximum density. Non-sandy fill was compacted to 90% maximum density. Where possible, clay and other poor foundation materials were excavated away and replaced with sandstone. The fill was evaluated as follows. Miocene sandstones compact to the highest density and were used where the most stable fill was desired. These sandstones are found at the eastern end of the machine. Miocene sandstones were mixed with siltstone and claystone, for the next quality grade fill. Eocene shales are the next in strength and dependability. These were used in the moderately critical areas. The least dependable fill is Eocene clay shale and this is

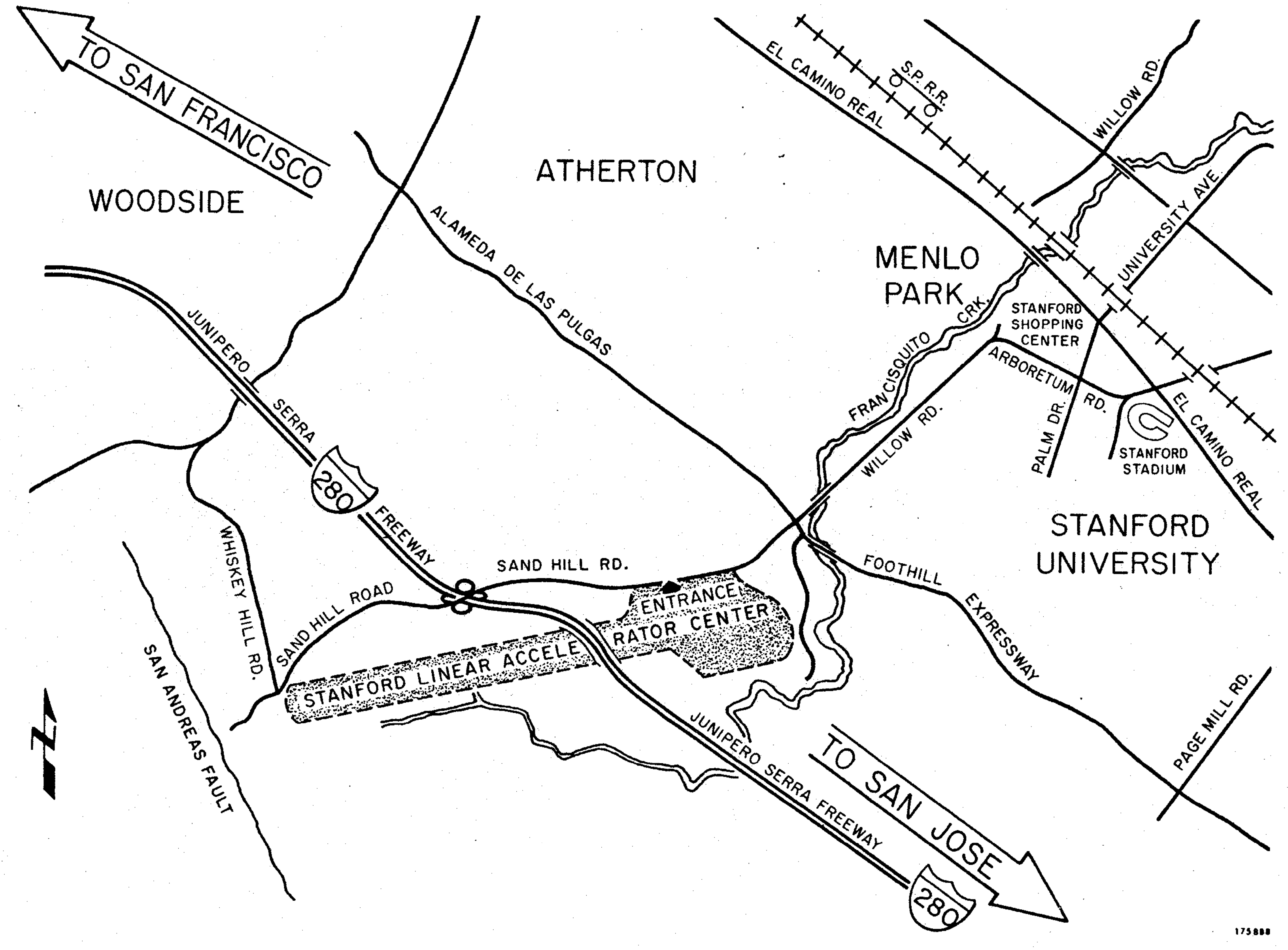

FIG. 3--Location map of SLAC.

used only in noncritical fill areas. In some fill areas the fill material was compacted, then a surcharge or preload was compacted over this and left for a year. The trenching was done after the year of consolidation right through the fill, after removing the surcharge. After the surcharge was removed, rebound was observed.

The accelerator long-grade slopes to the east, at a rate of 1/2%. The east end is 50 feet lower than the west end. The western 3000 feet of the construction served as an experiment to determine the construction technique for the eastern 7000 feet. Under the western 3000 feet the soil was fissured clay, shale or claystone, with clay materials in the fissures.

The alignment criterion for the completed housing was that "no point along the housing is to depart more than four in. above, nor two in. below a straight line, in October, 1965. Settlement and consolidation during the ten years succeeding 1965 shall be such as to make the floor straighter." The housing, excluding superfill will exert average foundation pressures on the order of 1000 pounds per square foot. For this reason, no special foundation is required.

DATA AND ANALYSIS

The data consists of corrected alignment errors in SLAC for a period of four years, beginning with the first re-alignment in 1966 (the 288th day of 1966) and ending with the most recent re-alignment in 1970 (the 275th day). Most of the line showed only small displacements over the years, similar to those shown in Fig. 4 for sectors 8-5 to 11-1. In contrast, relatively large displacements occurred between sectors 11-1 to 16-5 also shown in Fig. 4. The vertical component is generally larger than the horizontal one, and no particular correlation between the two components of displacement can be seen. Positive vertical and horizontal displacement are up and southward, respectively.

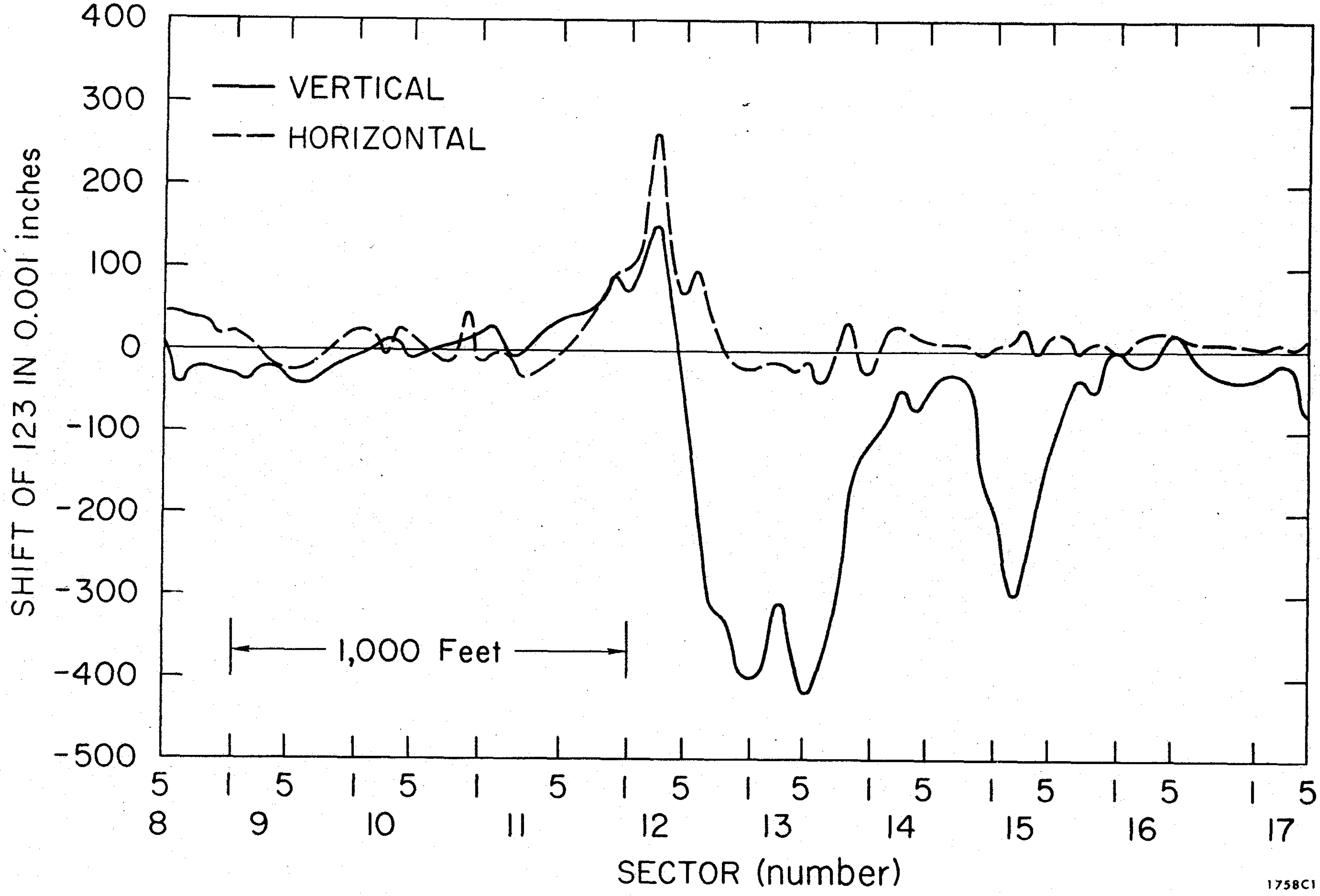

FIG. 4--Cumulative shifts of sectors 8-5 through 17-5 from spring 1966 to fall 1970.
Shift in .001 in. Positive vertical and horizontal displacements up and southward,
[illegible]

The way the displacement varies with time along the accelerator is shown in Fig. 5 for intervals of about six months. The Julian dates are shown, with the year first, then the day number; for example the 66/227 is the 227th day of 1966.

Clearly, the strong activity is confined to the area of nominally sectors 11-5 to 16-1. Specifically, considering the vertical movement, stations 12-8 through 14-1 settle about 0.1 in. every six months period for the first several periods, whereas the more recent data shows a somewhat lower rate of settlement. As will be discussed later, during the period 69/325-70/107 there is an uplift in the area from 13-1 to 14-1. Sectors 14-1 through 14-8 are built upon a stable sandstone wedge, and less movement occurred here. Sectors 14-9 through 15-7 are built upon fill which was not preloaded. The fill is Miocene sandstone. The settling around sector 15-2 was initially as great as in sector 13, but by the second six-month period was only half as great. At present, the settling around 15-2 is less than 0.040 in. per year, as shown in Fig. 5. This section was built on sandstone fill, which has several drainage pipes across its base to allow the creek unimpeded flow. The horizontal displacement in this section is vanishingly small. In marked contrast, the displacement in sector 11-5 to 14-5 has a pronounced horizontal component, and the magnitudes of both components do not diminish rapidly with time. Furthermore, the displacement region exhibits an oscillation as a function of time, which is clearly shown in Fig. 6, for selected points along the line of the accelerator.

Both displacement components indicate an oscillation of one cycle per year. The motion of the section upward in winter and downward in summer is superimposed on a gradual steady settling, similar to that of section 13-5 (Fig. 5). The horizontal component of the displacement consists mostly of the periodic motion, with only a small long term trend. The periodic nature of the displacement

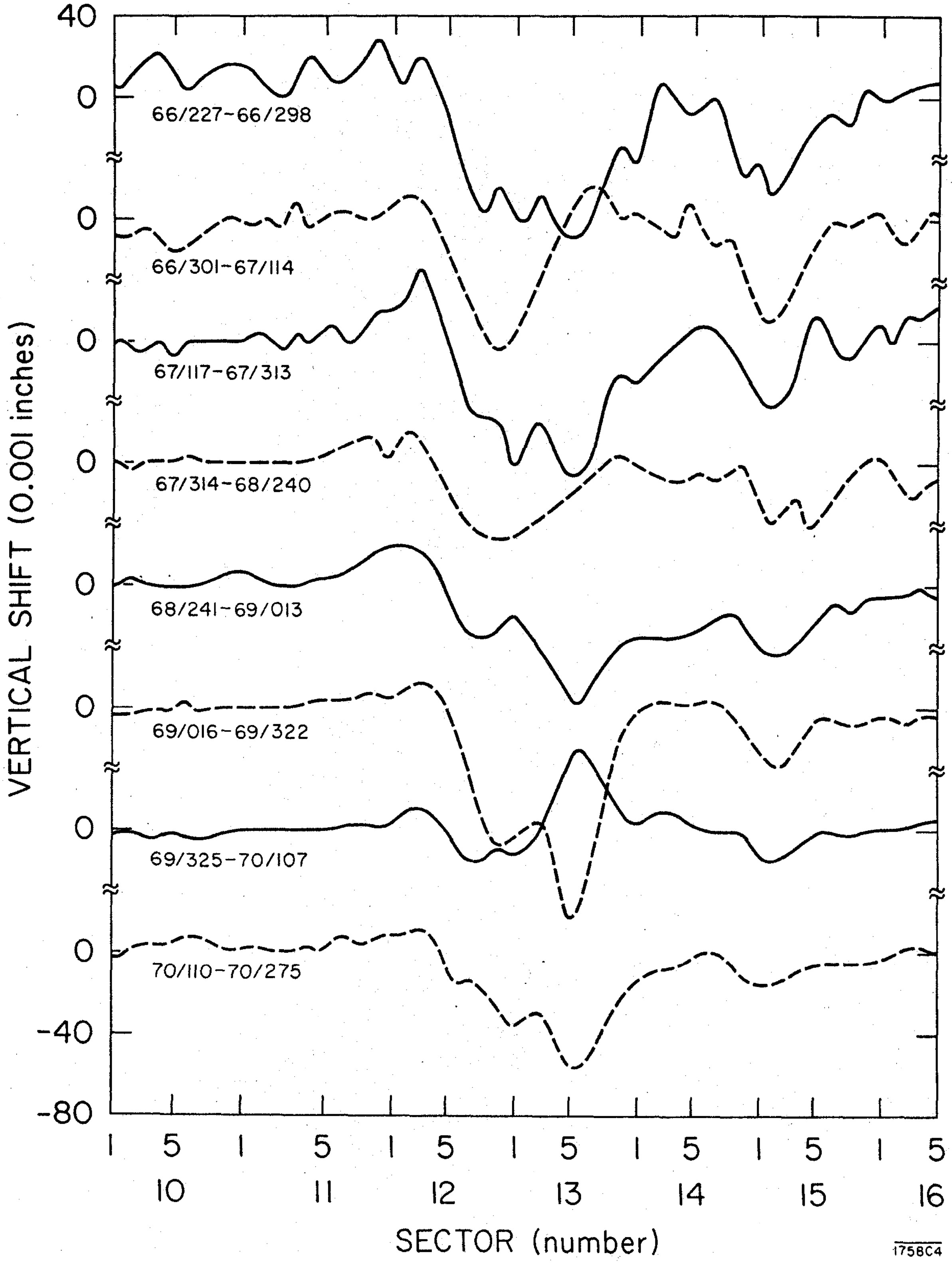

FIG. 5a--Vertical displacements for periods of six months from 1966 through 1970. Numbers indicate year and day of measurement. Solid lines show change through winter, dashed lines through summer.

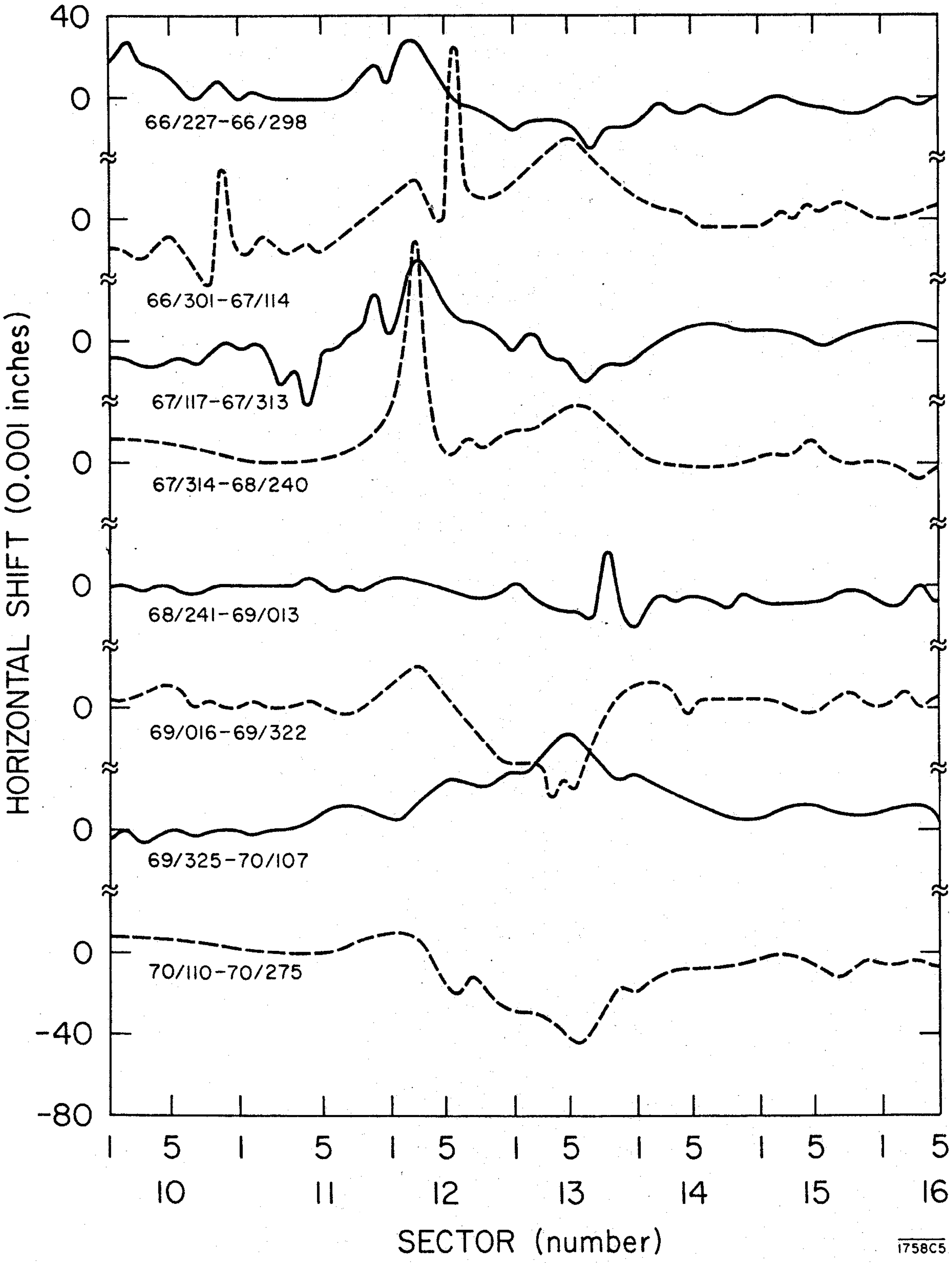

FIG. 5b--Horizontal displacement for periods of six months from 1966 through 1970. Numbers indicate year and day of measurement. Solid lines show change through winter, dashed lines through summer.

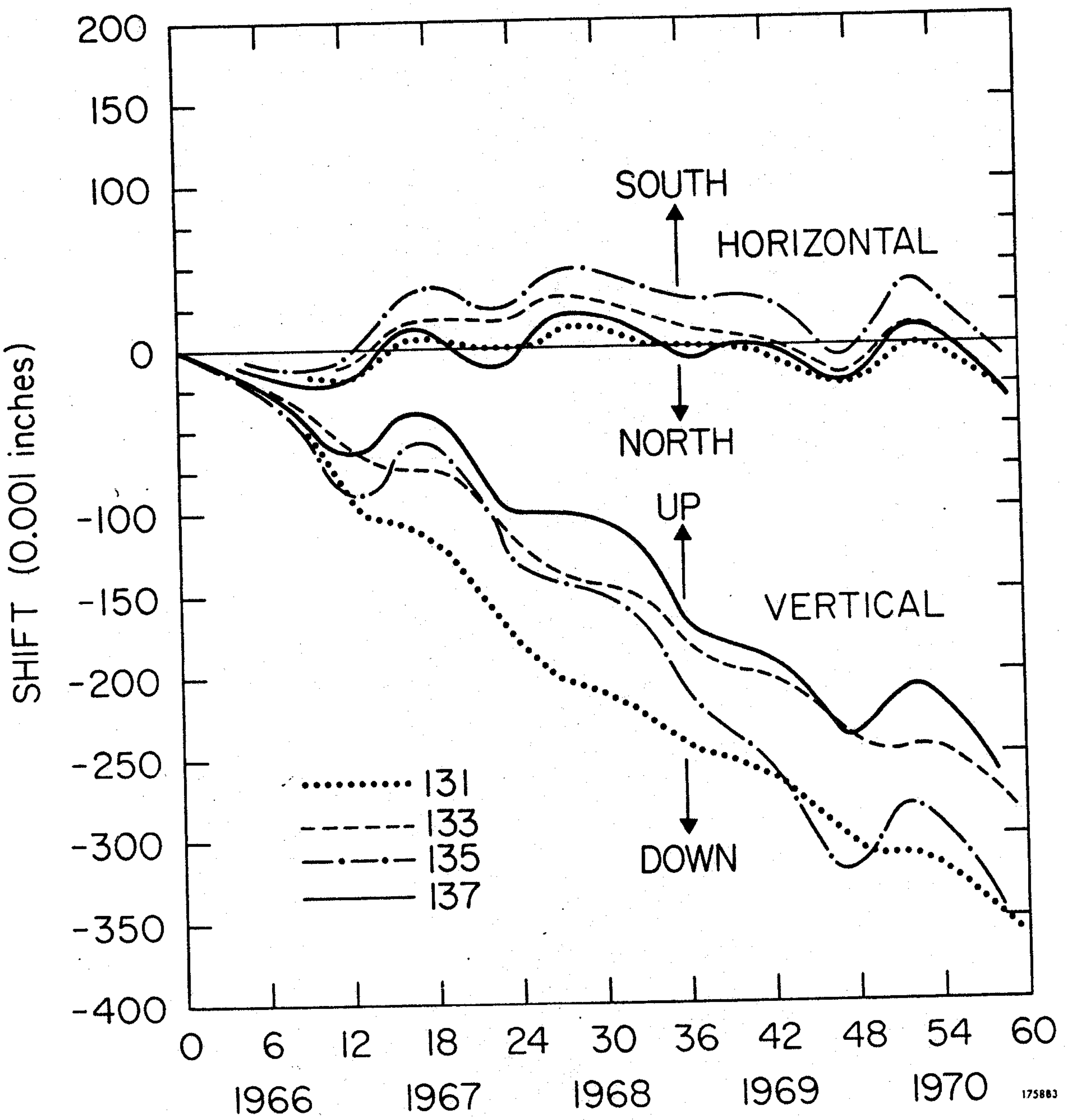

FIG. 6--Displacement as a function of time for several points in the active section of SLAC. Notice the periodic shift in both vertical and horizontal components of displacement.

is also clearly shown in Fig. 7 in which the vertical and horizontal displacements during the winter of 1969-1970 are compared with the inverted displacements during the following summer. Apparently, the displacements during the winter (upward and southward) are almost exactly reversed during the summer (downward and northward).

The slow steady vertical settling is caused most likely by consolidation of the fill across the creek. This consolidation occurs in all parts of the active area, whereas the cyclic displacement is of the greatest amplitude in the region of the fill which contains the original soil. Here, no soil was removed before adding fill to the grade line. This soil has chaotic structure (Mitchell (3)) with a mixture of sand, claystone and clay which consists mostly of Montmorillonite. A smaller cyclic amplitude over the 15-2 region, which crosses the creek, is probably the result of superior drainage. The periodicity of the cyclic displacement component, with one cycle per year suggests a relationship to the weather, particularly to the water cycle. In Fig. 8 both local rainfall and water table fluctuation in a nearby well are compared with the displacement, as a function of time. The correlation between the level of the water table and the vertical displacement is clearly positive: when the water level is high then the displacement is upwards. At the same time the horizontal displacement is southward. The periodic horizontal shift is most likely caused by the local slope on which the accelerator was built. The slope of ≃30 degrees faces south. There is a small but noticeable phase lag of about 1-2 months of the water table in the well and the uplift of the ground. This last fact provides a clue to the source of the periodic uplift: If the uplift were due to simple seasonal pore-water pressure increase, which can cause a small apparent ground expansion, as shown by Nur (4), then practically no time lag would be anticipated. Expansion of the Montmorillonite, on the other hand, can be large, and would lag somewhat behind the water level rise.

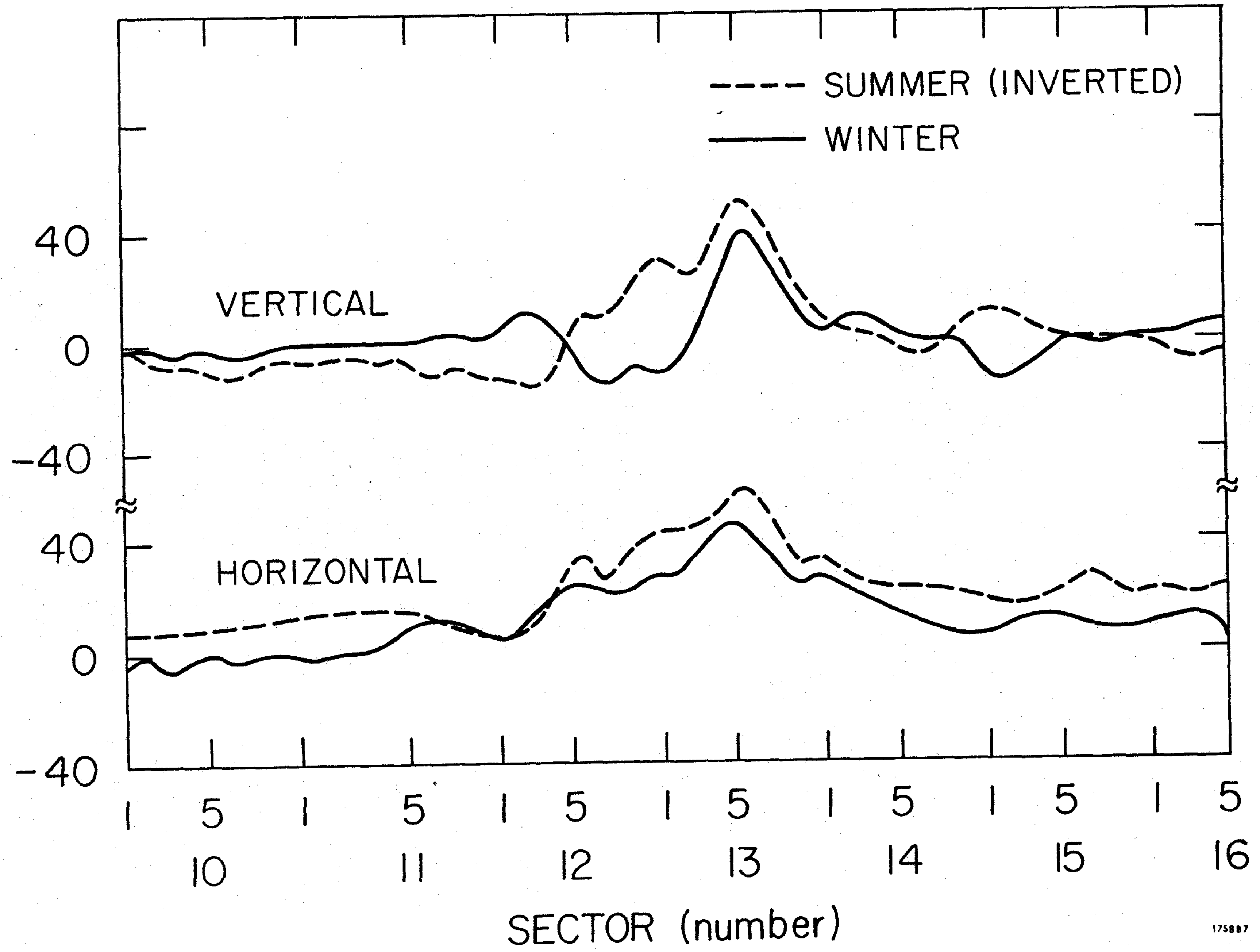

FIG. 7--Comparison between displacements in winter 1969-1970 and inverted displacement in summer 1970. The similarity in shape and amplitude indicates the relative importance of the yearly displacement cycle.

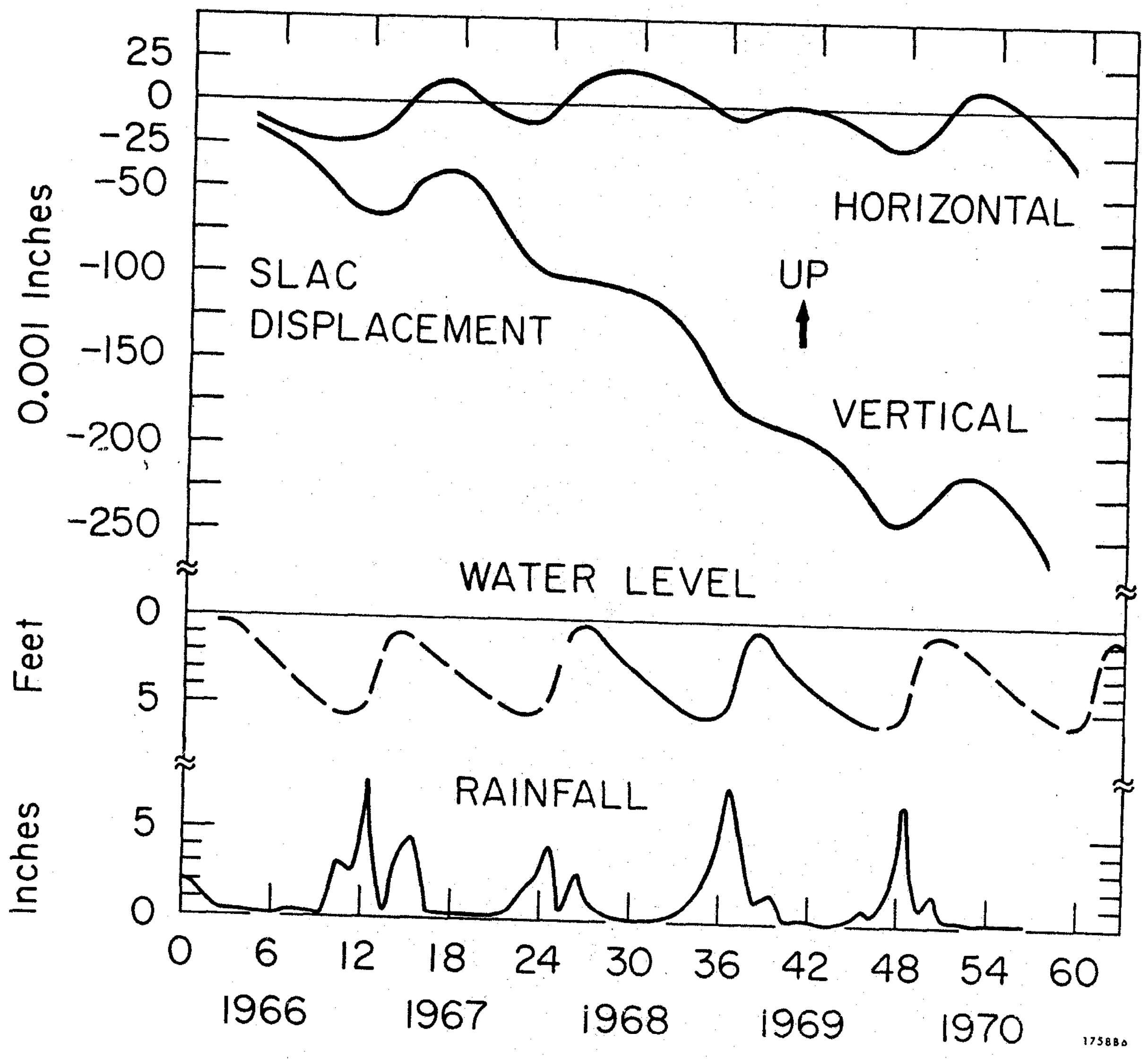

FIG. 8--Comparison of displacements, water level in well and rainfall at SLAC as a function of time.

CONCLUSIONS

The systematic pattern of displacement as a function of time along the geologically active part of the accelerator offers a reliable prediction for future displacements. In general, the settling of the fill is decreasing with time, to less than .020 in. per year in the next year. The cyclic part of the deformation is likely to continue, with the largest yearly, peak to peak amplitude of about .050 in. Although settling deformation is now small, the effects of catastrophic events such as earthquakes, are not known. In fact, the data contains some singular, unexpected movements which are well above tolerance level. One such movement occurred at 12-3, where in the period of approximately one month, the girder moved 0.107 in. Movement during the nine following months was in the same direction, and at a rate of about 0.010 in. per month.

The proximity of the installation to the San Andreas fault raises not only the question of earthquake hazard (which remains unanswered) but also the possibility of deformation due to tectonic strain which is associated with the fault. Strain around this fault is commonly considered as localized, as shown by Savage and Burfurd (6), with a corresponding time dependent displacement which decreases as a small-inverse-power-law of distance away from the fault. The alignment system of the accelerator cannot detect the homogeneous component of a strain field change, but it is sensitive to more localized features such as the curvature of the deformation of a straight line. The horizontal displacement around the accelerator is expected to be concave to the north, but such a trend is not observed during the period of measurements. The observed strain is practically all due to local processes in the ground. It is quite clear, therefore, that detailed local measurements of tectonic strains on a scale of a few miles are quite sensitive to local conditions. Small triangulation networks and short strain meters are particularly susceptible to such undesirable transient strains.

Finally the results demonstrate the important role that ground water plays in the occurrence of transient strains. However, it is conceivable that the measurements of small strains, combined with the knowledge of water table level fluctuations could be utilized in turn to study local properties of the ground.

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