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Instrumentation and Development of Techniques to Measure and Evaluate Meteorological Problems Important to Hydrology

Utah Water Research Laboratory/College of Engineering

By Duane G. Chadwick

November 1970

INSTRUMENTATION AND DEVELOPMENT OF TECHNIQUES TO MEASURE AND EVALUATE METEOROLOGICAL PARAMETERS IMPORTANT TO HYDROLOGY

By

Duane G. Chadwick
Principal Investigator

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ABSTRACT

Hydro-meteorological instrumentation concepts are discussed. The necessity for an economic and reliable telemetering system is recognized and ways are shown how to achieve this objective. Particular discussion is given on total-precipitation and water-content-of-snow sensing. A method is also presented showing how to make isohyetal plots of telemetered precipitation information on an x-y plotter by use of a resistance paper method in conjunction with an analog computer.

ACKNOWLEDGMENTS

This work was made possible through funds supplied by the Water Resources Research Act of 1964 (Public Law 379, 88th Congress) and administered by the Department of the Interior.

Recognition is also made of numerous professional associates and graduate assistants whose help and suggestions have been invaluable.

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INSTRUMENTATION AND DEVELOPMENT OF TECHNIQUES TO MEASURE AND EVALUATE METEOROLOGICAL PARAMETERS IMPORTANT TO HYDROLOGY

Introduction

Accurate and economical sensing of hydrologic parameters located in remote areas is essential to efficient water management practices. Considerable effort in expenditure of time and money is made each year by public and private agencies to accumulate hydro-meteorologic data. Data are collected primarily by physical visitation to the site in question where manual measurements are taken. In the more remote locations, a full day's time may be required to visit the site. Since traveling alone in the mountains in the wintertime is not considered to be a safe practice, at least two man days are required for such a visit. The use of an oversnow vehicle is also required having operating expenses as high as $3 or $4 per mile for the larger type machines. Costs incurred in visiting one of these more remote stations can range from $200 to $500. Clearly then, automatic data collection from remote areas is desirable. The biggest obstacles to such an automatic system are the cost for the installation and maintenance, and the station reliability. In the hostile environment of the winter months in mountainous regions, power supplies, electronic circuits and/or mechanical components are likely to fail if the design, fabrication techniques, and installation are inadequate.

Experience gained in the last several years' operation in telemetering hydro-meteorologic information from mountain regions during the wintertime have demonstrated both the difficulties and the practicalities of automatic monitoring systems which can operate unattended for long periods of time.

The philosophy of the project approach was to "do the easy things first," provided they were important to the project. By so doing, the greatest progress could be made in the least amount of time and those things requiring more time and money for development were considered second. Although, in some instances, the type of work undertaken may seem quite unrelated to other phases of the research, all of the work undertaken did have a direct bearing on the development of techniques to better instrument parameters important to hydrology. The measurements which occupied the principal effort were measurements related to total precipitation and water-content of snow. These two measurements seemed most important. Other measurements which were successfully made and telemetered include such things as temperature, barometric pressure, humidity, wind, etc.

As hydrologic instruments or telemetering techniques were developed and proved useful, these items were incorporated into ongoing programs which had use for them. Several government agencies have adapted and/or are further experimenting with instrumentation concepts initiated or otherwise expanded under this project.

Transducer Design

General discussion

In any type of automatic sensing system, the heart of the system is the basic sensor which senses the desired parameter and converts it into some type of electrical or mechanical variation. This output can either be recorded at the site for future reference or transmitted to a base station where data are more readily available. Considerable priority is placed on being able to obtain data in real time. The need for this can be dramatically shown in the case of a flood warning system. In order to obtain remote real time data, information is generally transmitted via a telephone line or a radio telemetering system. The transmission of information by these means requires that the sensor output be converted into an electrical signal. This is generally done by a mechanical-to-electrical transducer. Things mechanical, relating to hydrologic data, include water level, water-content of snow, precipitation, wind speed and direction, barometric pressure, rain rate, etc. Other information which is also readily converted to mechanical motion includes such things as solar radiation, humidity, and temperature.

Conventional ways of transforming mechanical motion into an electrical signal generally link the mechanical motion to a variable resistor, a variable capacitor, or a variable inductor. Sometimes these variable elements take on a special form such as strain gages, or linear voltage differential transformers (LVDT's). Since one of the objectives of this project is to provide economical instrumentation, a transducer was required which would enable the adaptation of existing types of instruments to the telemetering system.

The most common type of transducer is the variable resistance element. After some experimentation, this type transducer was abandoned for two reasons: (1) The inaccuracy caused by friction of the wiper on the variable resistance element and (2) The finite lifetime of a variable resistor where friction is present. The strain gage, which is also a type of a variable resistance transducer, overcomes both of these disadvantages but is handicapped by low output and requires the use of expensive signal conditioning equipment. A variable capacitance transducer was also considered. It has the advantage of having essentially zero dynamic friction and an infinite life expectancy. The major drawback of this system is the difficulty of designing a subcarrier oscillator which will detect subtle changes in conditions and still exhibit sufficient stability to meet the demanding stability requirements imposed on it. The subcarrier oscillator generates a low frequency signal which is the information that is transmitted over the telemetering system. The frequency of this oscillation varies as some electrical parameter varies, i.e. resistance, capacitance, or inductance. Slight changes in humidity, temperature, or in physical location of the sensing element, or relocation of nearby parts, tend to adversely affect the accuracy of the capacitance sensing system. Variations in capacity are easily obtained in the submicrofarad range; however, for a stable LC oscillator, capacitance variations in the microfarad range are required. Because of these problems with the resistance and capacitance type transducers, a variable inductor transducer appears best for making many types of hydrologic measurements. Existing, commonly used, instruments can be adapted for a variable inductance transducer by the attachment of a three or four gram soft iron plunger to the movable element. As the indicating device moves, the iron plunger is lowered into the coil of wire which is about the size of a spool of thread. (See Figure 1.) This configuration permits the use of an extremely large C to L ratio which is highly desirable from a stability standpoint. Perfect alignment of the iron plunger in the center of the coil is not necessary and the hole is large enough such that the plunger does not at any time come in contact with the sides of the coil form. Thus the transducer is frictionless. The frequency is changed in a continuous manner as the plunger is lowered into the coil giving essentially infinite resolution. This transducer, costing little to manufacture and having nearly ideal characteristics has been used extensively on this project.

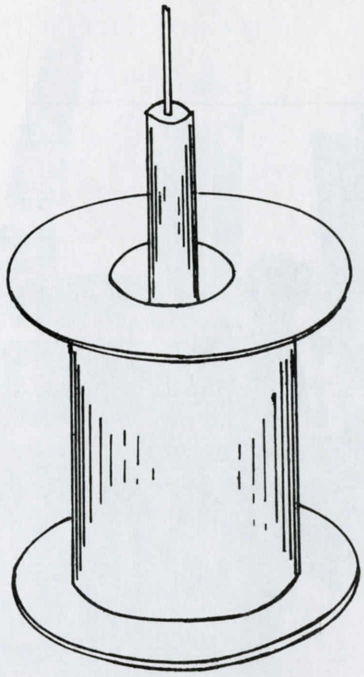

Figure 1. **A transducer coil mounted on a nylon spool with a soft iron laminated core partially inserted.**

Many transducer coil configurations were investigated and applied to various instruments during the course of the project. Coil configurations as long as 30 inches and as short as one-half inch were investigated. The coil shown in Figure 1 is 1½ inches high and was determined to be optimum for many kinds of instruments which have a mechanical motion of about two-thirds the length of the coil itself. Figure 2 illustrates how the coil, which in this case is 1 inch long, can be adapted to a microbarograph. The plunger is mounted on the pivot arm which is linked to the pen of the recorder. A counter balance is also included to maintain the original balance of the unit.

Water-content of snow transducer

The water-content of snow is frequently measured with a snow pillow. This consists of a flexible rubber tank filled with a nonfreezing liquid. At the time of the initiation of the project, the transducer almost universally used on snow pillows was a stilling well and a water level recorder connected to a float existing in the stilling well. Such a device required a house to shelter the stilling well which was required to be longer than the column of liquid rising in it; in some instances this could be longer than 100 inches. The water level recorder was mounted at the top of this pipe. Not only was there the disadvantage of having to build a house for the transducer, but considerable liquid had to be displaced from the snow pillow to fill the stilling well, which in many cases would amount to five or more gallons of liquid displaced. This tall column of liquid, in a shelter which is often exposed to sunlight, experienced temperature excursions during the spring months which caused liquid expansion and contraction and thus, objectionable diurnal effects are especially noticeable. The mercury manometer shown in Figure 3 was designed to help solve the transducer size and temperature problems. Since the density ratio of water to mercury is approximately 13½ to 1, the column of liquid can be reduced in height by that same factor. For example, a 13 foot high transducer column is reduced by using a mercury column to a column 1 foot high. The transducer, a small nylon float on which the soft iron slug is mounted, provides an inductance variation as the surface of the mercury rises and

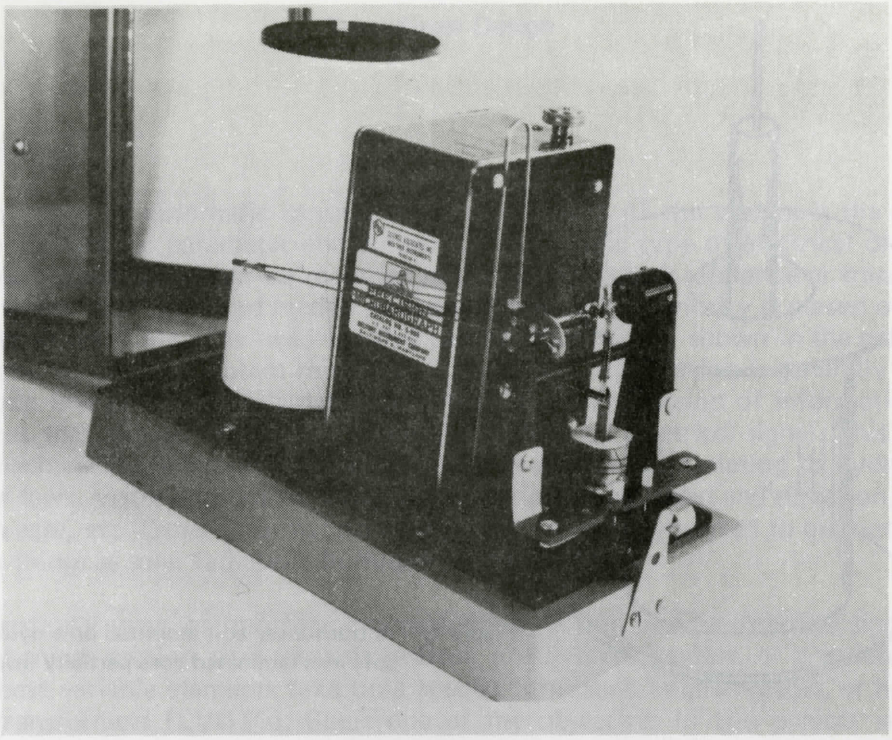

Figure 2. Variable inductance coil attached to a microbarograph.

falls. This transducer can be seen in the photograph (Figure 3). The low freezing point of mercury (-39° C) was considered acceptable.

Tests of the mercury transducer demonstrated two disadvantages: (1) The system must work with an open reservoir in order to cancel out effects of barometric pressure variations which would produce erroneous snow pillow readings. The open reservoir allows contamination and moisture to accumulate on the mercury surface, which in turn causes the miniscus on the surface of the mercury to vary somewhat. This effect is further aggravated by the occurrence of natural oxidation. There is also a tendency for the miniscus to be of one value in the receding column and a different value in an ascending column of mercury. Although these variations are slight, they are amplified by the density ratio of the alcohol used in the pillow to that of mercury, which is in excess of 14 to 1. (2) Mercury is difficult to handle and transport without occasionally spilling it.

Because of these problems, a second type of transducer, a bellows unit (Figure 4), was designed to overcome some of the disadvantages inherent in the mercury system just described. Liquid pressure applied to a tube that conducts the liquid from the bellow to the instrument extends the bellows and pushes an iron rod into a coil whose inductance is proportional to the depth of penetration of the rod. The advantages of this system over that of the mercury manometer are that it is a closed system and will not become contaminated with foreign materials or tend to spill as is the case with mercury. Although the system is sealed it is not closed in the sense that the barometric pressure changes would affect readings. The bellows are

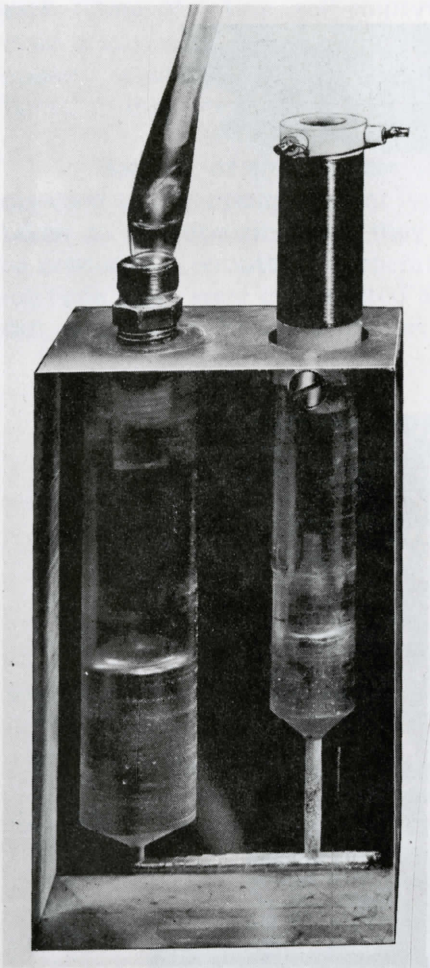

Figure 3. Mercury manometer used to effectively compress the height of the alcohol manometer column in proportion to the density ratio of mercury to alcohol; i.e., 14 to 1. An iron slug floating on the mercury column varies the inductance of the coil in proportion to the pressure applied to the manometer.

exposed to the atmosphere and differential pressures caused by the atmosphere are canceled out. There is some possibility that a lag in pressure increase or decrease occurs when acting upon and through the snowpack. No conclusive evidence is available to answer this question as yet.

After a year's operation of the bellows type transducer, a modification was made which provided some improvement. The nickel material in the bellows was replaced by a copper alloy, ni-span C, which has essentially a zero temperature coefficient. For evaluation of this type bellows (Figure 5) two units were connected to the same source and the outputs compared. Deviations which occurred between the two transducers, i.e. 1 percent, were considered to be negligible in comparison to snow pillow sensing errors.

Total precipitation measurement transducers

A great deal of hydrologic information is obtained through precipitation measurements. The two types of measurements most commonly made are weighing and liquid level. Either type measurement is readily converted to inches of precipitation.

Classification of the weighing type gage can be subdivided into a totalizing, and an incremental (tipping bucket) type gage. The totalizing gage accumulates the total amount caught. In the instance of the tipping bucket gage the catch is generally not accumulated but

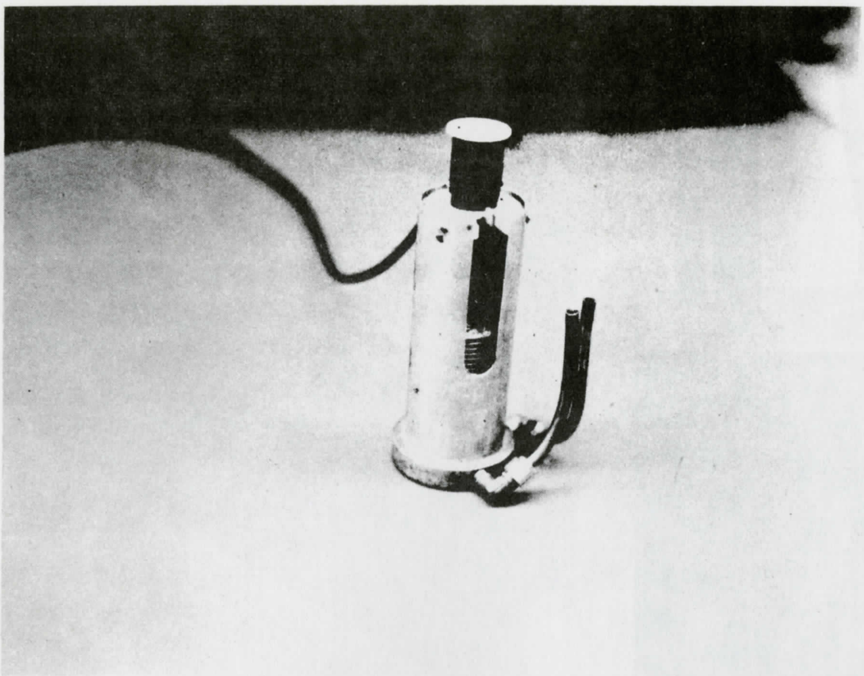

Figure 4. **Liquid pressure sensing instrument used for measuring static head; i.e., total precipitation, water-content of snow, and stream level. Extension of bellows due to applied pressure changes inductance of coil which results in telemetry signal.**

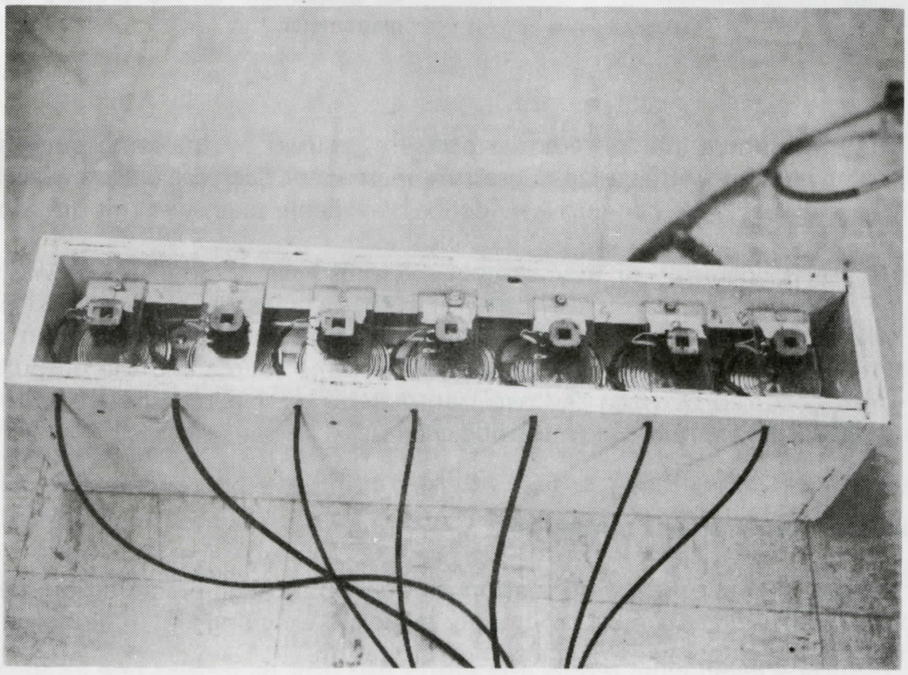

Figure 5. **Seven frictionless pressure transducers using improved bellows design. The transducers were used on the project to measure snow pillow pressure. (The pillow pressure is proportional to water-content of snow.)**

each filling of a tiny, self-emptying bucket is recorded on a chart. In order to determine the total precipitation a count must be made of the number of times the bucket is filled. In order to operate satisfactorily when snowing, the gage must be heated sufficiently (i.e., small propane flame) to melt the snow falling in the gage.

Because of the intrinsic simplicity of liquid level and weighing type totalizing gages as opposed to the tipping bucket type gage and because a great deal of snow data has already been taken on the totalizing gages, they were selected initially as being the most practical for adapting to unattended remote T/M operation. Consequently, both the liquid level and totalizing weighing type gages were constructed and evaluated. A picture of the totalizing precipitation gage, or can, is shown in Figure 6. In this particular picture, the transducer is shown to the right of the

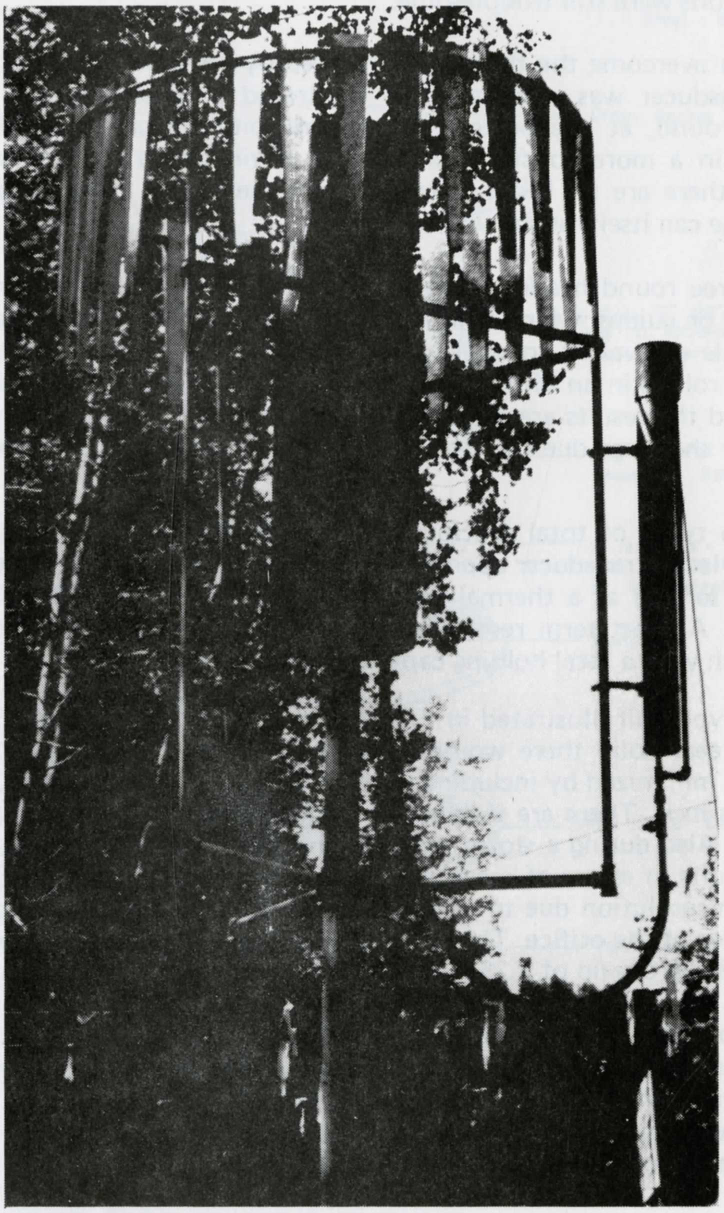

Figure 6. Precipitation gage with liquid level transducer mounted in the tube on the right side of the can.

can, mounted on the vertical support which holds the windscreen. The liquid of the can is connected to the transducer through a hose. The transducer coil in this particular instance is designed to extend 18 inches. As the liquid level rises, the float which buoys the soft iron rod penetrating the coil is gradually lifted or withdrawn from the coil in proportion to the amount of liquid present.

A weighing type precipitation transducer is illustrated in Figure 7. This transducer was mounted at the end of a 2½ inch pipe column which served as the stand for the precipitation gage. Figure 8 illustrates the position of a transducer mounted in this manner and the precipitation can resting upon it. The operation of this unit during the winter season showed that variations in temperature cause errors due to the change in modulus of rigidity of the springs as a function of temperature. Even though these springs were changed to a ni-span C material, the temperature variations were still troublesome.

In order to overcome the fluctuations caused by temperature variations, the precipitation weighing transducer was redesigned, as illustrated in Figure 9. The placement of the transducer underground, at the bottom of the precipitation can assembly, as illustrated in Figure 10 results in a more constant temperature environment for the weighing device. To minimize friction there are no bearings to maintain the can in a vertical position other than rollers placed on the can itself, as shown in Figure 11.

Initially three round headed bolts positioned 120° apart in the same horizontal plane served as bumpers, or guides, which held the can centered on its pedestal. In this configuration the static friction is equivalent to about ± .03 inches of precipitation. The bolt guides were replaced by nylon rollers in an effort to reduce the static friction. The resulting improvement was appreciable and the results are shown in Figure 12. When one considers that the rain gage has a 36" capacity the error due to friction calculates to be about ± .03 percent when nylon rollers are used.

Of the two types of total precipitation transducers evaluated, viz., the float and the weighing type, the latter transducer appears to be the most satisfactory. Once a blanket of snow is on the ground serving as a thermal insulator, there is no detectable thermal variation in day-night readings. A short term resolution of this type of system has been demonstrated to approach ± .01 inch with a total holding capacity of 36 inches.

The float type unit illustrated in Figure 6 has the disadvantage that if the liquid in the can should ever freeze solid there would be an error in the liquid level. The chance of this occurring has been minimized by including an antifreeze solution in the can which tends to melt the snow as it falls in it. There are instances, however, when inadequate mixing occurs and an ice plug can form. Also during a storm much of the snow may stick to the inside walls of the can. This again results in errors of measurement. Another disadvantage of the liquid level unit was a slight loss in resolution due to the surface area of the reservoir being appreciably larger than the surface area of the orifice. Thus an 8-inch orifice and a 12-inch reservoir would have an area ratio of $12^2/8^2$ or a ratio of 2.25:1. The loss in accuracy is proportional to this same ratio.

Of the two gages designed, built, and tested, the weighing type, having its transducer located below ground proved to be very satisfactory. Resolution of readout is considered to be excellent, and diurnal temperature effects are less than .02 percent which is about the practical limit of the readout resolution. Long term accuracy is not known precisely but it is considered much better than are errors due to can catch effectiveness.

Wind miles transducer

Two types of wind information can be obtained from a cup-type anemometer. These are wind miles and wind rate. Wind miles are obtained by periodic contact closures. The contactor

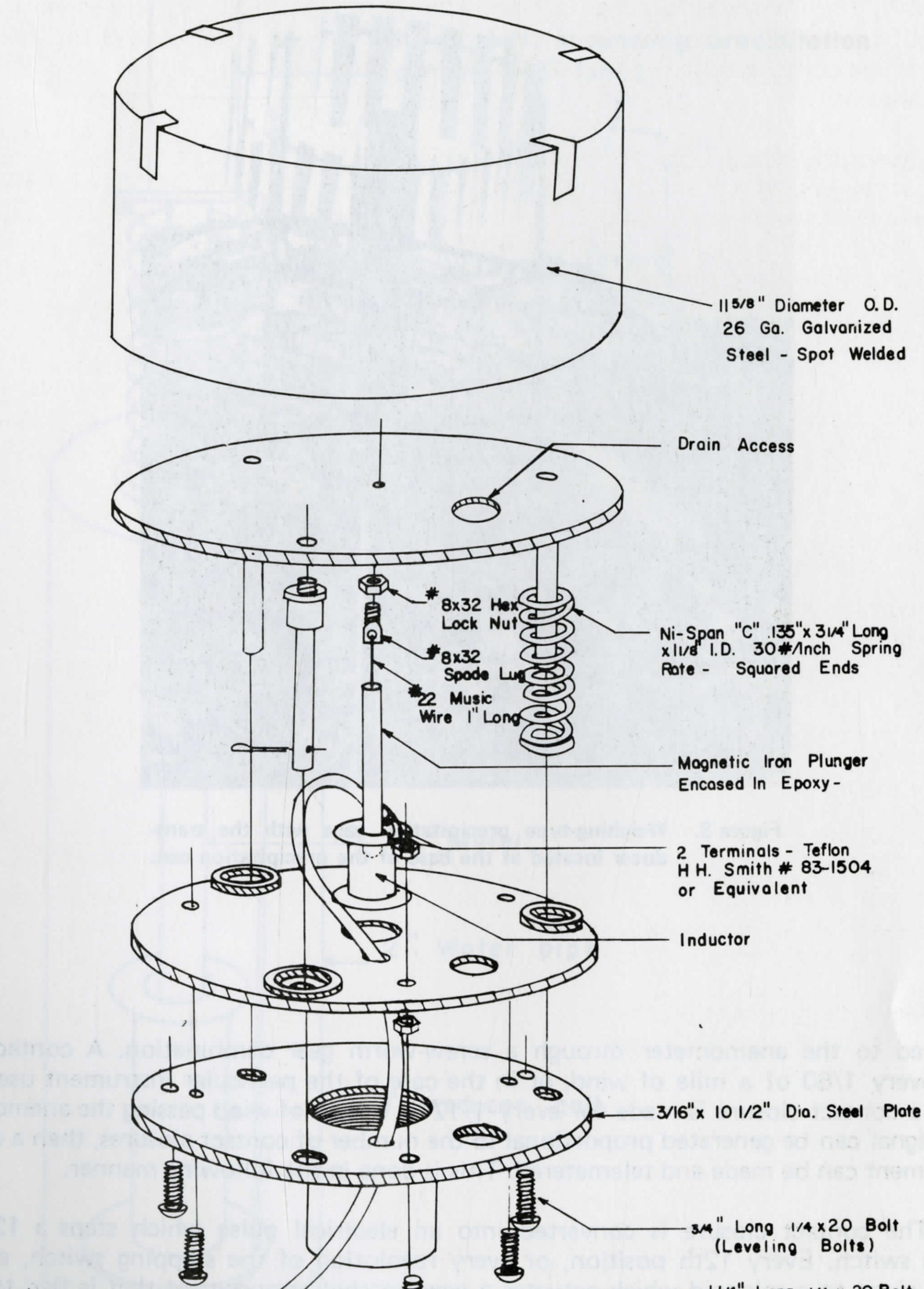

Figure 7. **Weighing precipitation gage transducer designed to be mounted at the base of the precipitation gage.**

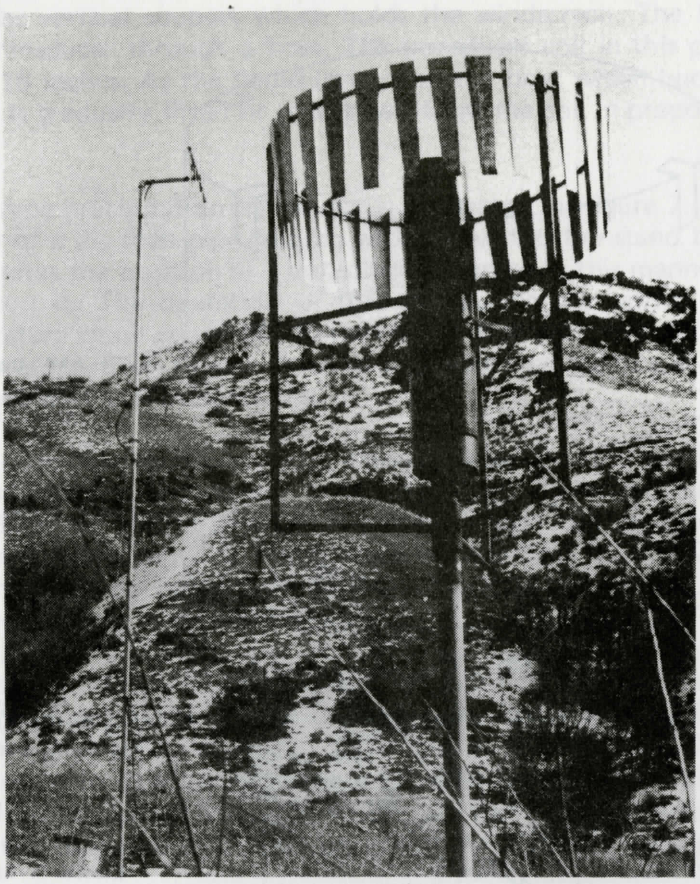

Figure 8. Weighing-type precipitation gage with the transducer located at the base of the precipitation can.

is coupled to the anemometer through a screw-worm gear combination. A contact closure occurs every 1/60 of a mile of wind, or in the case of the particular instrument used on this project, a contact closure is made for every 1/12 of a mile of wind passing the anemometer. If analog signal can be generated proportional to the number of contact closures, then a wind mile measurement can be made and telemetered. This is done in the following manner.

The contact closure is converted into an electrical pulse which steps a 12-position stepping switch. Every 12th position, or every revolution of the stepping switch, an output pulse is given to a solenoid which actuates a pawl ratchet arrangement that is tied to a worm gear which in turn rotates a "spiral of archimedes"-type cam. Rotation of the cam actuates a plunger which inserts a ferrite core into a coil of wire. A pictorial diagram of this system is illustrated in Figure 13. The actual system hardware is shown in Figure 14. The gear ratio between the contact closure of the cup anemometer and the actuating cam is 6000:1. Since there are 12 contacts per mile, the total capacity of the storage device is 500 wind-miles without ambiguity.

A review of the operation of the system as sketched in Figure 13 illustrates how the measurement of wind is first converted to a mechanical analog-type signal, i.e., cup rotation of the anemometer. Thereupon the signal is digitized by means of the contacts on the worm driven

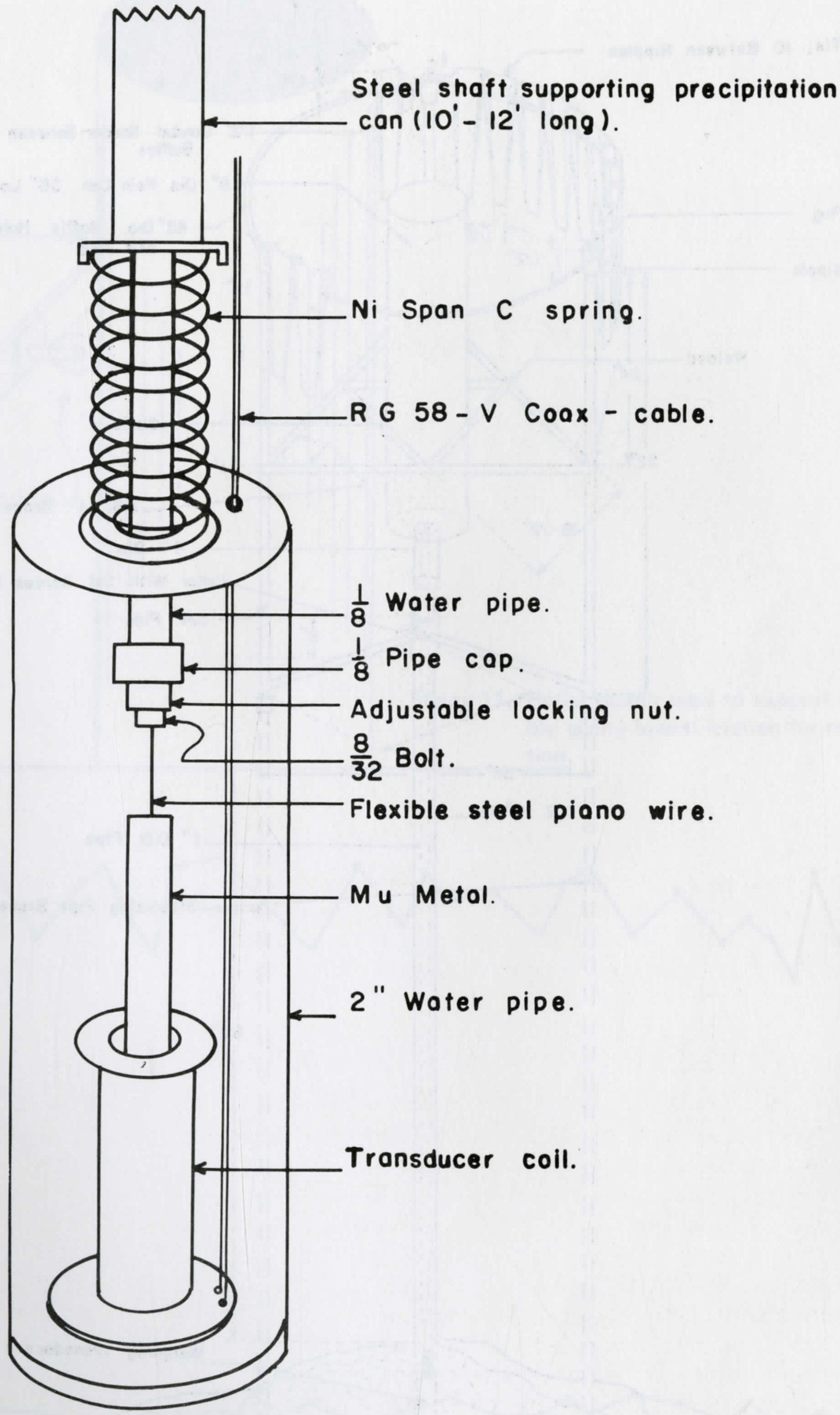

Figure 9. Sketch of transducer assembly which fits inside the 2½" pipe column used to support the precipitation can.

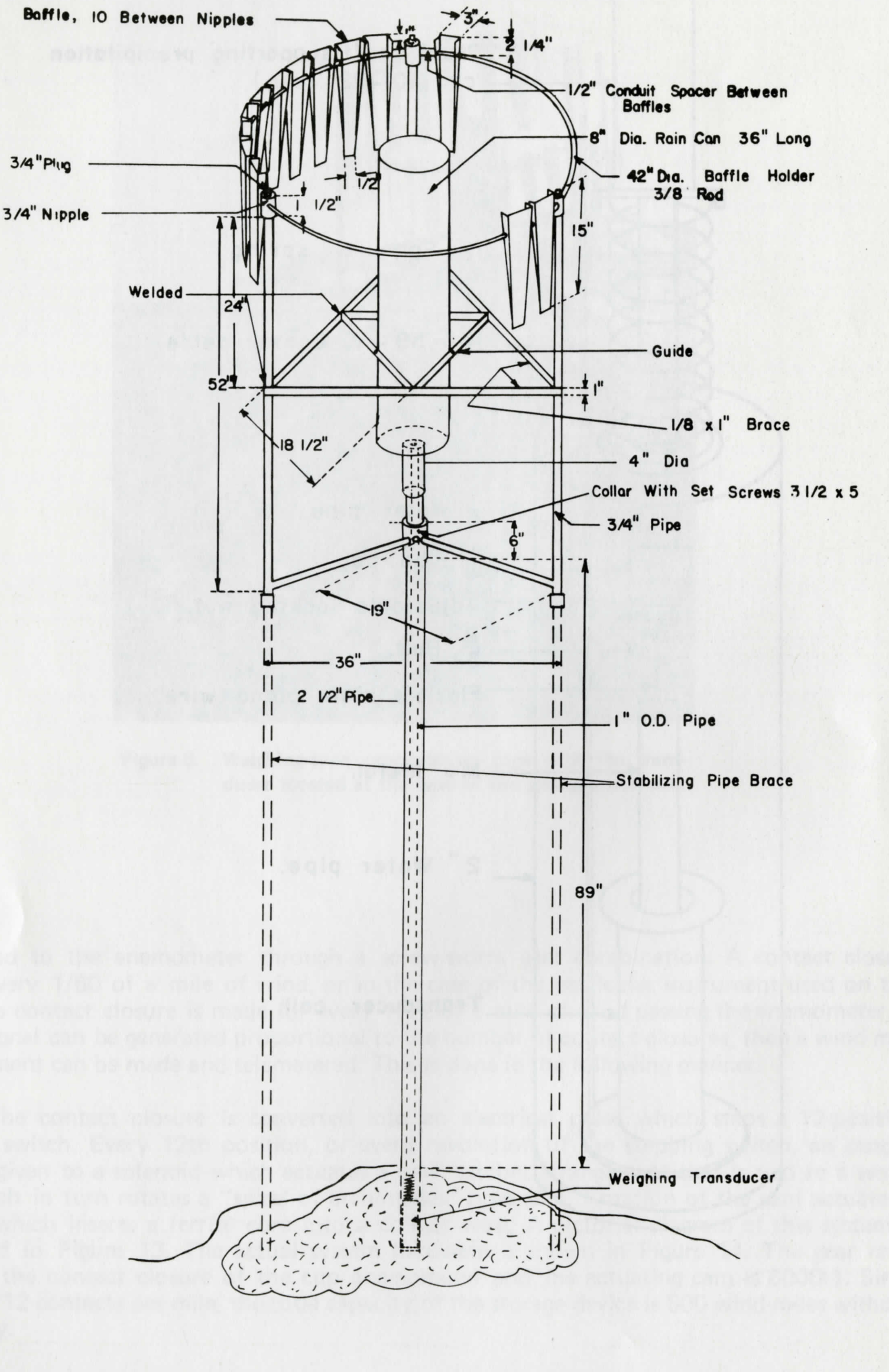

Figure 10. Rain gage assembly with underground transducer. Gage holding capacity is 36 inches. With minor modification a 70-inch gage can be installed.

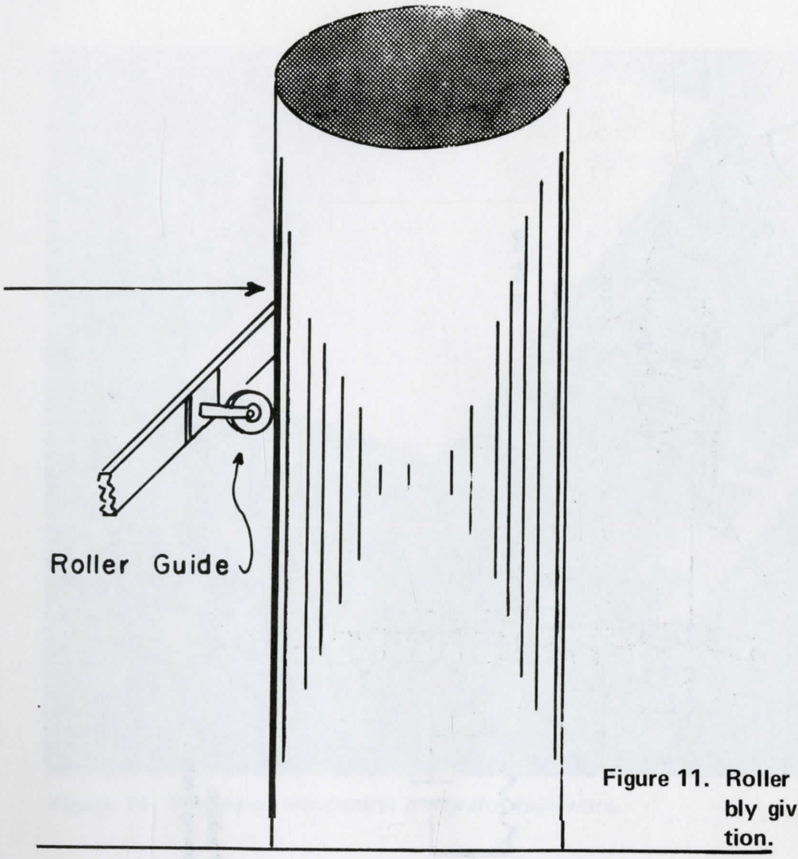

Figure 11. Roller guides used to support rain gage assembly giving lowest friction for maximum resolution.

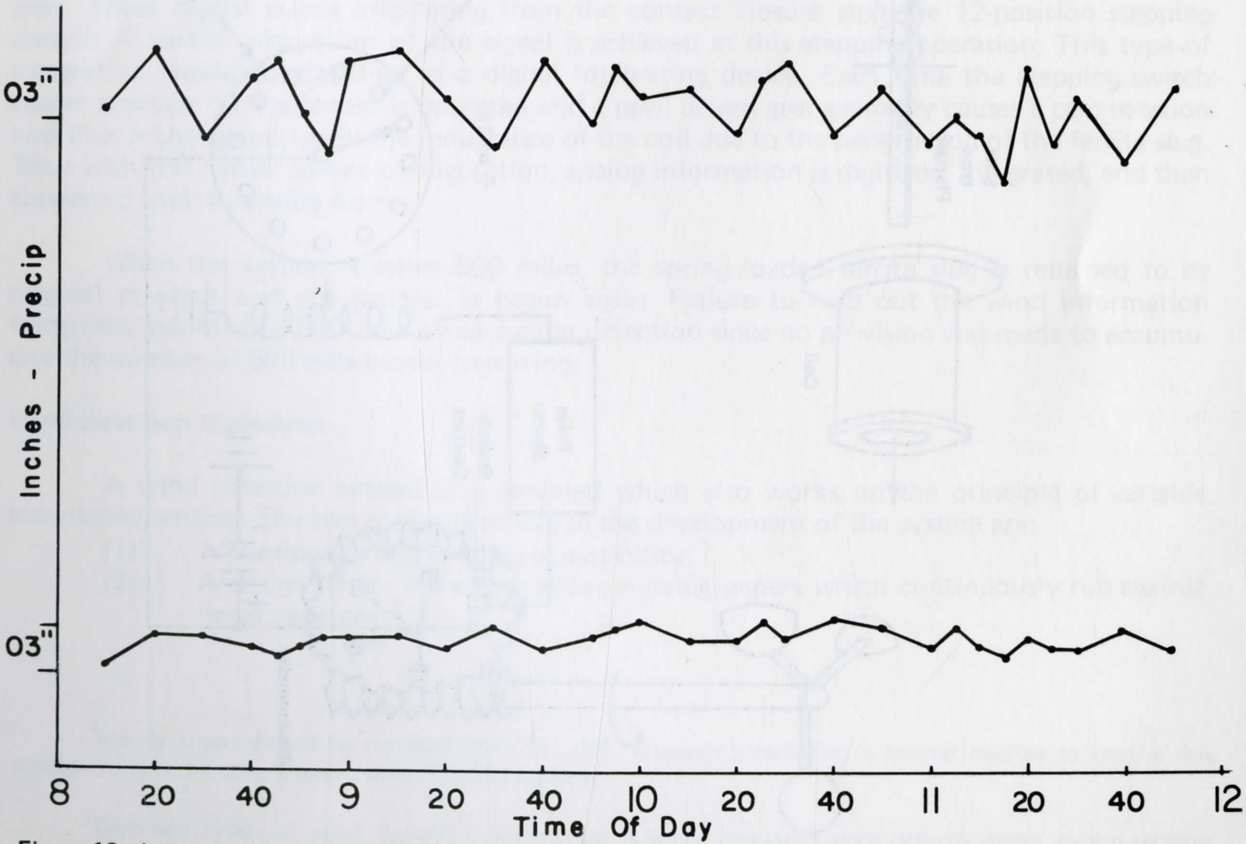

Figure 12. Improvement of T/M accuracy made possible in a 36-inch capacity gage by use of rolling guides in lieu of sliding guides.

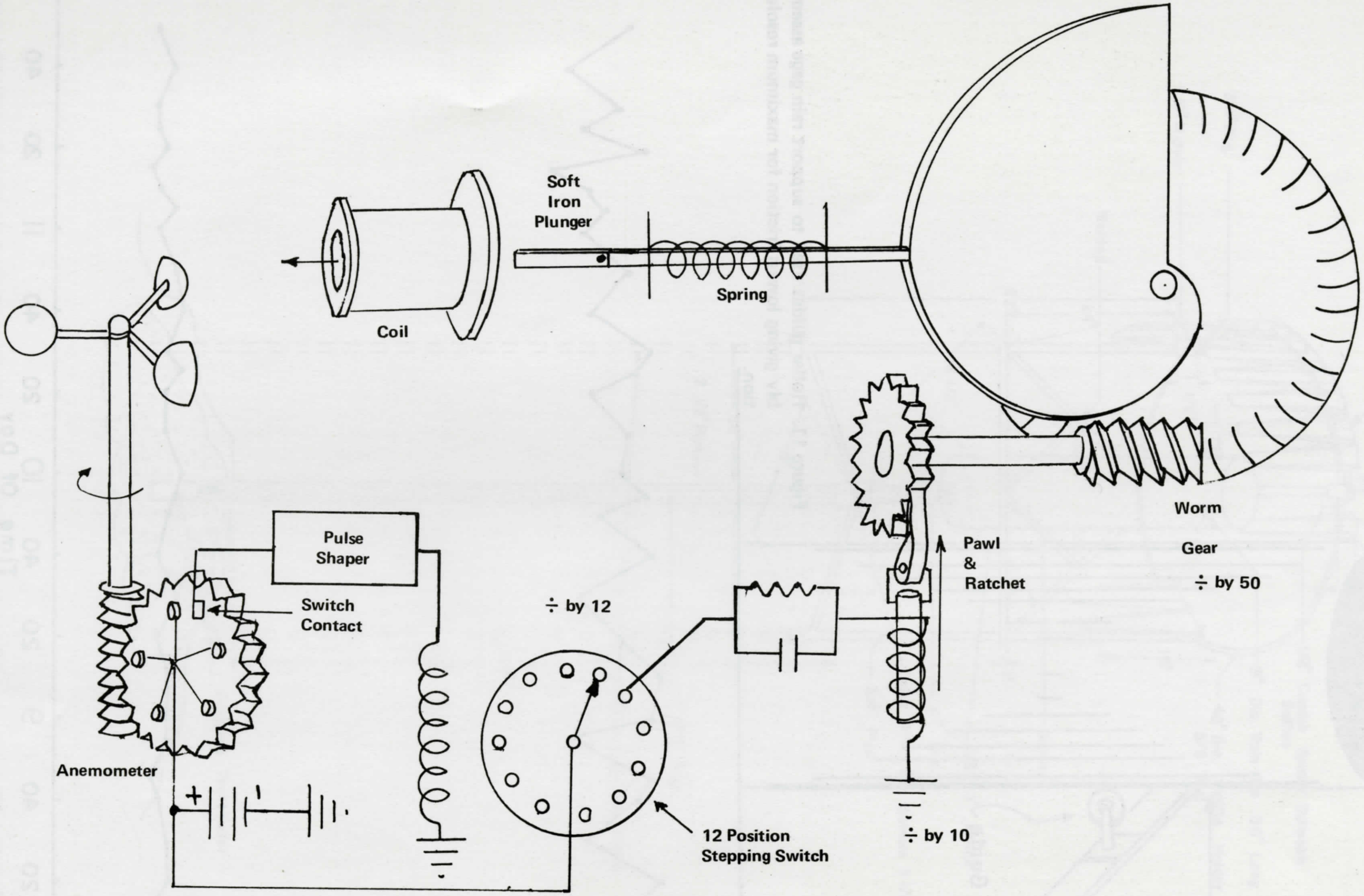

Figure 13. Wind-miles integrator assembly. Six thousand switch closures are required for one stroke of iron plunger into coil.

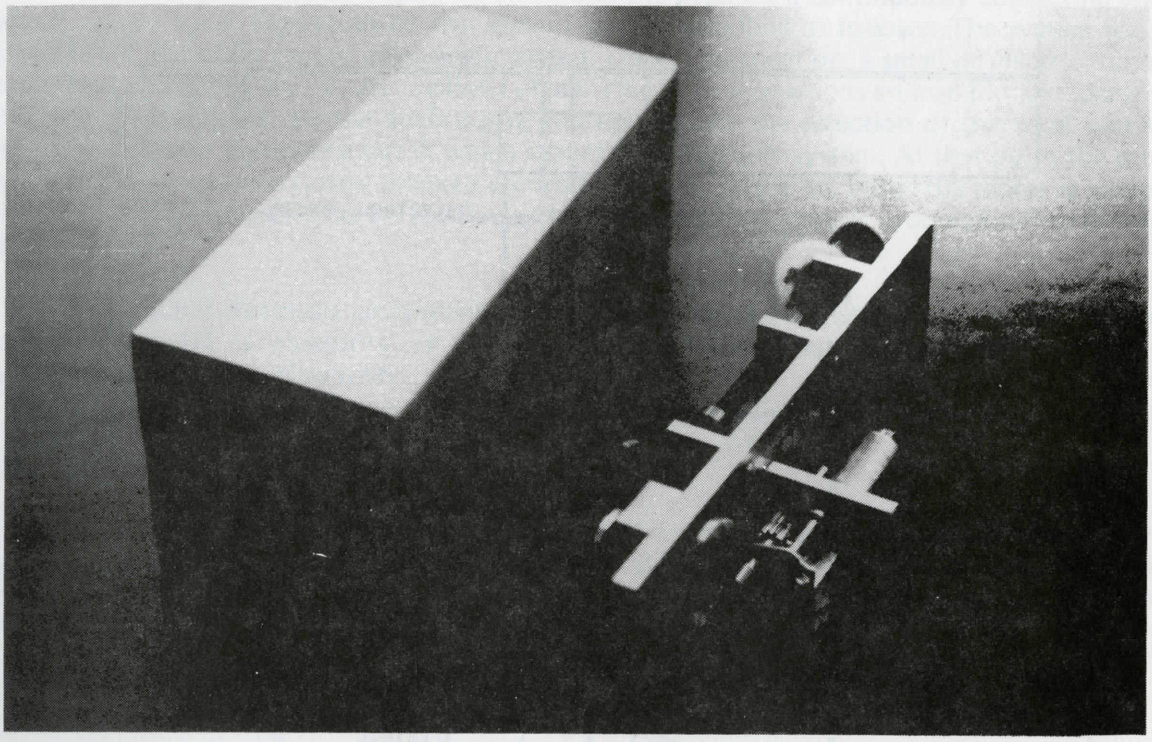

Figure 14. Picture of wind-miles integrator hardware.

gear. These digital pulses originating from the contact closure step the 12-position stepping switch. A partial integration of the signal is achieved in this stepping operation. This type of integration would be classified as a digital integrating device. Each time the stepping switch passes position 12 a solenoid is operated and a pawl driven gear assembly causes a cam rotation and thus a change occurs in the inductance of the coil due to the penetration of the ferrite slug. Thus with this rather simple configuration, analog information is digitized, integrated, and then converted back to analog form.

When the system registers 500 miles, the spring loaded ferrite slug is returned to its original position and the process is begun again. Failure to read out the wind information frequently could let a 500 mile cycle escape detection since no provision was made to accumulate the number of 500 mile blocks occurring.

Wind direction transducer

A wind direction system was designed which also works on the principle of variable inductance sensing. The two main objectives in the development of the system are:

(1) A continuous 360° resolving capability.[1]

(2) A design which does not require moving wipers which continuously rub against linear resistors.[2]

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[1] Ideally there should be no possibility for 180° ambiguity requiring a second reading to resolve this ambiguity as is the case in many wind direction sensors.

[2] Common types of wind direction sensors use a linear resistance type potentiometer as the sensing element. Experience has shown that the wiper frequently wears out and must be replaced at considerable cost.

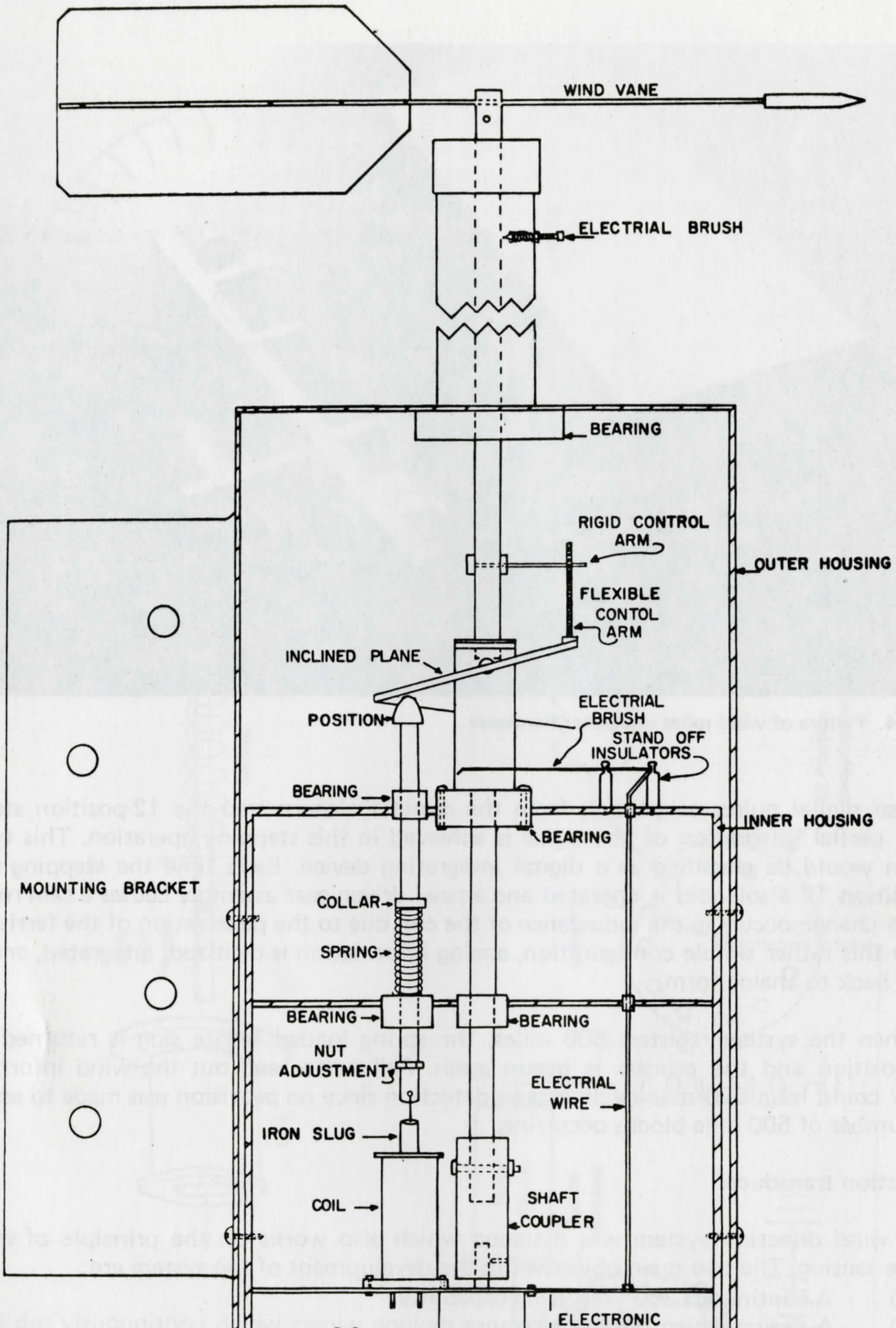

Figure 15. Drawing of wind direction indicator with telemetering sensor system attached (coil and slug).

The design shown in Figure 15 eliminates the need for a continuously contacting sensor which causes wear. Operation of the system can be described as follows: The system is completely free to rotate except when interrogated. Upon interrogation, a small dc electric motor is turned on and drives the circular inclined plane. This in turn positions an iron plunger located in the coil as illustrated. As the shaft turns and approaches the direction of the wind vector, a flexible contactor contacts a brush which signals the electronic system. At that point the motor stops as the mechanism is now indexed according to wind direction. When the motor is stopped, the indicator is connected to an oscillator circuit whose frequency is proportional to the wind direction.

This wind direction equipment has been operated during winter months and has been found to operate satisfactorily. It is now being used on a weather modification evaluation project in the Wasatch Mountains.

Other transducer applications

A number of other transducer applications have been made and reported previously in annual reports. Details are not included here for the sake of brevity. In general any graphic recording type instrument may be readily instrumented. This list includes such instruments as thermographs, hygrographs, actinographs, etc.

Telemetering Radio Link

Remote stations and repeaters

In order to evaluate various types of hydrologic instrumentation effectively, some of the equipment was installed in remote mountainous regions. During the period of this research project, three remote sites were utilized. These sites were located at Garden City Summit, elevation 7850 feet, Providence Lake on Mt. Logan, elevation 8800 feet, and Providence Traps located on Mt. Logan, elevation 8800 feet. (These sites were used primarily to test snow pillow designs which are discussed later.) A fourth location used for instrumentation test purposes was located at the mouth of Logan Canyon near the Utah Water Research Laboratory, elevation 4650 feet. Pictures of these four locations are shown in Figures 16, 17, 18, and 19. Each site basically was equipped in the configuration illustrated in Figure 20. Figure 21 gives a block diagram of the remote station in addition to the mountaintop relay and the base station also shown.

The Garden City Summit site was established in cooperation with the Soil Conservation Service who provided a 12 foot rubber snow pillow, which was used as a standard against which other types of pillows were evaluated. This instrumentation site was selected because of its close proximity to the highway and relative ease of access. A disadvantage of this site was its remoteness from the base station. In order for information to be telemetered from Garden City Summit, two relay stations had to be installed, one on Swan Peak and one on the Wellsville Mountain Range. A sketch of this configuration is shown in Figure 22. Since radio path transmissions are essentially line of sight, transmission between the base station and the remote station directly was not possible. This initial mountaintop relay installation consisted of 10 meter transmitters and receivers operating on government assigned frequencies of 32.180 and 34.620 MH_z. The antennas at the mountaintop sites were vertical dipoles mounted on a 20 foot tower. The surprising element of this relay system was that the remote station as well as the

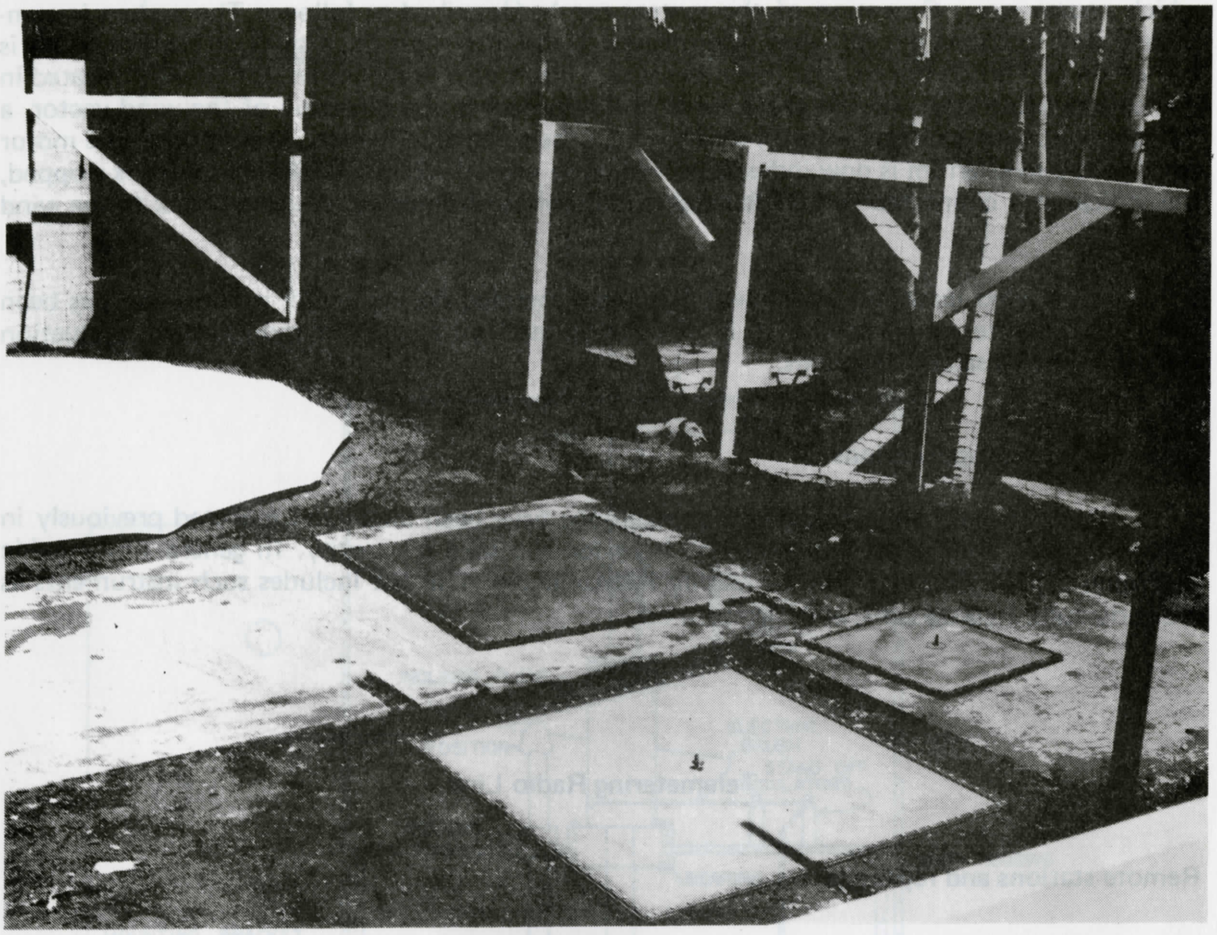

Figure 16. **Snow pillows installed at Garden City Summit snow course. The large white pillow at the left is a 12-foot butyl rubber pillow. Concrete aprons shown in the foreground were initially used as a foundation for the small pillows, but were later abandoned. This site was operated in cooperation with the Soil Conservation Service.**

mountaintop relay transmitted with a power input of only 100 milliwatts. Transmission range of this low level power was in excess of 50 miles. The radio transmitter and receiver operated from dry cell batteries and consisted of citizen band equipment which was modified for telemetering purposes. Schematic diagrams of the remote electronics and mountaintop repeaters are shown in the appendix.

After the first year's operation at Garden City Summit where various types of rain gages and snow pillow transducers were evaluated, the site was abandoned in favor of a new location, Providence Lake. The Providence Lake location had the advantage of requiring only one mountaintop relay to reach the laboratory. It is at a higher elevation than Garden City Summit and being close to the Wasatch Front receives considerably more snow. This location thus provides more severe conditions under which the tests could be conducted. The Providence Lake site is on the east side of Mt. Logan and the base station is located at the laboratory at the base of the west side of Mt. Logan. Consequently, a radio repeater was placed on top of Mt. Logan for relaying information to the laboratory. Since the laboratory is in a particularly disadvantageous position with respect to the mountain peak, it was necessary to locate the antenna for the base station some 400 yards from the base station proper. A land line was used to transmit the audio signals and commands from the base station to the actual transmitter site.

Figure 17. Providence Lake pillow test site. This site was abandoned after one year due to snow drifting problems.

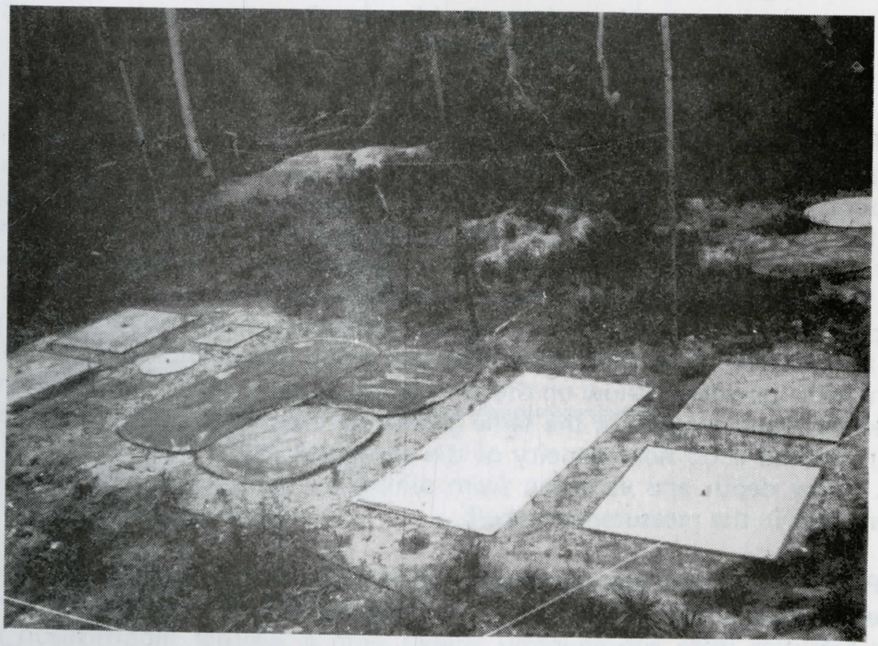

Figure 18. Providence Traps pillow test site. A 12-foot pillow is just outside of the picture to the right. The photo is taken from the precipitation gage tower.

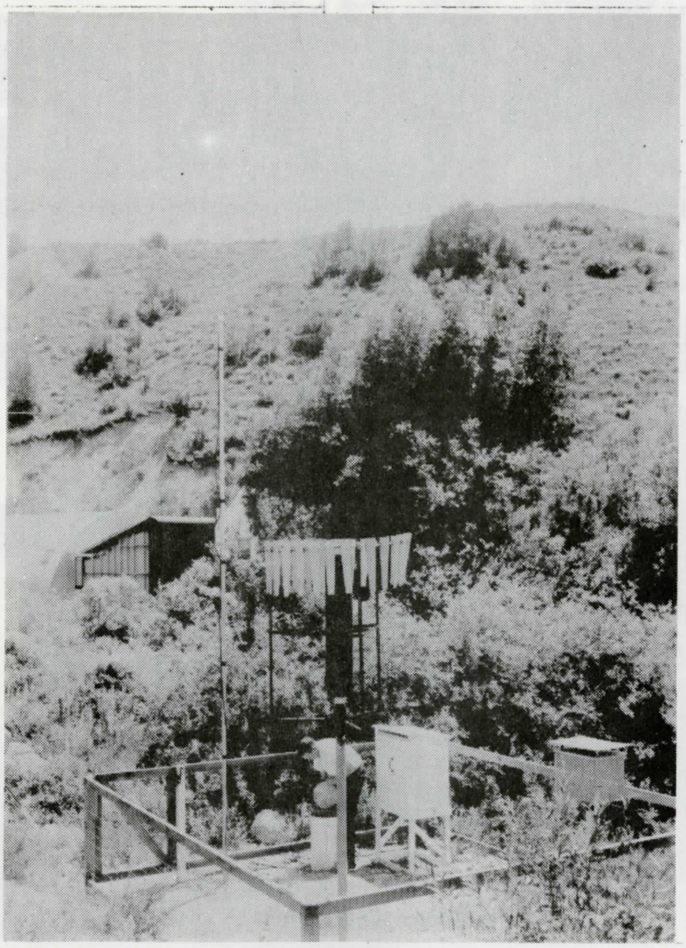

Figure 19. Utah Water Research Laboratory test site. This site was located near the laboratory for convenience in instrumentation checkout.

The Providence Lake instrumentation site was visited on numerous occasions during the winter months with the use of snow machines. These periodic visits to the site showed that there was serious drifting in the area. Numerous ridges were cut through the area by wind action. This fact was surprising since the area is quite well sheltered by trees. Due to the lack of homogeneity of the snowpack, it was difficult to make effective evaluations of the instruments being tested. The natural variability between measurement points was considered to be excessive. The experience thus gained illustrated the importance of selecting a good snow measurement site in the wintertime as opposed to selection in the summertime. The effects of wind are visibly evident with powdered snow on the ground. As a result of the wind problem, a third site called Providence Traps, located in the same general area but free of wind, was selected. Snow samples taken showed good homogeneity of the snowpack in the clearing chosen for this new snow course. Snow depth and variation from sample to sample appeared to be less than the error of uncertainty in the measurement itself.

The Providence Traps instrumentation site has been used for the past three snow seasons. In order to help alleviate the cost of maintaining the site and the repeater site on Mt. Logan, these facilities were subsequently shared with a weather modification project. That project was concerned with increasing snowpack in the mountains by seeding clouds. The data obtained from this station, therefore, were used jointly in evaluation of instruments as well as evaluation of cloud seeding effectiveness.

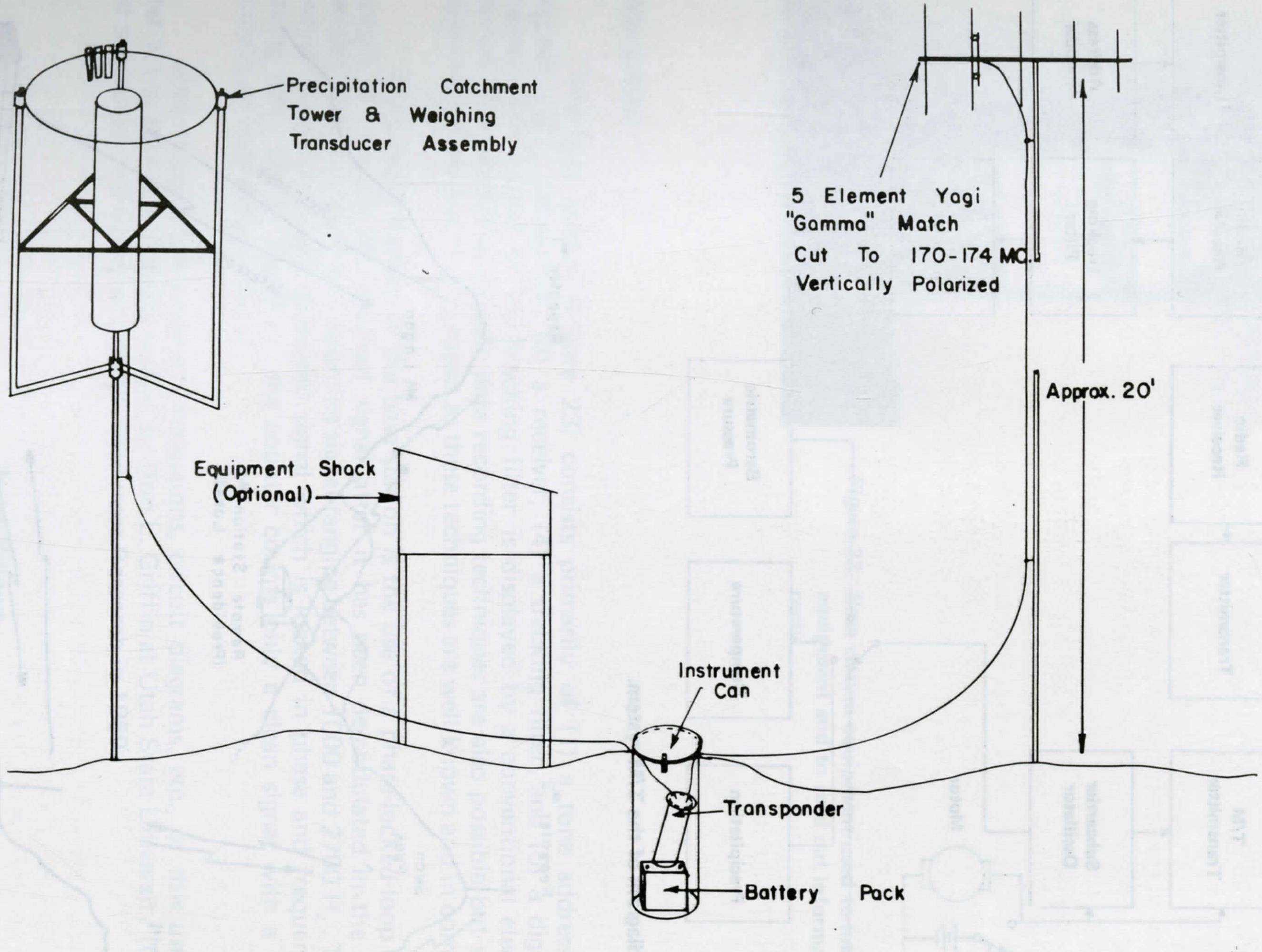

Figure 20. Pictorial diagram of telemetry station.

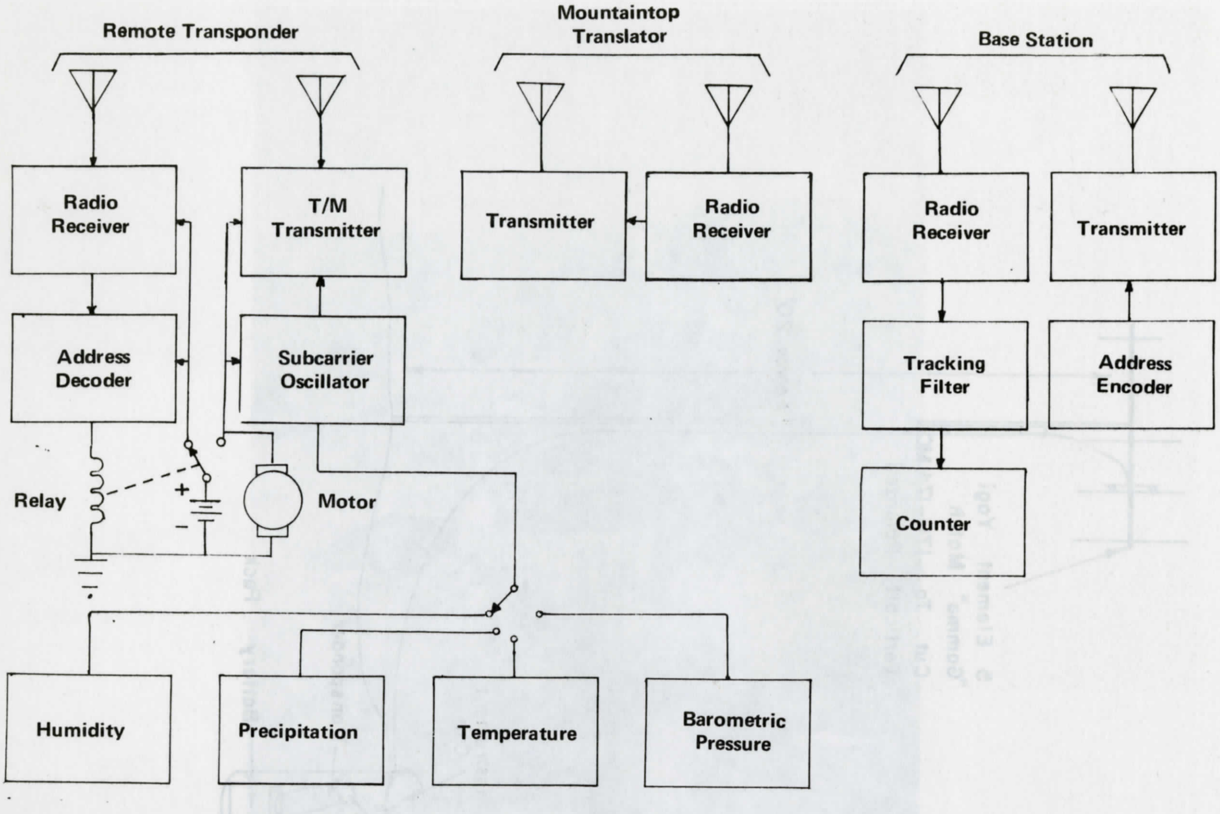

Figure 21. Block diagram of the T/M system.

Figure 22. Pictorial diagram showing the T/M repeater configuration. The initial system extended from Garden City Summit via Wellsville to UWRL. The second system was routed through the Mt. Logan repeater from the Providence Lake or Providence Traps site.

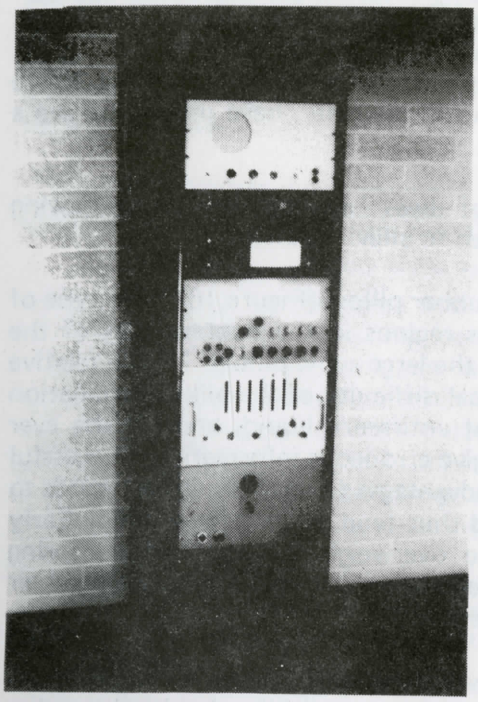

Figure 23. Base station equipment used to interrogate remote equipment and to read out information received in reply.

Base station

The base station (Figure 23) consists primarily of (1) a tone address generator or encoder, (2) a transmitter, (3) a receiver, (4) a tracking filter, and (5) a digital frequency counter. The output of the tracking filter is displayed by a conventional electronic digital counter. Subsequent automatic data recording techniques are also possible but are considered beyond the objective of the project as these techniques are well known and in common use.

The unique feature of the base station is the use of a phase-locked-loop tracking filter capable of tracking the received signal after it has been demodulated in the receiver. This tracking filter can track any incoming signal ranging between 1000 and 2700 H_z. The frequency counter counts a locally generated signal which is locked in phase and frequency to the incoming noisy signal. Therefore, the counter counts only a clean signal with a demonstrated accuracy of 5 significant figures.

More details, performance evaluations, circuit diagrams, etc., of this unique tracking filter are provided in a thesis written by Don L. Griffin at Utah State University (Griffin, 1969) and submitted to the Office of Water Resources Research in 1969.

Snow Pillows

General discussion

A large rubber bag that holds an antifreeze solution can be used to measure the water-content of snow. This bag, called a "snow pillow," has a liquid pressure buildup within it that is proportional to the force exerted upon it. Evaluation studies on these flexible rubber snow pillows has been conducted for a number of years. This work was originally done at Mt. Hood, Oregon, by the Soil Conservation Service, and at Moscow, Idaho, by the University of Idaho. Both research groups have recommended the use of large volume, large diameter, pillows. These pillows, typically having a 300 gallon volume and 12 feet in diameter, have proven to give a reasonably accurate indication of the snow-water content.

Practical problems, however, persist in the use of these large pillows. The following discussion presents these problems and the approaches taken to alleviate them.

The snow pillow chiefly used, is a 12-foot butyl rubber pillow (Figure 16). This type of pillow has been installed in many places in mountainous regions in the western part of the United States. There are three disadvantages to the use of the large snow pillow: (1) the relative high cost of the pillow and its initial installation, (2) physical difficulty of the pillow installation in inaccessible regions with its associated 300 gallons of antifreeze liquid, and (3) the ever present tendency of the pillow to develop leaks, and thus give erroneous information. Successful operation of the smaller pillows would overcome the disadvantages (1) and (2). With regards to (3), smaller pillows could be structurally more secure and thus tend to have fewer leaks. Early tests, however, demonstrated that small pillows tend to overweigh the snow in the spring months when the snow is dense and snow bridging problems are most severe. Because of their tendency to overweigh, small pillows have not been used regularly.

Upon re-investigation of the problems associated with the small pillow, several interesting aspects arise. The practical use of small pillows appears to be a possibility, despite the earlier objections cited. This possibility is raised through a more detailed look at the physical phenomena taking place, and adjustment in pillow design to better cope with these phenomena.

The errors associated with snow pillows in determining water-content of snow can occur in several ways: (1) the pillow does not accurately sense the weight of snow falling on it, (2) the snow falling on the pillow and subsequently melting is not representative of the areal distribution, (3) the pressure sensing mechanism is inaccurate, and (4) the visual readout or telemetry-recording system is inaccurate. Of these four types of error-inducing factors, item (1) is of chief concern in the present research. The significance of item (2) is alleviated by selecting a snow site with an evenly distributed snowfall pattern. (Irregularities in the snow pattern may still require that the snowfield be manually sampled occasionally when making detailed pillow performance evaluations.) Error contribution by items (3) and (4) is greatly reduced through the use of a pressure transducer and telemetering system, discussed previously, which exhibits high resolution and zero static friction in the mechanical sensor and essentially zero error in the readout device.

With the minimization of the errors in items (2), (3), and (4), the errors occurring in item (1) can be investigated more easily.

Small pillow design criteria

Practically any size or shape of snow pillow will measure correctly when placed in a large tank of water, i.e., a swimming pool. Snow, however, may be more characteristic of a solid than a liquid. Therefore, assurance that a pillow works in a tank filled with water is no assurance that it will function well as a snow pillow in the actual situation.

The chief concern about satisfactory pillow performance is that snow may tend to bridge over the pillow and in so doing a pillow tends to weigh the snow inaccurately. The bridging coefficient is a function of the perimeter of the pillow, i.e., $2\pi r$ for circular pillows. The snow weight on the pillow is a function of pillow area, i.e., πr^2. The bridging-to-weight ratio is, therefore, proportional to $2\pi r/\pi r^2$ or $2/r$. This demonstrates that the larger the pillow the less noticeable the bridging effect since the effect is inversely proportional to radius r. As a practical matter, there are limitations on how large a snow pillow should be. The objective is to maximize the performance for small size pillows. Consequently, to obtain more satisfactory operation from the smaller diameter pillows, greater care in design, installation, and operation must be practiced.

With regards to obtaining a reduction of bridging and improved snow-water measurements from small pillows, the following observations are made:

(a) Heat transfer from the ground to the snowpack through the snow pillow should be at the same rate as ground-to-snow heat transfer in the absence of a snow pillow. This implies that the pillow should have high thermal conductivity and low thermal mass. As snow lies in contact with the earth, the gradual flow of heat from the earth into the snowpack may occur at a greater rate adjacent to the pillow than it does through the pillow and into the snowpack. This process causes an undermining of snow adjacent to the pillow. Such an effect tends to cause overweighing, since the burden of the undermined area is carried by the area of slower melting rates (or pillow).

(b) Surface deflection of the pillow should be infinitesimal, if possible. The pillow and ground under the pillow should exhibit the same compliance as the ground surrounding the snow pillow.

(c) A very low-volume pillow per given pillow surface area should be used in order to minimize the surface deflection of the pillow due to fluctuations in liquid temperature. Stated differently, the depth of the liquid in the pillow should be kept to a minimum. As a practical matter, the minimum liquid depth for a 4 foot square pillow is about 1.0 inch. Ground slope and ground surface roughness tend to make lower liquid depths impractical. Consequently, for a thermal expansion that increases total volume by 0.1 percent, the pillow diaphram must raise 0.1 percent of 1.0 inch to accommodate the increase in volume. The small pillow diaphram adjustment is, therefore, only one-fourth that for a large pillow having initial liquid depths of 4 inches as is typically the case. Us of a liquid having a low coefficient of thermal expansion is also desirable for these same reasons.

(d) Since some liquid expansion is inevitable, at least one pillow surface must be sufficiently flexible to permit volume expansion within the pillow with a minimum of internal pressure buildup resulting. If an all metal pillow is used, there can also be a tendency for the bottom surface to "oil can," or suddenly snap from one steady-state condition to another. Such a condition is aggravated if the pillow is placed on rough ground. This oil can action may result in a large pressure buildup in the semirigid pillow configuration having a metal top and bottom. This problem can be alleviated through good mechanical design and care in installation procedures, or by use of a flexible rubber top instead of the metal top.

(e) A low displacement transducer should be used. Conventional float-type recording transducers displace as much as 5 gallons of liquid for a full scale reading; this amounts to about .07 inch of diaphram deflection in a 12 foot pillow. The low displacement bellows type transducer, requiring 1 cubic inch of liquid for full scale displacement, should be used on a small pillow. Withdrawal of 1 cubic inch of liquid causes an upper surface deflection of .0043 inch for a 4 foot x 4 foot pillow surface. This reduction of surface deflection helps improve the relative performance of the small pillow. If a large float-type transducer were connected to the small pillow, surface deflection would be so great as to likely render it inoperative.

Pillow construction

Special consideration was given to the pillow construction in order to maintain uniform liquid distribution at shallow liquid depths.

Several types of pillow configurations were used in the experiment. These include pillows made of all rubber, a rubber top diaphram with a steel bottom plate, an all sheet metal top and bottom, and a sheet metal flexible top plate with a three-sixteenth inch steel bottom plate. The unit made with the steel bottom plate and sheet metal top plate held the least liquid, 3 gallons, for a 4 foot × 4 foot pillow size. The all-rubber 4 foot × 4 foot pillows held the most, 15 gallons. The larger amount of liquid was required in the all-rubber pillow, to prevent inadvertent high centering due to ground roughness and slope. The compromise design using a steel plate on the bottom and rubber top held 7 to 8 gallons. Its design is illustrated in Figure 24.

The 4 foot × 8 foot all sheet-metal pillow was constructed of two 24 gage sheets of galvanized steel. The top sheet was reduced in size slightly so that the bottom edge could be rolled over the top sheet and soldered. This type pillow is probably best suited for use in pairs to give an 8 foot × 8 foot effective area. They should be interconnected hydraulically. Since the bottom side is flexible, it should be mounted on a sand or soft dirt base and configured to the profile of the pillow to permit the pillow ground base interface to have continuous contact. If this is not done with care, faulty performance results.

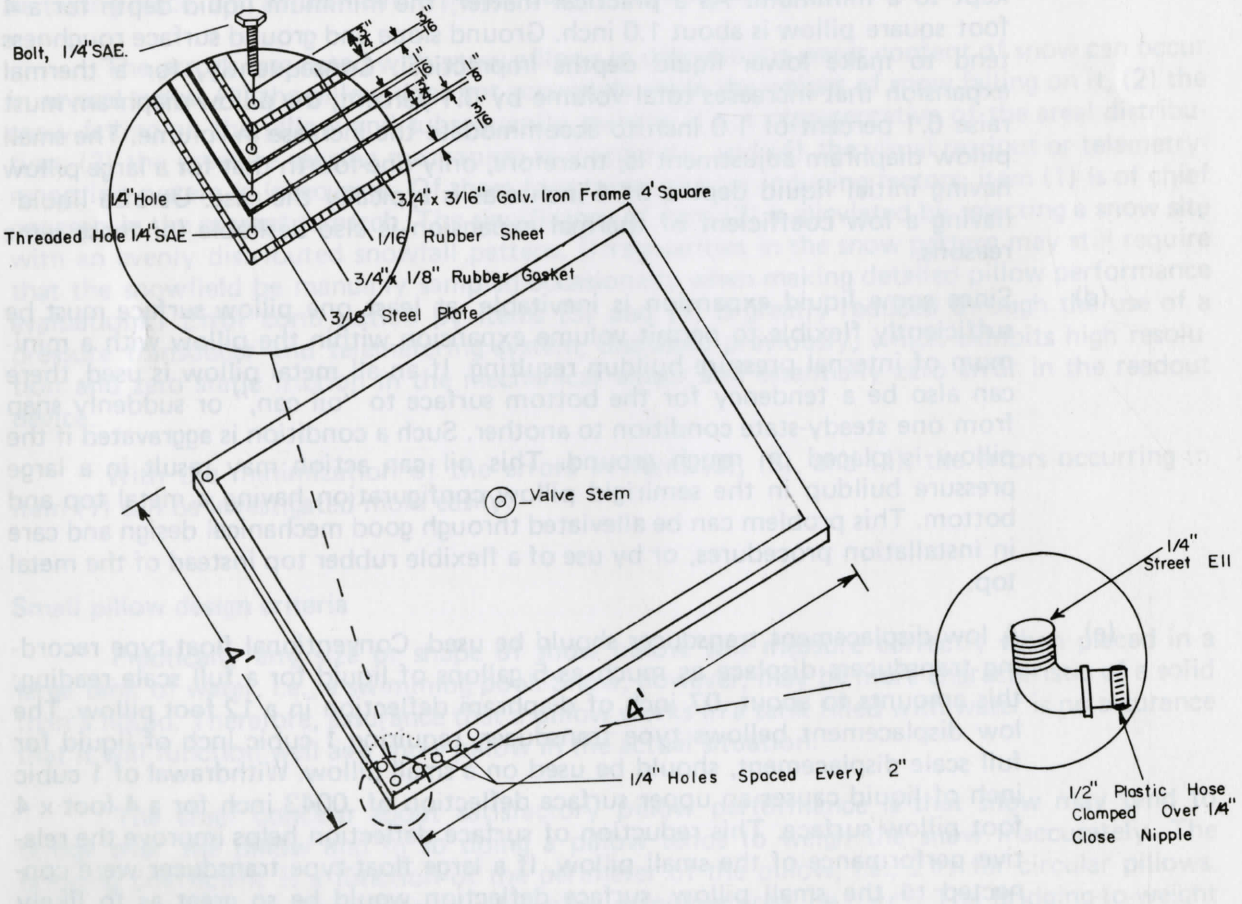

Figure 24. Snow pillow construction detail.

The small all-rubber snow pillows used were originally built to serve as 50 gallon tanks useful in storing liquids. They were manufactured by the Goodyear Rubber Co. and were made of butyl rubber. They have exhibited no tendency to leak or otherwise deteriorate much in a 4-year period.

Of the various pillows used, the optimum type pillow has not been completely determined. The many materials and the various sizes that can be used would require a number of years of evaluation in several geographic areas of the country to give definitive answers. Available funds under the present project were not adequate for the extensive program needed to resolve the many facets of the problem.

At this time, in light of the limited testing, the safest small pillow approach appears to be to use the 4′ x 4′ ruggedized rubber tank-type pillows or 4′ x 4′ rubber top-steel bottom pillows (Figure 24) and interconnect them into an 8′ x 8′ configuration. This design has the advantages of:

(1) Relatively low liquid volumes approximately one-tenth that of a 12 foot diameter rubber pillow.
(2) Ease of installation and maintenance.
(3) If a section is damaged, it can be replaced at about one-tenth the cost of the single large rubber pillow.
(4) The "nesting" interconnection configuration gives an equivalent large pillow configuration. This is considered to be a "conservative approach" when using small pillows.

Snow pillow performance

For the convenience of pillow performance evaluations, the pillows were placed relatively close together as illustrated in Figures 16, 17, and 18. This was done as a practical matter in order to house all visual manometers, electronics, and transducers in one instrument shelter and also to take advantage of the local uniformity in the snowfield as much as possible. Experience has now shown that there are serious disadvantages to this configuration in the event a leak occurs in one or more of the pillows as the area of effect created by the leak is difficult to determine.

If an alcohol solution is used and a leak occurs, the leaking fluid will evaporate and then condense on the surrounding snow, causing the snow to melt. One pillow which was noted to behave erratically, subsequently, was found to have a large dome shaped void existing above the pillow. This void was centered over a leak found in the pillow. The reason for the void is attributed to the alcohol evaporation and condensation as it comes in contact with the snow. If a glycol solution is used, the vapor pressure is not as high as that of alcohol and evaporation is not as rapid. However, if enough liquid is present, it may flow through and under the snow causing it to melt by reason of the lowered freezing temperatures. This last year of operation the 12 foot rubber pillow used as a "standard" developed a leak of significant size which virtually emptied 300 gallons of an alcohol-water mixture in the test bed area. As a result, much of the data was lost from this test.

Of the various pillows tested, the nylon reinforced butyl rubber units manufactured by Goodyear did not leak. Also, those constructed as shown in Figure 24 did not leak. Two of this type have been used for five years. The soldered 4′ x 8′ all sheet-metal pillows with soldered seams tended to develop hairline cracks in the seams, which resulted in leaks. The 12-foot butyl snow pillow also developed a number of leaks. Doubtlessly, fabrication processes have improved since this unit was made and it may not be typical of new pillows now on the market. It did leak to some extent three out of the five years it was tested, however. The last two years it was also badly damaged by porcupines during the summer. The fact that porcupines found it found it palatable suggests there may be some mineral in it which they like, i.e., salt. The smell of alcohol or glycol may also arouse their curiosity. This is somewhat discounted, however, since they ate far more than was necessary just to get to the liquid.

Snow pillow data

With regards to snow pillow data, several figures on performance are presented below. In general, snow pillows 4 feet square or larger that were tested appeared to measure snow quite satisfactorily during the snow accumulation periods. During the melt period, the issue is somewhat in question. Trouble developing with leaks had an undetermined but harmful effect on accuracy. Some four foot pillows appeared to give good accuracy; others did not. The delineation of those affected and those unaffected by other pillows that leaked is not clear.

A sample of snow pillow data is presented which typifies accuracy and relative performance of some of the pillows tested. Figure 25 shows relative performance of late season pillow operation. The fluctuations are diurnal in nature and only occur during the melt season. Similar fluctuations have also been noted to occur on the so-called standard 12-foot pillow in April and May.

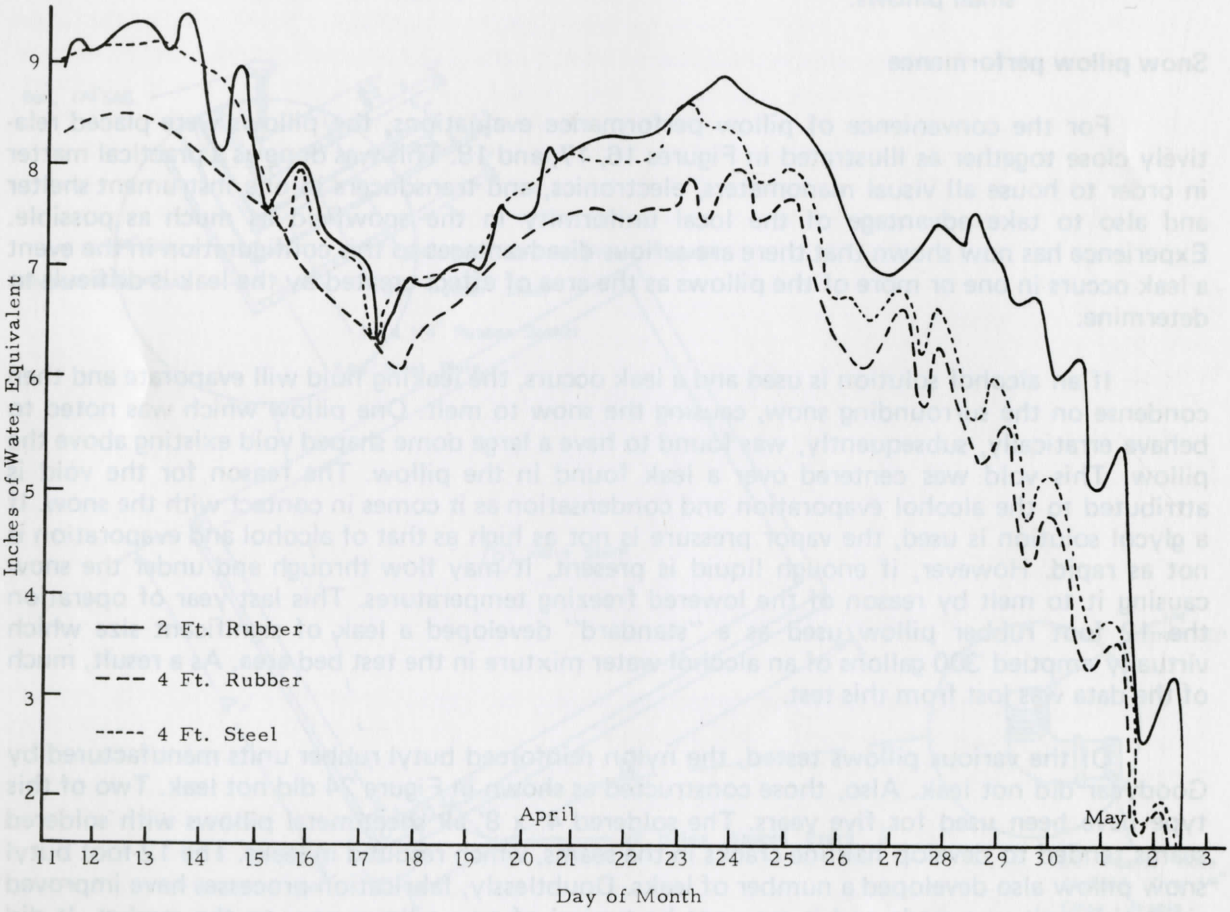

Figure 25. Plot of water-content of snow as indicated by telemetry versus time.

Figure 26 shows data plotted from two types of 4-foot square pillows, one with a top diaphram made of rubber and one with a steel diaphram. As this relationship was compared in the month of April, the scatter is shown for the worst period experienced. A similar plot is made for a 2-foot pillow plotted against a 4-foot pillow in Figure 27. Clearly, the relationship here is quite poor. The reason for the erratic behavior of the smaller pillow is not well understood. Since the area increases as the square of the diameter, the larger pillow has four times the averaging capability for localized pressures that may periodically occur.

The effects of a leaking pillow are demonstrated graphically in Figure 28. Comparisons are also made in this figure with manual snow tube measurements taken at points adjacent to the pillows. (The particular snow tube instrument used is known to overweigh about 10 percent.) These measurements were taken when the site was accessible by snow machines. The steep terrain between the valley floor and the pillow site makes accessibility a problem during a considerable part of the winter and spring months.

The effects of selecting the proper site can be illustrated by comparing the relative amounts of water as indicated by the pillow to that of the precipitation gage in Figures 29 and 30. In the first instance, the precipitation gage shows accumulation in excess of that indicated

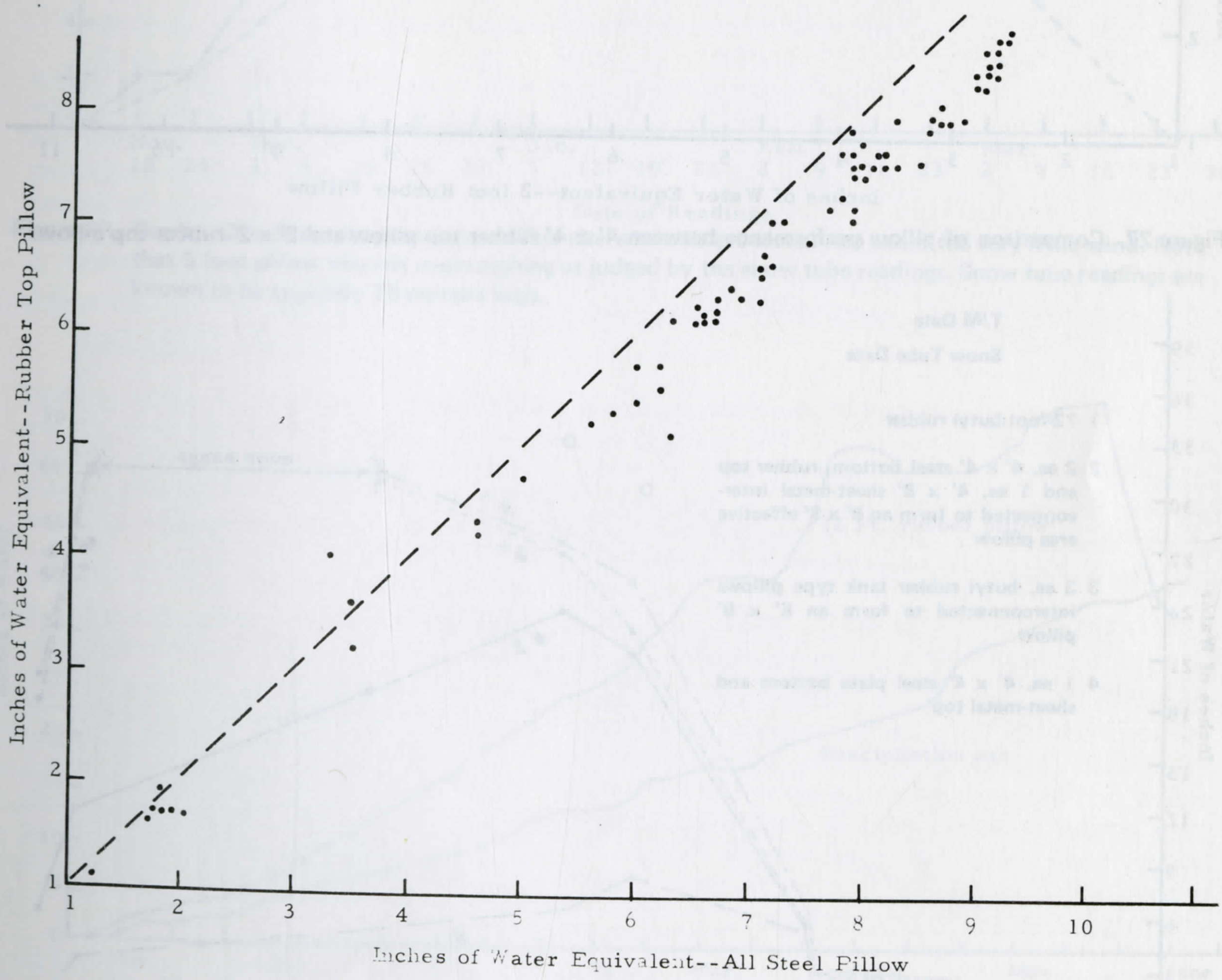

Figure 26. Comparison of pillow performances between 4′ x 4′ rubber top and 4′ x 4′ steel top.

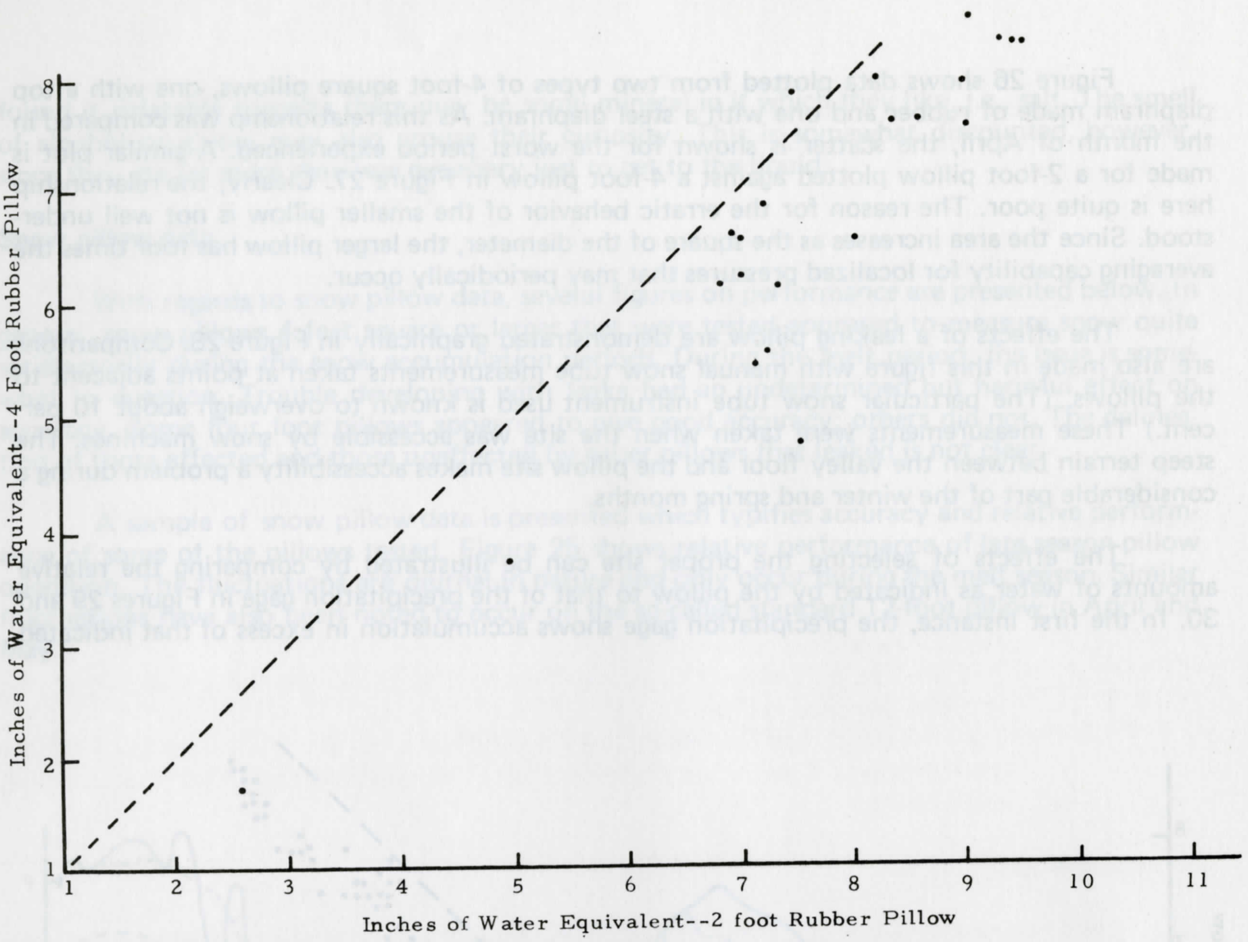

Figure 27. Comparison of pillow performance between 4′ x 4′ rubber top pillow and 2′ x 2′ rubber top pillow.

Figure 28. Plot of snow pillow performance for 1969-70 snow year.

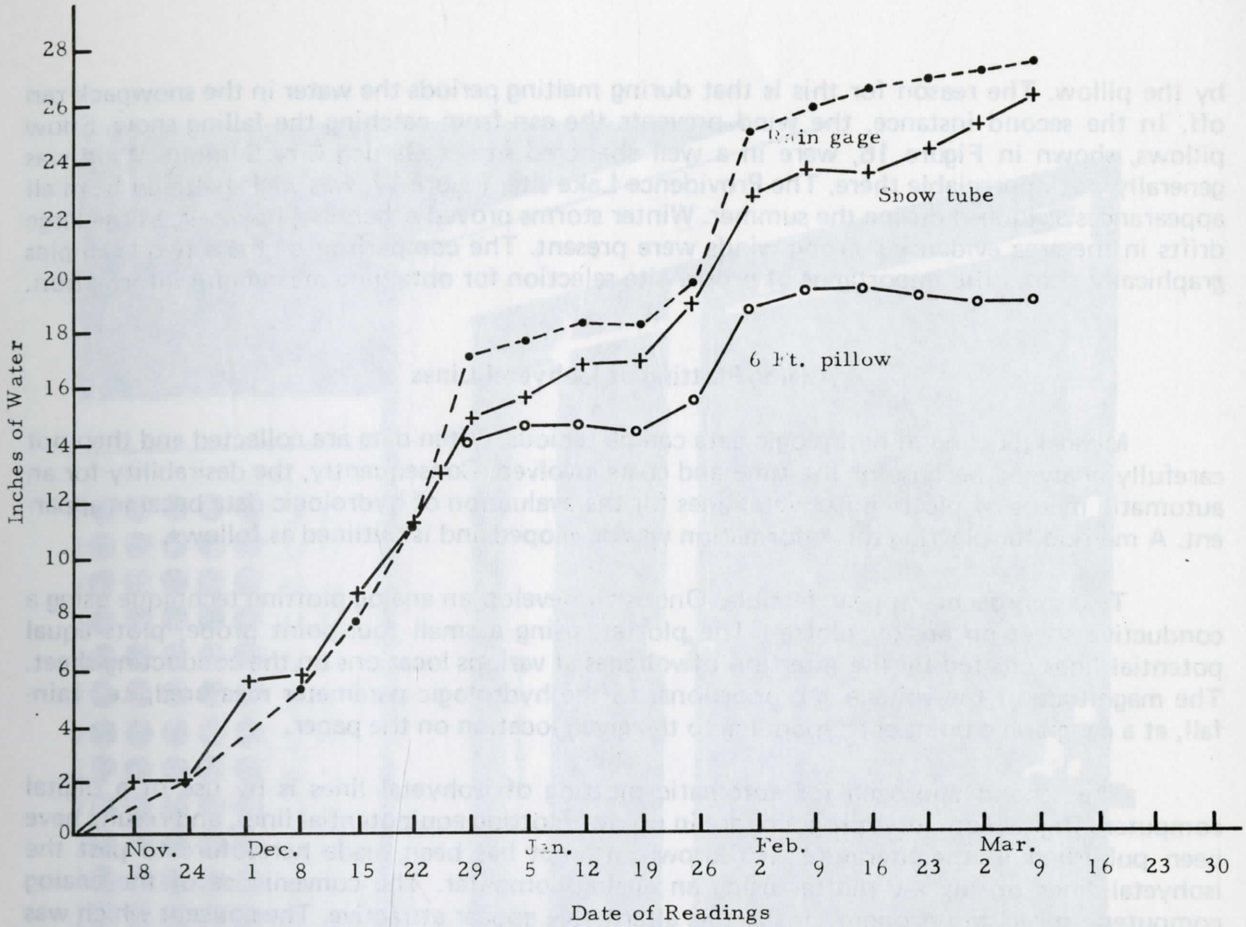

Figure 29. Garden City Summit snow course. This site was well protected and exhibited very little wind. Note that 6 foot pillow was not overweighing as judged by the snow tube readings. Snow tube readings are known to be typically 10 percent high.

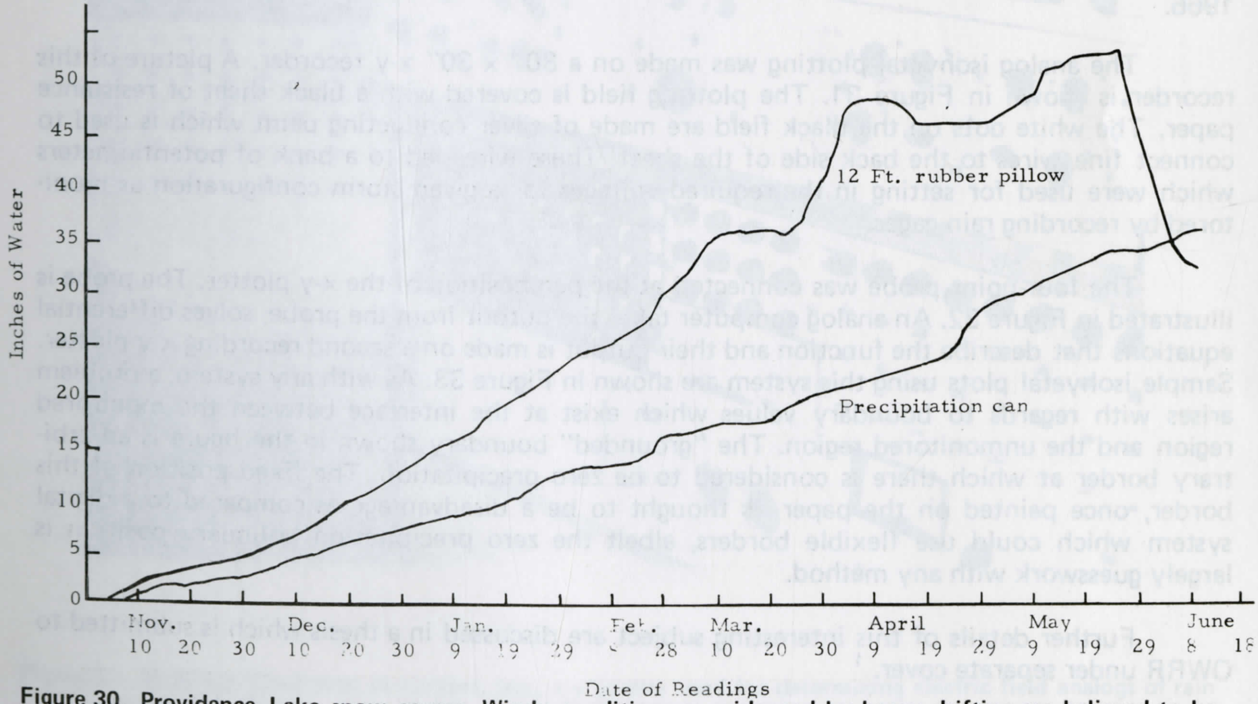

Figure 30. Providence Lake snow course. Windy conditions as evidenced by heavy drifting are believed to be the cause of the poor catch in the precipitation can.

by the pillow. The reason for this is that during melting periods the water in the snowpack ran off. In the second instance, the wind prevents the can from catching the falling snow. Snow pillows, shown in Figure 16, were in a well sheltered site at Garden City Summit. Wind was generally not appreciable there. The Providence Lake site, Figure 17, was well sheltered from all appearances as judged during the summer. Winter storms proved otherwise, however, as the large drifts in the area evidenced strong winds were present. The comparison of these two examples graphically shows the importance of proper site selection for obtaining meaningful information.

Analog Plotting of Isohyetal Lines

Manual plotting of hydrologic data can be tedious. Often data are collected and then not carefully analyzed because of the time and costs involved. Consequently, the desirability for an automatic means of plotting isohyetal lines for the evaluation of hydrologic data became apparent. A method for plotting this information was developed and is outlined as follows.

Two approaches appear feasible. One is to develop an analog plotting technique using a conductive sheet on an x-y plotter. The plotter, using a small four-point probe, plots equal potential lines created by the insertion of voltages at various locations on the conducting sheet. The magnitude of the voltage is proportional to the hydrologic parameter measured, i.e., rainfall, at a geographic point corresponding to the given location on the paper.

The second approach for automatic plotting of isohyetal lines is by use of a digital computer. Digital computer programs are in use for plotting equipotential lines, and results have been published in the literature. No known attempt has been made heretofore to plot the isohyetal lines on an x-y plotter using an analog computer. The convenience of the analog computer's speed and economy make this alternative appear attractive. The concept which was employed is called the "method of steepest descent" and it can be used to determine the values for which a function takes on a minima. This method was first proposed by Cauchy in 1847. A general theoretical presentation of this method was published by Lym, 1965, and by Ostrowski, 1966.

The analog isohyetal plotting was made on a 30" x 30" x-y recorder. A picture of this recorder is shown in Figure 31. The plotting field is covered with a black sheet of resistance paper. The white dots on the black field are made of silver conducting paint which is used to connect fine wires to the back side of the sheet. These wires led to a bank of potentiometers which were used for setting in the required voltages for a given storm configuration as monitored by recording rain gages.

The four-point probe was connected at the pen position of the x-y plotter. The probe is illustrated in Figure 32. An analog computer takes the output from the probe, solves differential equations that describe the function and their output is made on a second recording x-y plotter. Sample isohyetal plots using this system are shown in Figure 33. As with any system, a problem arises with regards to boundary values which exist at the interface between the monitored region and the unmonitored region. The "grounded" boundary shown in the figure is an arbitrary border at which there is considered to be zero precipitation. The fixed position of this border, once painted on the paper, is thought to be a disadvantage as compared to a digital system which could use flexible borders, albeit the zero precipitation boundary position is largely guesswork with any method.

Further details of this interesting subject are discussed in a thesis which is submitted to OWRR under separate cover. [1]

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[1] This particular work was funded in part by OWRR and part by the Agricultural Research Service.

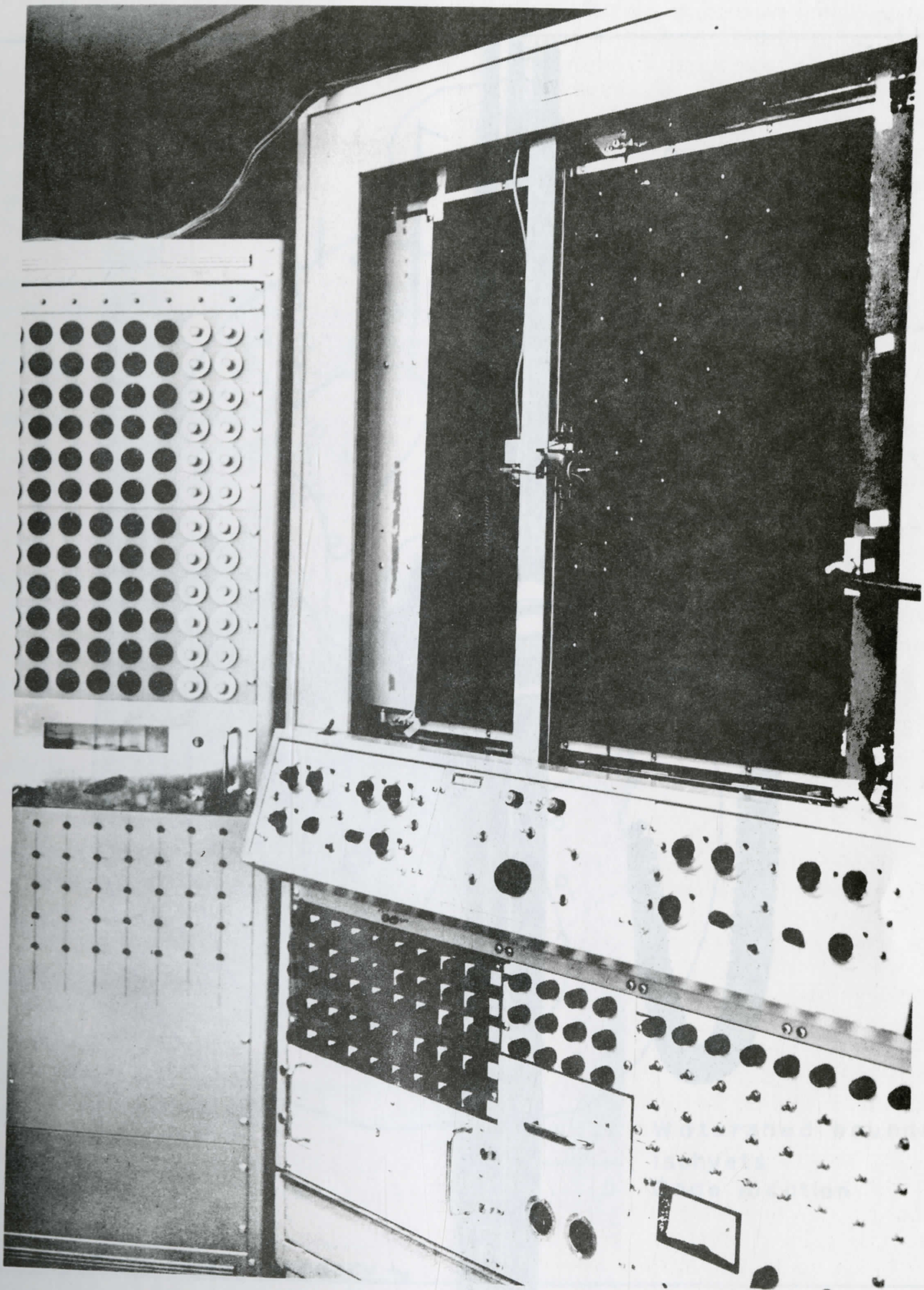

Figure 31. Modified, Electronic Associates, Inc., x-y plotter used for determining electric field analogs of rain fall patterns.

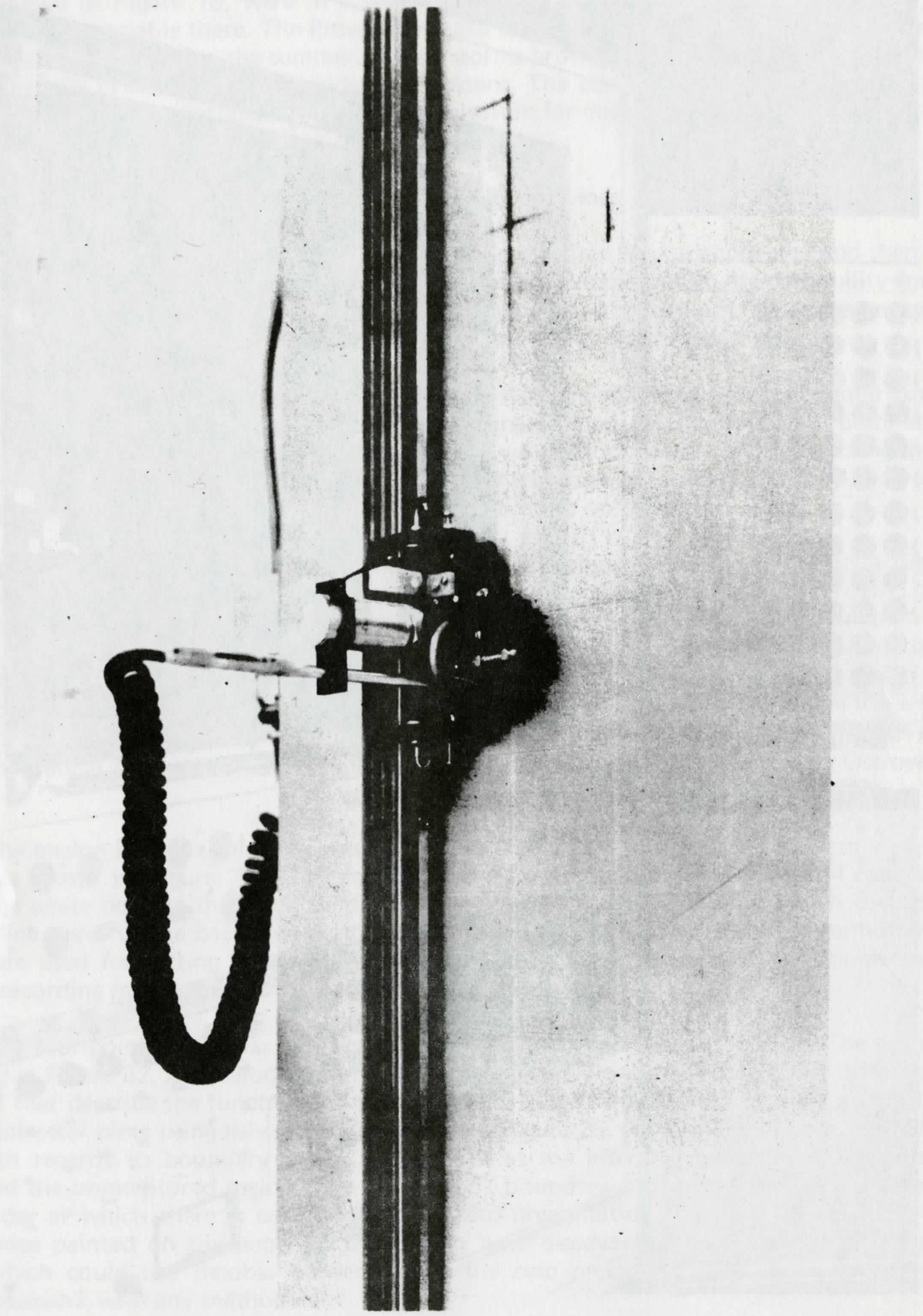

Figure 32. Close-up view of the four-point probe mounted at pen position of plotting arm on the x-y plotter.

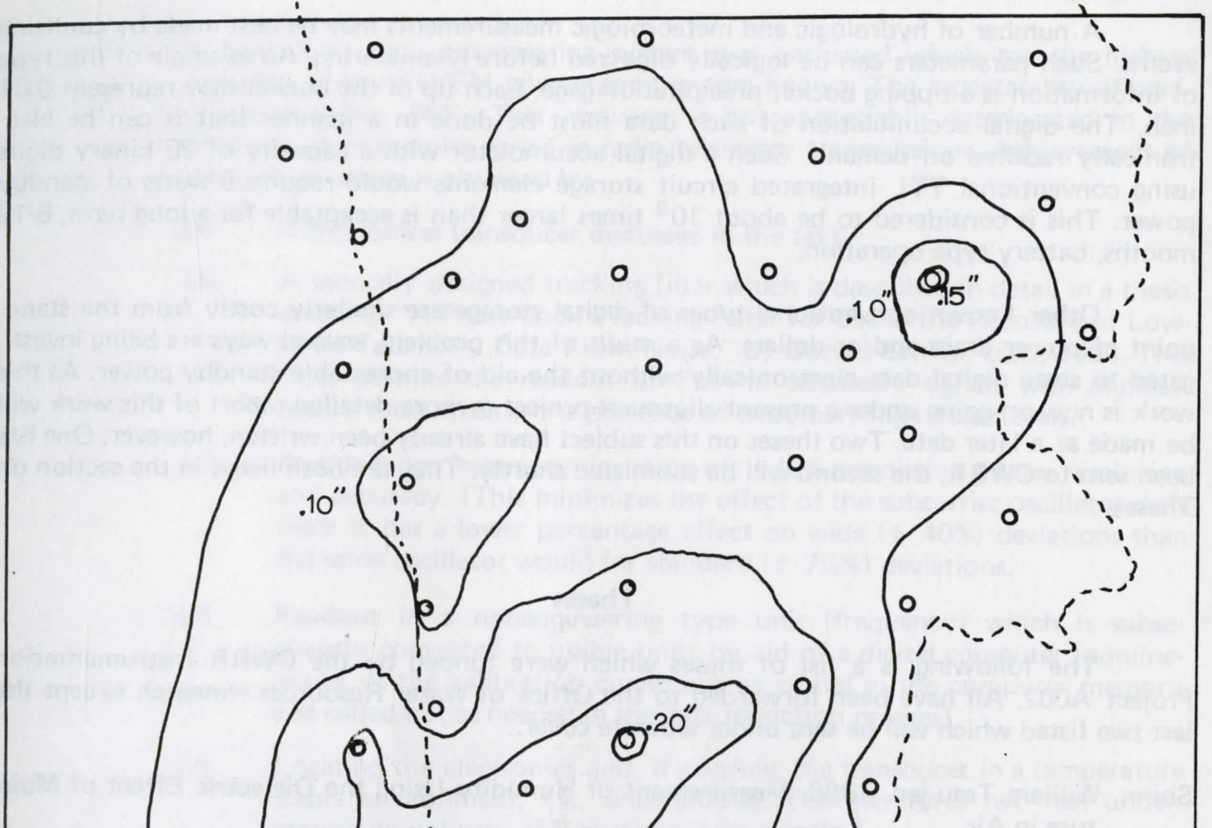

Figure 33. Isohyetal lines plotted on an x-y plotter with the aid of an analog computer.

Dynamic Digital Storage of Data Requiring Zero Standby Current

A number of hydrologic and meteorologic measurements may be best made by counting events. Such parameters can be logically digitized before telemetering. An example of this type of information is a tipping bucket precipitation gage. Each tip of the bucket may represent 0.01 inch. The digital accumulation of such data must be done in a manner that it can be electronically recalled on demand. Such a digital accumulator with a capacity of 20 binary digits using conventional TTL integrated circuit storage elements would require 5 watts of standby power. This is considered to be about 10^3 times larger than is acceptable for a long term, 6-12 months, battery-type operation.

Other known conventional types of digital storage are similarly costly from the standpoint of power drain and/or dollars. As a result of this problem, several ways are being investigated to store digital data electronically without the aid of appreciable standby power. As this work is now on-going under a present allotment project, a more detailed report of this work will be made at a later date. Two theses on this subject have already been written, however. One has been sent to OWRR, the second will be submitted shortly. They are both listed in the section on Theses.

Theses

The following is a list of theses which were funded by the OWRR Instrumentation Project A002. All have been forwarded to the Office of Water Resources Research except the last two listed which will be sent under separate cover.

Shinn, William Tsau-jen. 1966. Measurement of Humidity Using the Dielectric Effect of Moisture in Air.

Shih, Chung-chih. 1969. A Digital Counter Using Magnetic Flux Increments Requiring Minimum Power.

Griffin, Don L. 1969. A Phase-Lock Tracking Filter for Use in the Recovery of Low-Level Telemetry Data From Noise.

Kirwan, Maurice G. 1969. A Method for Plotting Isohyetal Maps Using an Analog Computer.

Groll, John. 1970. Digital Data Storage Using Magnetic Cores and Digital Stepping Motor Requiring Zero Standby Current.

Publications

Chadwick, D. G. 1966. Hydrologic Instrumentation-Guiding Philosophy and Practical Solutions. Paper presented at the ASAE and I&D Division Conference, ASCE, Las Vegas, Nev., November 2.

Chadwick, Duane G. 1967a. A Hydrologic Monitoring System. *Proceedings,* IBM Scientific Computing Symposium on Water and Air Resource Management, Thomas J. Watson Research Center, Yorktown Heights, N.Y., October 23-25.

Chadwick, D. G. 1967b. Development of a Low-Cost Hydrologic Sensing-Telemetry System. Utah Science 28(1):11-13, March.

Summary

A summary of practical contributions are cited which are considered worth noting.

(1) A hydrologic data telemetering system was perfected which has the highest accuracy of any FM/FM telemetering system known. The repeatability of readout approaches .05%. This accuracy is not appreciably deteriorated in the presence of high noise levels in radio telemetry transmissions. Achievement of this high accuracy is obtained by

(a) A frictionless transducer discussed in the text.

(b) A specially designed tracking filter which is described in detail in a thesis entitled, "A Phase-Lock Tracking Filter for Use in the Recovery of Low-Level Telemetry Data From Noise," by Don L. Griffin, USU, 1969. This filter permits the readout of FM/FM telemetry signals with unmeasurably small error in the presence of extremely high noise levels.

(c) A wide-range frequency deviation of ±40% permitting greater resolution and accuracy. (This minimizes the effect of the subcarrier oscillator drift since it has a lower percentage effect on wide (± 40%) deviations than the same oscillator would for standard (± 7½%) deviations.

(d) Readout in a nonengineering type unit (frequency) which is subsequently converted to usable units by aid of a digital computer (nonlinearities in the calibration curves can be stored in the computer memory and called out as needed in the data reduction process).

(e) Locating the electronics and, if possible, the transducer in a temperature stable environment, i.e., underground. (Temperatures two feet underground do not vary 1° F during winter months.)

(2) The frictionless transducer technique was used in developing a low-displacement type pressure transducer for measuring the water-content of snow. The original pressure transducer incorporating a length compression technique using mercury and a floating iron slug as a position pickoff was submitted to OWRR for its possible patent potential. Subsequently, an improved method using the more conventional bellows arrangement was substituted for reasons of convenience and mercury contamination problems.

(3) Use of the small snow pillows was re-introduced with extensive modification in design to alleviate problems associated with them in the past. Recommendations were made for performance improvement. The comprehensive testing program required before a comprehensive bill of endorsement could be given was too large and expensive to be completed under this project. Information has been passed on to other agencies who are conducting further evaluations. Much is left to be done to obtain definitive information regarding dynamics of snowpack behavior in the meso 1 square foot - 100 square foot areas.

(4) A method was developed for the automatic plotting of isohyetal lines on an analog computer. The detailed techniques of this procedure are reported in a thesis entitled, "A Method for Plotting Isohyetal Maps Using an Analog Computer," by Maurice G. Kirwan, 1969. The method is unique and was considered successful. It lacked convenience in regards to ease of "moving rain gage locations" or moving "boundary conditions." Each configuration was, in effect, painted on a sheet of conductive paper. New configurations required new paper.

Some hydrologic information is intrinsically digital in nature, i.e., the number of times a tipping bucket rain gage tips. Other information is intrinsically analog in form, i.e., streamflow, water-content of snow, etc. The analog system described herein is digitized once, and that is at the base station. No added complications of digital circuitry is required at the remote site for analog-to-digital conversion. To obtain the corresponding resolution in a digital system located at the remote site would require an A-D conversion system capable of a 13 bit word length. Clearly, the analog system as described has a marked advantage in economics, power consumption, and simplicity of circuits for those measurements that are initially in analog form.

The events that happen digitally or else can be readily digitized, such as wind that is measured on an anemometer, still may be most convenient to handle digitally. Some caution should be exercised, however, to ensure that the general swing of the pendulum toward digital systems is justified on technical rather than popular grounds.

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APPENDIX I

Electronic Circuit Details

Schematic diagrams of the mountaintop repeater electronics and the remote station electronics are shown in Figures 34 and 35, respectively. These units were packaged in watertight aluminum cylinders of the type shown in Figure 36.

The transceiver T/M units were powered by ignition-type dry cell batteries. Standby current was typically 4-5 milliamperes. Four 6-volt batteries were capable of lasting 10-12 months.

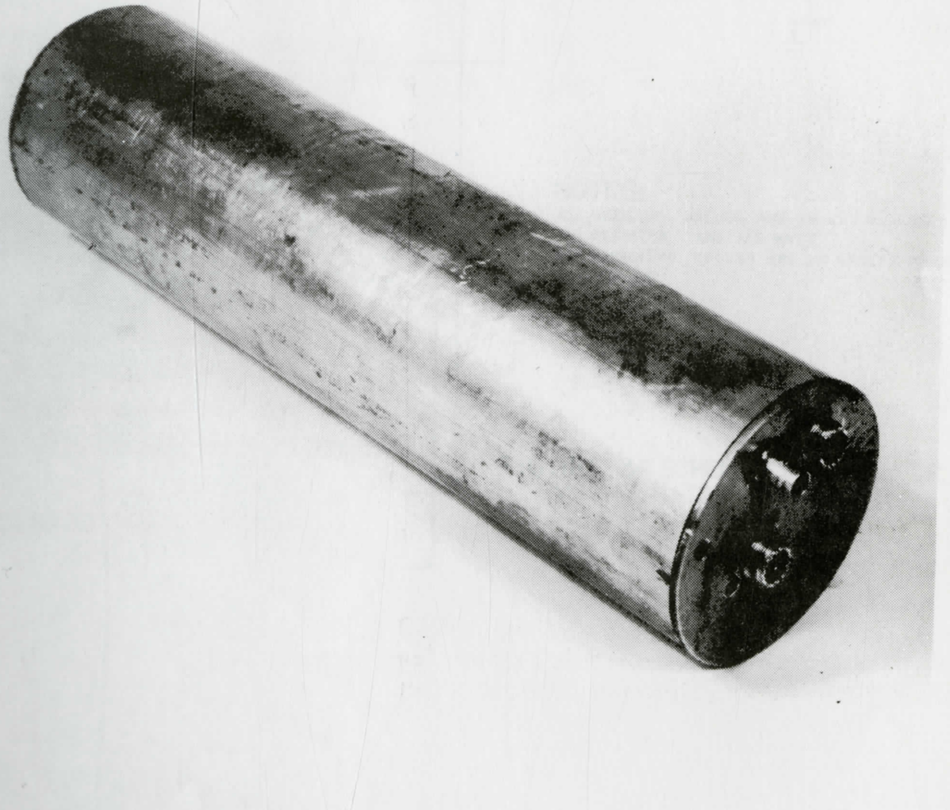
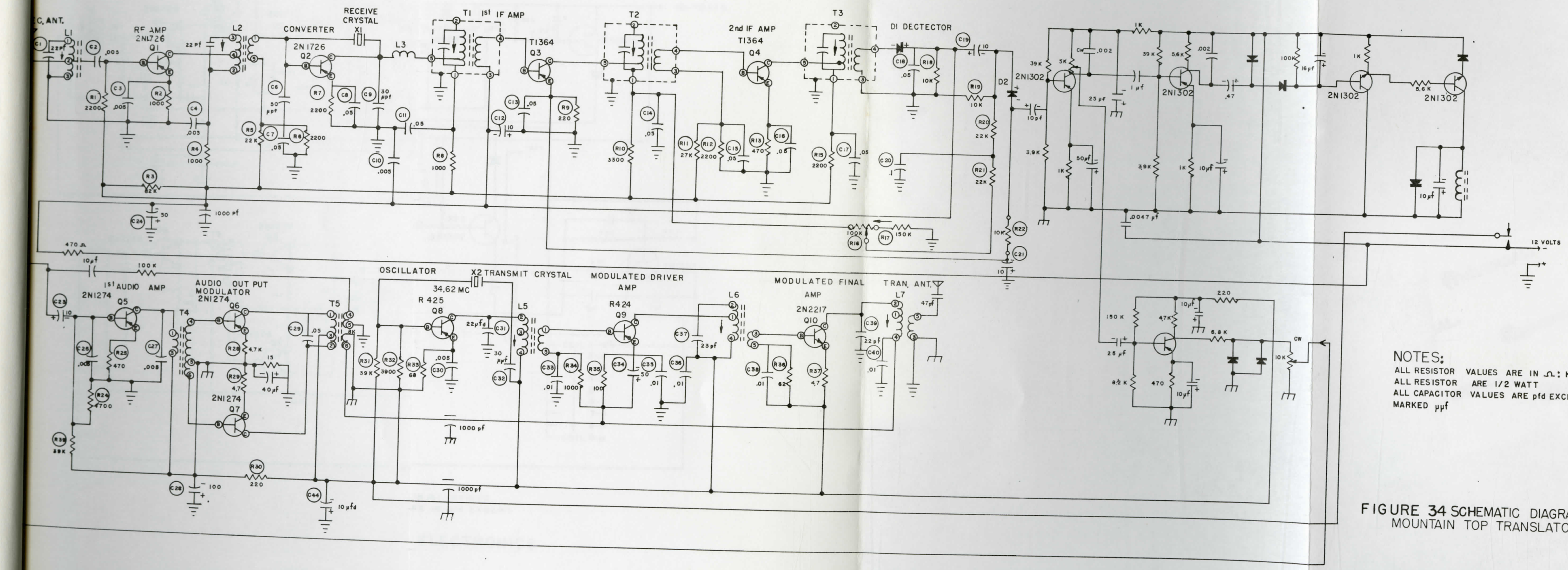


Figure 36. Picture of mountaintop repeater used on Swan Peak. Mt. Logan relay was similarly packaged. The unit was placed underground to provide a more favorable operating temperature.



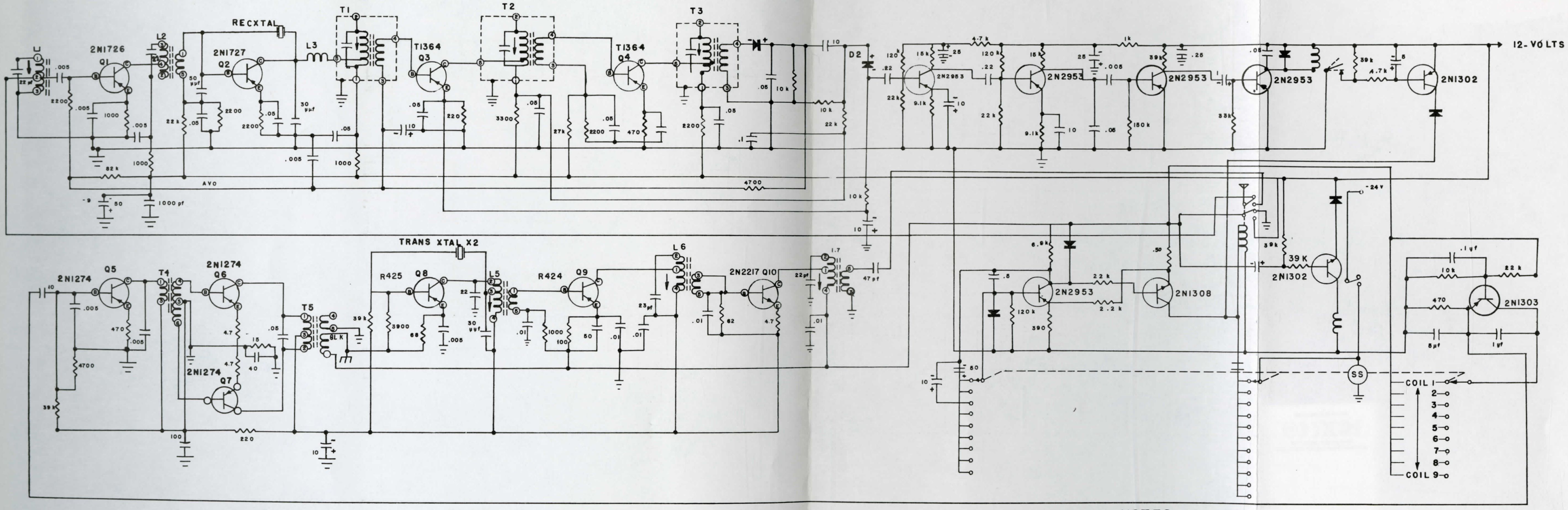
NOTES:

ALL RESISTOR VALUES ARE IN Ω: K= 1000.

ALL RESISTOR ARE 1/2 WATT

ALL CAPACITOR VALUES ARE pfd EXCEPT WHERE MARKED μμf

FIGURE 34 SCHEMATIC DIAGRAM OF SWAN PEAK MOUNTAIN TOP TRANSLATOR



NOTES:

ALL REGISTOR VALUES ARE IN Ω: K = 1000
ALL CAPACITOR VALUES ARE IN μfd EXCEPT
MARKED AS μμf.

FIGURE 35 GARDEN CITY SUMMIT ELECTRONICS