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GEOLOGICAL SURVEY

PRELIMINARY STUDY OF METHODS FOR UPGRADING USGS ANTARCTIC SEISMOLOGICAL CAPABILITY

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1. PURPOSE

The purpose of this study is to evaluate potential methods for obtaining higher quality seismic data from Antarctica. Currently, USGS-sponsored WWSSN stations are located at Scott Base, Sanae Base, and at South Pole Station. Scott and Sanae Stations are located near the coast; data obtained from coastal installations are normally degraded by noise generated by ocean wave action on the coast. Operations at South Pole are rather difficult because of the severe environmental characteristics and the extended logistics which are required to provide supplies and operating personnel to its remote location. Short-period data quality from Pole Station has been moderately high with a short-period magnification of 100K at 1Hz. Long-period magnifications have been rather low (<1K @ 15 s period). Recent relocation of the seismic recording facilities at South Pole Station as a result of the construction of a completely new station facility has caused serious degradation of the data quality due to faulty installation techniques. Repairs have been implemented to remedy these deficiencies and to regain the data quality which existed before the move to new facilities. However, the technology being used at South Pole Station is of WWSSN vintage; as a result it is about 20 years old. Much has been learned about achieving higher magnifications since the WWSSN was designed. This study will evaluate the feasibility of applying recent technological advances to Antarctic seismology.

Seismological data from the Antarctic Continent is important to the world's seismological community because of the Antarctic's unique geographic position on the globe. Land masses are scarce in that part of the world; the Antarctic sits right in the middle of the void. Therefore, its data are important for completing the data set for the southern hemisphere.

Upgrading the USGS seismic capability in the Antarctic should also prove to be a wise investment from another point of view. Although the initial costs of an Antarctic upgrade program would be high, and the cost of routine maintenance and support would be greater than in other parts of the world, the ease of upgrading is aided by the unique nonpolitical aspect of the continent. In addition, the danger of losing our investment due to political unrest or change is almost zero. In the past, political complications have severely impacted operations at several SRO stations. Therefore, an effort to improve data quality from the Antarctic would be a prudent long-term investment.

2. SOUTH POLE STATION

2.1 GENERAL

South Pole Station is situated on the great Antarctic ice sheet which comprises all of the interior plateau of Antarctica. It is a very isolated location at the end of one of the world's longest supply lines. All food, fuel, equipment, spare parts, personnel, and mail must be flown in from McMurdo Station, which is over 1200 km (720 statute miles) away. Access to the station is limited to approximately 3.5 months of the year extending from late October to early February. During the remaining months of the year, the combination of weather and darkness makes flying to the station not feasible. The severe weather conditions at the pole make it a very hostile place for both people and equipment. The ice sheet and the weather extremes place unique requirements on scientific studies not normally encountered in other parts of the world. The bitter cold (average annual temperature is -49 degrees C,

(-56 degrees F), (see Schwerdfeger, 1977) is hazardous to personnel, and requires that scientific instrumentation must sometimes be specially designed to function successfully. Wind adds to the difficulty of installation and adjustment of equipment because of the windchill factor and accompanying blowing snow. The ice surface complicates some measurements due to the fact that it is constantly moving. This motion results in surface tilt and velocity shear as a function of depth. The ice at pole is approximately 2741 meters (9000 feet) thick. Therefore, good earth electrical grounds and firm mechanical foundations are nonexistent. During high winds, which are always accompanied by blinding, blowing snow, large static charges build-up on any metal object exposed to moving snow particles, thereby creating very large potential differences between various surfaces and unknown potentials between the station complex and earth ground. The combination of all of these aspects of the environment at South Pole Station should be considered when contemplating scientific investigations there.

These conditions are especially troublesome for seismology. There is no bedrock on which to install instruments; they must be somehow coupled to a constantly moving, deforming, and tiling 2741-meter thick ice sheet. Wind-generated seismic surface noise degrades the data, and the cold sometimes necessitates heating areas containing electronic instrumentation. The total lack of good earth grounds means that the seismic equipment design must assure that static charge build-up does not interfere with the low level signals. Designing the system to be immune to RF interface is also complicated by the lack of good grounds.

2.2 LIMITED POTENTIAL OF SURFACE INSTALLATIONS AT SOUTH POLE STATION

There are several factors which place limits on the ultimate potential of a seismometer installed on or near the surface at South Pole Station. First, seismological instruments installed on the earth's surface or near the surface, are subject to varying degrees of locally generated noise which interferes with recording distant signals. The most obvious potential source of interference is seismic cultural noise, which results from human activity in the vicinity of the station. For this reason, the quietest sites are usually sufficiently separated from sources of cultural noise. Second, the motions of the atmosphere also generate seismic noise which intereferes with surface installations. Pressure variations associated with high and low pressure centers disturb the ground, but the frequencies involved are usually out of the passband of normal seismic observations. However, wind generates broad spectrum earth noise, which sometimes severely degrades the performance of surface installations. Regardless of how good other aspects of the installation are, wind noise places a limit on the capability of surface instruments during significant periods of time. The effects of wind noise on surface instruments installed on thick ice in Greenland (Project Blue Ice) has been quantitatively documented by Lenton (1968). South Pole Station's geographic surroundings are similar to those of Inge Lehmann Station, where these studies were conducted. Both are situated inland on a large, thick ice sheet; as such, winds are not nearly as strong as those along the coastline of an ice sheet environment. Nevertheless, strong winds do occur frequently, and they do contaminate surface seismic records. Lenton's data indicates that if the wind is less than 20 km/hr, near-surface, short-period vertical instruments remain fairly quiet and the data are not measurably contaminated. For higher wind speeds, short-period, near-surface instruments become noisy for periods less than about 2 seconds. An 18 db increase in noise power spectral density was obtained between 0.3 and 1 s period for wind speeds of 40 to 60 km/hr for a near-surface vertical instrument. Short-period horizontal wind noise would probably be at least as severe as that reported by Lenton for verticals. At longer periods (periods ranging from 10 to 100 s) near-surface wind noise problems are usually considerably worse. South Pole WWSSN long-period modifications are low by modern standards (<1K) because they are limited by the lack of environmental control around the seismometers and by persistent tilting of the seismometer pier at the new South Pole Station. Even if the instruments were protected from the environment and a stable pier could be constructed, surface-installed, long-period instruments could not be successfully operated at Pole at high magnifications because of atmospherically generated noise.

Both the short- and long-period data at South Pole Station have been degraded in the past by interference due to transmissions from the various high frequency (HF) radio transmitters located at the station. The severity of this problem has been reduced by system modifications performed during the Antarctic summer of 1980-81. However, some interference still persists. This problem is probably due to the fact that because the seismometers and associated amplifiers are located close to the HF transmitting antennas, the nearfield electric fields are quite high, thereby making complete RF proofing of the seismic system quite difficult.

2.3 THE ADVANTAGES OF BOREHOLE INSTALLATIONS

Borehole installation of both short- and long-period seismometers is a well established technology. A borehole presents a stable environment for a seismic system. The temperature is essentially constant if the hole is deep enough and temperature gradients are very low because it is limited by the earth's natural heat flow gradient and instrument self-heat emmission. Stable temperatures and low thermal gradients are ideal for seismic instruments. If the top of the hole is sealed, pressure is also constant in the borehole, thereby isolating the sensors from atmospheric pressure variations. If the borehole has an iron casing, it should be relatively free of interfering magnetic or electric fields.

However, the primary reason for installing sensors at depth is to attenuate non-propagating seismic noise which atmospheric pressure variations generate at the surface. The results of Project Blue Ice established that significant reductions in wind-generated surface noise could be achieved by installing vertical short-period instruments at approximately 60 meters depth. During calm conditions the seismic background at Inge Lehmann Station was comparable with those obtained at some of the best continental United States stations. Side-by-side tests during the high wind conditions mentioned above (40 to 60 km/hr) proved that 60 meters of burial was sufficient to reduce the wind noise to undetectable levels. In windy locations, such as South Pole Station, the data quality improvement gained with a shallow short-period borehole installation should be worth the effort.

As far as is known, no one has installed long-period instruments at significant depths in ice. Therefore, the success of such an installation cannot be guaranteed by any means. However, the same general principles should govern the rate of reduction of long-period noise at depth in ice as in rock. The rate of noise reduction is probably slower in ice, thereby requiring a deeper hole for a given reduction factor, but low levels of noise should be achievable. (See Sorrells and Der, 1969). A long-period borehole installation would have the capability of providing up to two orders of magnitude of improvement in the long-period magnification capability at South Pole Station if the mechanics of such an installation can be accomplished in the South Pole environment.

2.4 FEASIBILITY OF A SHALLOW BOREHOLE SP INSTALLATION AT SOUTH POLE STATION

A short-period vertical, shallow borehole installation, such as was used in Project Blue Ice at Inge Lehmann and in the seismic array at Byrd Station, Antarctica, is quite feasible at South Pole Station. The ability to drill and case a hole 60 feet deep under polar conditions has been demonstrated at these two locations; although it is definitely colder at the pole, constructing a shallow borehole there should not be significantly more difficult. Although they are no longer manufactured, some of the Teledyne-Geotech Model 20171A short-period, vertical borehole seismometers are available, either as surplus or lying in warehouses (USGS, Albuquerque Seismological Laboratory has several instruments stored). As factory adjusted, the 20171A temperature specification is from 30 to 140 degrees F, which is nowhere near the -56 degree F level anticipated at South Pole Station. However, the limits of operating range are selectable by partially disassembling the unit to gain access to the adjustment.

To complete the short-period installation, it would be desirable to deploy a set of horizontal instruments in conjunction with the vertical system at the bottom of the borehole. In the past, this has not been possible because horizontal instruments small enough for borehole use were not available. Recently, reasonably compact, horizontal instruments have been developed primarily as prospecting tools for use in the oil industry. Some of these instruments are of quite high quality and may be capable of resolving earth-noise at quiet sites. Preliminary evaluation at the Albuquerque Seismological Laboratory indicates that at least one of these (a Mark Products L-4) may be capable of measuring low, short-period noise levels. Most of these compact short-period instruments are of conventional design; they contain a spring-suspended mass and electromagnetic transducer system which requires at least some leveling if operated in the horizontal mode; a leveling mechanism would require development work because borehole installation would dictate at least minimal remote leveling capability. Sensors such as the Geotech S-500 or the much newer S-750 sensors are based on a unique design which does not require that the instrument be level. They can be operated in any position without adjustments, an ideal situation in a borehole. Evaluation of the S-500 at ASL indicates that it is too noisy to detect SP background levels found there. Extensive testing of the S-750 series sensor has been conducted by Sandia Laboratories and Teledyne-Geotech at ASL. The S-750's are essentially upgraded versions of the S-500 which have been engineered to achieve lower background capabilities by adding more gain to the sensor itself and by upgrading the amplifying electronics to achieve lower noise figures. An orthogonal set of S-750's can be packaged to be installed in a borehole whose diameter is approximately 7". They are active seismometers in that electronic gain is an integral part of the sensor package; through the use of mil spec electronic components, their operating range extends down to -55 degress F, which is close to the -56 degrees F borehole temperature anticipated at Pole. However, the Sandia/Teledyne-Geotech tests indicate that these sensors become noisy at longer periods which limits their usable bandwidth (the signal-to-noise ration (S/N) is high at very short periods, decreasing to about 10 at 0.25 seconds and down to a S/N of 1 at about 2 seconds, all based on a quiet earth model approximating ASL short-period background levels (Jim Durham, Sandia Laboratories, personal communication, 1981). This noise characteristic significantly infringes on the typical short-period response such as the WWSSN or SRO responses at longer periods.

Therefore, despite their many desirable characteristics for a cold borehole installation, the S-750 series seismometer cannot be used to record conventional short-period data at a quiet site.

Another alternative for producing shallow borehole short-period data is the Geotech KS-36000 borehole instrument. Since the standard version of this instrument contains many active devices, it will not function at the anticipated -56 F ambient temperature existing in the borehole, but it can be assembled with mil spec electronics at added cost. Consultations with O. D. Starkey (Teledyne-Geotech) indicate that a specially constructed KS-36000 (degreased and arctic lubricated mechanical parts, redesigning of key components containing temperature-sensitive magnetic materials, readjusted vertical component spring tension for operation at 90 degrees south plus 2741 meters (9000 feet) of elevation, and mil spec electronic components throughout) should operate at these temperatures. This approach to providing short-period data becomes especially attractive when we consider long-period data below.

2.5 FEASIBILITY OF A DEEP BOREHOLE LP INSTALLATION AT SOUTH POLE STATION

The success of improving the long-period data at the South Pole rests on the possibility of drilling and casing a relatively deep (over 500 feet) borehole and selecting instruments which will function at cold temperatures. These two goals will be difficult to achieve, but with special design it should be possible to achieve a high quality long-period station. One method of circumventing the temperature problem would be to take advantage of the earth's natural heat flow temperature gradient by installing the sensors at great depths, where the temperature would be moderated enough for standard design instruments to operate. This scheme is probably not feasible as discussed below. However, a moderate depth hole (of the order of 1000 feet deep) in which a specially designed cold-hardened active-component instrument such as the KS 36000 should be capable of providing high quality long-period data. The details of such an installation will be developed below.

2.6 SOUTH POLE DEEP BOREHOLE TEMPERATURE ENVIRONMENT

Temperatures at South Pole Station are among the lowest naturally occurring temperatures in the world. Wintertime minimums of more than 73 degrees C below zero (-100 degrees F) occur almost every year and the mean annual temperature is about -49 degrees C (-56 degrees F). Near-surface borehole temperatures should be near the average annual temperature of -49 degrees C if they are measured at a depth sufficient to be isolated from annual variations, say 100 meters down. This is too cold for most active component instrumentation, such as a standard KS-36000 seismometer. The electronic components just will not function reliably at this extremely low temperature. The borehole temperature should increase at greater depths, thereby raising the possibility that the seismic system could be installed at great depth in a warmer environment. To date, no deep holes have been drilled at the South Pole which could provide data about gradients as a function of depth. However, temperature gradient data is available from a deep hole at the Russian Vostok Station. Barkov and others (1975) have measured the temperature gradient to a depth of 800 meters in the deep borehole at Vostok. A rough average over that depth is about 0.011 degrees C per meter. Although South Pole Station is approximately 250 kilometers south of Vostok, and Vostok is about 10 degrees C colder on the average, they both sit on deep ice. The temperature gradient at Pole should not be significantly different than at Vostok; it should just start at about 10 degrees C higher at the surface. Assuming a similar gradient structure, and starting with a surface temperature fixed at the average annual Pole temperature of -49 degrees C, a hole depth of approximately 2636 meters would be required to reach the minimum operating temperature for the KS-36000 at the South Pole. This is much deeper than is probably necessary to achieve low levels of long-period surface noise, and the cost of constructing a cased borehole this deep at Pole would be prohibitive. In addition, drilling a straight hole in ice is not as easy as it might appear. Admittedly, ice is a fairly homogeneous media which is almost free of lateral variations in density, or cracks and fissures that might tend to deflect a drill from its extended path. However, unique problems appear if one drills a deep hole in ice. There is the ever present danger of freezing the drill in the hole if any part of the drilling process permits liquid water into the hole. This happens frequently in spite of all precautions. As drilling progresses to great depths, the pressure of the overlying ice causes the walls of the hole to collapse if counteracting pressure is not provided. Opposing pressure is normally provided by filling the hole with a hydraulic fluid, since the hydrostatic head provided by the liquid helps to eliminate the collapse of the ice walls. Drilling a hole large enough to accommodate a KS-36000 or similar type of instrument would require a fairly large and sophisticated drill rig. The extreme cold would make an enclosed work space around the drill rig highly desirable, and two or more seasons might be required to complete a hole of over 2000 meter depth. Finally, to achieve a high gain installation, the hole would probably have to be cased with the casing rigidly bonded to the ice, at least in the area in which the instrument is to be installed. This may be difficult to do at these depths, and would probably involve the application of new and unproven techniques. Water would be an ideal bonding agent, but it would be extremely difficult to get the entire casing-ice wall void uniformly filled over an extended depth before the water froze thereby creating voids over significant volumes. The presence of a nonfreezing hydraulic fluid in the hole would further complicate a water-based cementing operation.

2.7 LONG-PERIOD SHALLOW BOREHOLE DESIGN

Constructing a shallower long-period borehole at the South Pole would be much simpler than drilling to the extreme depths just discussed. In the past, drilling on ice sheets has been primarily restricted to core drilling conducted for the purposes of obtaining samples of the ice as a function of depth. These samples are then used to determine the history of various constituents of the atmosphere at the time the ice was deposited. However, the technology required to drill an ordinary hole as opposed to drilling and retrieving an ice core should be a simpler process. For our application, the only specifications for the raw drillhole are depth ($\sim$1000 feet), diameter ($\sim$10 inches), verticality (<3.5 degrees off vertical). These three factors indicate that the drill rig must be larger than those commonly used in shallow core drilling in ice; the rig size might be comparable to that which drilled the Byrd Station drill hole. Ideally, a relatively shallow hole (1000 feet) could be drilled without adding fluid to the hole since pressures involved should not be sufficient to cause rapid wall collapse. The details of drilling the raw hole should be worked out in a later design phase of this project by experts such as the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), who have extensive experience in drilling deep holes in ice, both in Greenland and the Antarctic.

Casing the successfully drilled hole will involve as yet unproven technology because standard techniques such as were used in the SRO program cannot be applied to ice. For SRO boreholes, standard oil industry casing capped with a float shoe were installed in the holes and a self-setting cementing mixture was pumped down the casing, through the float shoe and back up into the void between the casing and the surrounding rock. This technique will not work at -56 degrees F because of the danger of freezing the water-based grouting mixture before the pumping operation is completed. Therefore, another technique for finishing the borehole must be developed.

If possible, it would be advantageous to utilize the unique conditions at pole to assist in constructing a useable borehole. A brief outline of a scheme involving the unique medium is presented here. It should be feasible to construct a borehole in which only the lower portion is rigidly attached to the ice with the upper portion serving only to restrain the ice walls. The hole would be constructed as follows. An open-ended casing is first inserted along the entire depth of the drilled hole. This casing might be plastic if it is found that plastic casing can withstand anticipated ice wall collapse pressures at the maximum hole depth. The use of plastic casing would create a substantial savings in shipping costs due to the weight difference and would also facilitate handling on site. Next, a specially designed (see Figure 1) section of steel casing would be installed in the ice at the bottom of the hole through the open-ended upper casing. This piece of casing would be installed with a thermal insertion tool, which heats the entire length of the steel casing, thereby allowing the entire assembly to melt its way into the ice at the bottom of the hole. Special detents similar to those used to afix the SRO holelock to its insertion tool would hold the steel casing to the thermal insertion tool, while lowering the assembly into the hole and while melting the assembly into the ice. The thermal insertion tool would be heated by electric heating elements powered through a connecting cable from the surface. After the assembly has melted its full length into the bottom, the power to the heaters would be turned-off to allow the water to refreeze, thereby locking the steel casing into the surrounding medium. The thermal insertion tool would then be pulled out of the casing to complete borehole construction.

This procedure for constructing a borehole has a secondary advantage; that is, the process of melting the steel casing into the ice at the bottom of the hole tends to vertically orient the casing parallel to the local gravity vector. The originally drilled hole could, therefore, be off vertical considerably more than the 3.5 degree tolerance for the KS-36000; the instrument would still operate in the cased hole because the final section would be nearly vertical provided the heat installation tool operated long enough for the assembly to melt its way to a vertical position. The only limits on the original raw hole vertically would be that the corner between the upper cased-hole and the lower hole could not be too sharp; one must be able to remove the relatively long heated insertion tool and insert the slightly shorter seismometer.

The rest of the procedure for installing the seismometer follows standard SRO techniques. A standard SRO holelock would be installed with the impact wrench installation tool, the orientation of the holelock would be determined using a gyroscopic tool, and the seismometer would be installed in the steel casing at the bottom of the hole.

After construction is finished, the borehole will slowly tilt due to deformation of the surrounding ice as a result of velocity shear as a function of depth. In order to estimate the useful lifetime of the borehole, the rate of change in the tilt of the casing must be estimated. Data obtained from the Byrd Station borehole by Garfield and Ueda (1975) indicates a change in tilt at a depth of approximately 1000 feet of around 0.03 degrees per year. If this rate of tilt were typical at the South Pole, the seismometer would require leveling about every 3 years. However, the hole itself would be usable for up to 100 years if initially drilled straight at the operating level. Both of these figures are acceptable values for successful operation. More recently, measurements in a relatively shallow borehole (100 feet) for a short-period of time (50 days) at South Pole Station itself suggests that the tilt rates there are even smaller than in the Byrd Station drill hole. Measurements by personnel from UCLA yielded rates of approximately 0.002 degrees per year (B. Smythe, personal communication, 1981). This extremely low rate of tilt may be reasonable as compared to the Byrd Station values because the Byrd ice flow pattern is believed to be severely disturbed by a local perturbation in the subglacial bedrock. In any case, tilt should not be a problem at South Pole Station. If necessary, a hole constructed as discussed herein, could be repaired by simply reinserting the heated insertion tool and remelting the steel casing into a new vertical position.

The site for a borehole sensor system should be carefully selected or all of the advantages gained by installing the instrument in a borehole will be lost due to external interference. The main source of interference at the South Pole is culturally generated seismic noise arising from human activity, such as the station electrical power generators, vehicular traffic, airplane activity, and stray RF pick-up in the instrumentation itself. The only way to reduce the cultural seismic noise is by physically isolating the sensors from the station. This means that the borehole should be distant from the aircraft runway and taxiways, the station itself, and ideally from routes commonly used by vehicles. It would be advisable to perform a site noise survey using portable short-period instruments to assist in selecting the best location for the borehole. Assuming that the data processing and recording will be conducted within the station itself, this means a relatively long data line between the borehole and the station. This long exposed line increases the chances that RF interference will be a serious problem unless adequate precautions are taken to reduce it. However, it should be possible to thoroughly engineer the system to suppress RF interference to acceptable levels.

2.8 SOUTH POLE DATA RECORDING

Now that a method for improving the quality of the seismological data at Pole has been developed, some thought on how to process the data is in order. Currently, the WWSSN data at Pole is recorded on helicorders. Once a day the station operator analyzes the record for event arrival times and transmits this data via high frequency (HF) radio back to the States. During the Antarctic summer (from late October through early February), the analog paper records can be shipped out by air; during the winter, the records must be stored for shipment in late October. Therefore, during approximately 8 months of the year, the only access to South Pole data is through the HF radio messages. For the past several years, the station operators have had limited seismological training. Prior to accepting South Pole duty, the operators have had no seismological experience. They receive about 2-3 weeks of intensive instruction before leaving for the Pole. Although the majority of the operators do a conscientious job, the quality of the radio-reported readings may be questionable at times due to the lack of operator experience. Therefore, an upgraded system for processing Pole data would seem to be in order.

First, the use of analog-recording techniques is rather archaic and hinders efficient use of the data obtained at Pole. Regardless of any other aspects of an upgraded capability, digital data should be available in a format compatible with existing USGS digital systems such as the Global Digital Seismic Network (GDSN), which is composed of the SRO, ASRO, and DWWSSN stations or the proposed Global Telemetered Seismic Network (GTSN). This data could then be integrated into the digital network day tapes on receipt of ASL.

Second, a means for supplementing the judgments of semi-skilled analysts should improve data credibility. Since the seismic data will be digitized prior to tape recording, a microprocessor-based event-detector could be implemented to supplement or replace the station operator as a data analyst. There are now several efficient algorithms for performing automatic event detection, some of which can be easily implemented on microprocessors (see Berger and Sax, 1981 for a review of several of the more well known approaches). Some of these algorithms are capable of making estimates of phase arrival times. One of these microprocessor detectors could be used to process the short-period data in real time and automatically compile a listing of arrival times for subsequent manual HF radio transmission back to the States. Depending on the reliability of the detector algorithm, the station operator might be required to verify the automatically picked results or to compile a completely independent list of arrivals for transmission. An automatic detector would at least provide a check on the analysis by the station operator.

Third, a means of circumventing the 8 month unavailability of the data would be a big improvement in the overall operation. This is not an easy problem to address because of the uniqueness of the geographic location. Continuous satellite telemetry would be the ideal method for making the data available in near-real-time. However, continuous satellite telemetry is impossible from the South Pole because synchronous satellites are not visible from the pole. The next best method would be to utilize a satellite in a polar orbit to relay the data. It would then be available in near-real-time being delayed a maximum of approximately one orbital period. However, many of the polar satellites have limited data rate capabilities since the data must be stored on board the satellite from the time it passes over the source ground station until it retransmits the data to the receiving station. An SRO type seismograph station generates data at the rate of approximately 48 bits per second. In contrast, the NOAA ARGOS satellite-based data collection and location system falls far short of the required capacity; it is capable of handling a maximum of 256 bits per second per platform per satellite pass. Each platform can handle up to 32 sensors making a total of only 8192 bits of data per pass of the satellite. The last resort is to utilize more than one platform to increase the overall data rate. Since the satellite period is approximately 100 minutes, 1125 individual platforms would be required to achieve a real time rate of 48 bits per second; this number of platforms is clearly out of the question. Currently, it appears that none of the polar satellites could support the data rates required by a three component long- and short-period seismic station. Another alternative is to transmit only short-period event waveforms as detected by the event detector via a polar satellite relay. This would drastically reduce the overall data rate, but the rate would still be too high for polar satellite relay.

Therefore, satellite telemetry of seismic waveform data is not feasible from South Pole Station. Any improvements in the USGS seismic capabilities there will remain limited by the long delay in obtaining data from that geographic location.

2.9 SUMMARY OF SOUTH POLE UPGRADE

In summary, it should be possible to make significant improvements in the quality of both the long- and short-period seismological data from South Pole Station. This improvement can be accomplished by installing a modern borehole seismometer system in a borehole approximately 1000 feet deep at a site sufficiently removed from the station complex. A KS-36000, which has been specially designed for very cold temperatures is recommended as the sensor system for the upgrade. The probability that the KS-36000 can be modified to perform at -56 degrees F is quite high. The proposed construction procedure for the borehole involves unproven technology, but it appears to be quite feasible. It is recommended that the upgrade provide the capability to record the data digitally on magnetic tape for later integration into the USGS day tape libraries. A software event detector should be part of the station data processor to supplement or eliminate operator analysis of the data on site. A satisfactory solution to eliminating the potential 8 month delay in data availability from the South Pole has not been found. However, if a new seismometer site is constructed at about 80 degrees south, the use of a synchronous satellite becomes possible.

3. HARD ROCK INSTALLATION

3.1 GENERAL

Currently, reliable borehole technology is based on boreholes in relatively competent materials, ideally bedrock, in order to gain a high attenuation rate of surface noise with depth. In the Antarctic, rock exposures are limited to locations in the mountain ranges and along the coastline. Considerations of accessibility for installation and maintenance narrow the possible choices to locations at or near existing permanent stations. McMurdo Station is the largest U.S. station and as a result it has the best transportation system to and from other Antarctic stations, as well as to remote areas in the immediate vicinity. It is situated on Ross Island near the Antarctic Coast, between 77 and 78 degrees south and 165 and 170 degrees east. Rock is exposed on Ross Island along narrow strips of its coastline. Ross Island itself is not an ideal hard rock site for a high grade seismological installation for two reasons. First, the island is of volcanic origin. Drilling to depths of 350 meters in the McMurdo station area reveals several layers of lava flows containing poorly consolidated material (AJUS, 1974). Second, the nearness of the sea introduces extraneous seismic noise from ice and water disturbances (Eiby, 1979). Scott Base WWSSN winter magnifications of 25K (12.5K in summer) for the short-period and 1.5K (0.75K in summer) for the long-period are indicative of the noise levels on the island. However, a site sufficiently removed from the coastline with competent rock should be found in the Dry Valleys.

3.2 THE DRY VALLEYS

The Dry Valleys are a series of relatively snow- and ice-free valleys located approximately 100 kilometers due west of Ross Island in the Trans-Antarctic Mountain Range. Scientific studies of this area have been numerous because of the extensive exposure of earth surface. The results of these studies indicate that the Dry Valleys area should be considered as a third alternative for upgrading Antarctic seismological capabilities.

The area of exposed surface has a considerable extent; some of it lies as much as 60 miles inland from the coast. This separation from the coast should provide sufficient isolation for high-gain long-period operation and it should also be enough distance to provide quite good short-period data as well. The chief concern would be the short-period noise. A site survey to determine the level of the short-period background noise level at prospective sites located inland as much as possible would assist in determining the suitability of the western Dry Valleys as a high grade seismological site. Admittedly, the survey could only be conducted during the summer months, a time period during which the sea noise would be at its minimum. However, a sufficiently long noise survey should contain time periods during which the neighboring sea experienced stormy conditions. Extension of the noise survey to evaluating noise decay along a line extending from the coast inland to the limits of the western edge of the Dry Valleys would provide attentuation data for evaluating the rate of decay as one moves inland. Whatever its scope, a site noise survey should precede a Dry Valleys installation to assist in selecting a quiet site.

3.3 DRY VALLEY TEMPERATURE ENVIRONMENT

Borehole temperatures in the Dry Valleys should be considerably warmer than at Pole station because the mean annual temperature is much higher. Measurements of heat flow in the Dry Valleys boreholes by Decker (1977) indicate that borehole temperatures near the surface should be expected to be between -15 and -20 degrees C (+5 to -5 degrees F) with approximately linear warming to about -9 degrees C (+16 degrees F) at a depth of 200 meters. This is a much improved temperature environment for operating a borehole instrument as compared with that found at the

South Pole. It is well within the -20 to +160 degree C specified operating range of the KS-36000 seismometer. The temperature at depth should be quite stable and free of seasonal fluctuations just as it is elsewhere in the world. Thermal gradients in the Dry Valleys boreholes are approximately twice those measured at ANMO (20 - 40 degrees C/km for the Dry Valleys from Decker, 1977, as compared with 10 - 20 degrees C/km at ANMO from Reiter and others, 1975). Air convection in the borehole due to temperature gradients of this magnitude should not be a problem because they should be easily controlled with currently developed technology. Near-surface gradients could be troublesome if adequate precautions are not taken. During the summer, surface temperatures rise above the mean-annual-temperature and during the winter, they dip below the average, thereby creating widely varying gradients at the very top of the borehole. Seasonal variations in temperature have been known to cause long-period noise in boreholes as documented in Alaskan studies by Teledyne-Geotech (1972). However, adding volume-filling material at the top of the borehole, and providing a well designed insulation system around the wellhead area should isolate the borehole system from seasonal temperature variations.

3.4 CONSTRUCTING A DRY VALLEY BOREHOLE

The technology required for drilling a borehole in the Dry Valleys should not be significantly different from that used to drill the SRO boreholes. Core drilling has already been conducted at several sites in the Dry Valleys as part of the "Dry Valleys Drilling Project" conducted during the early 1970's. (See McGinnis, 1975, for a brief summary of some of that activity.) Probably the most difficult problem to solve in order to drill in the Dry Valleys is how to get the drilling rig to the site. At least part, if not all, of the transport from the ship terminous dock at McMurdo is by helicoptor. There is the possibility of hauling the equipment over the sea ice in early summer from McMurdo to the vicinity of Marble Point to the west. This was done for the Dry Valleys Project, thereby shortening the distance required for helicoptor transport. The use of helicoptors requires that the drilling rig be disassembled into pieces small enough for helicoptor transport. Another consideration would be the chance of the drilling mud freezing up. This problem can be defeated through the use of diesel fuel as the liquid medium for the drilling mud, or by choosing a rotary percussion drilling method. Otherwise, there should not be extreme difficulties involved in drilling a hole in the Dry Valleys.

3.5 UNIQUE PROBLEMS OF A DRY VALLEY INSTALLATION

An installation in the Dry Valleys introduces several technical problems. It would be an unmanned site. Maintenance would be impossible during approximately 8 months out of the year due to weather conditions and darkness. Therefore, the equipment must be highly reliable. Power is not available on site so a reliable source of power must be developed. A method of handling the data must be provided to compensate for the 8 months of unmanned operational status. Possible solutions for handling the data involve large volume data storage and telemetry.

3.6 POWER

Several methods should be initially considered as candidates for providing power for a Dry Valleys installation. These include solar, nuclear isotope, wind, thermoelectric, and simple batteries. Solar can be ruled out at the start because of the long period of time during which the sun is below the horizon in the Antarctic winter. In order to select the best source from the remaining possibilities, the power requirements of the equipment must be considered. The total power consumption of the equipment will depend in part on the particular telemetry configuration which may be selected and the final design of all of the on-site hardware. However, a good estimate of the operating power requirements is somewhere between 100 and 200 watts. Nuclear isotope power supplies tend to be very expensive sources of power in terms of cost per watt. An isotope power source capable of supplying power at these levels is not practical. There is undoubtedly sufficient wind in the Dry Valleys to generate enough power for the equipment. However, icing of a wind generator would be a problem during the Antarctic night. In addition, most wind systems are not designed to withstand anticipated wind speeds, which probably occur at times. (Winds well over 100 miles an hour occur regularly in coastal regions of the Antarctic.) Supplying the station for 8 or 9 months from batteries would require a formidably large battery pack. Fortunately, thermoelectric power sources are capable of quite large power production over extended periods of time. Sandia Laboratories has recently conducted an extensive study of potential power sources for their unmanned seismological station design. They considered all known candidates for providing power levels comparable to those needed for this application, and have selected a propane powered thermoelectric power generator for their application (Don Bauder, personal communication, 1981).

3.7 DATA RECORDING

There are several possible telemetry configurations which could be utilized to record data, depending on how the data is to be utilized. These include no telemetry at all, local, VHF telemetry to McMurdo Station, followed by conventional digital magnetic tape recording, or real time telemetry to ASL from either the site or McMurdo Station via synchronous satellite. The first alternative of no telemetry at all would require a very large volume data storage device on site because of the unmanned status. At least an 8 month storage capacity would be required because the site would be inaccessible for at least that long at a time during the Antarctic winter. Since such a storage device would be prohibitively expensive and the data would not be available for analysis, this is not considered to be a viable alternative.

VHF telemetry to McMurdo followed by operator-assisted magnetic tape recording would provide a relatively low cost data recording system. The viability of this link would be subject to selecting a borehole site in the Dry Valleys with a line-of-sight path to a receiver at McMurdo or the installation of a repeater site on a high point along the path. McMurdo Station is visible from certain sections of the Dry Valleys, but not from all areas by any means. A study of the USGS topographic maps of the Dry Valleys region indicates that careful site selection would be required if a line-of-site VHF telemetry system is selected, thereby severely limiting the possible choices. Therefore, the repeater option would probably be necessary in order to allow freedom for selection of a more optimum site for the sensors.

A drawback of this limited data recording scheme would be that the data would not be available for stateside analysis for about 8 months of the year since no surface or air transport is possible from McMurdo during the winter months. It would be desirable to have telemetry back to ASL during the Antarctic winter so that Antarctic data could be analyzed and incorporated into the day tapes, which are made about 60 days behind real time.

Satellite telemetry is feasible via synchronous satellite from that part of Antarctica. During the 1972-1973 time frame, Stanford University conducted field tests of an Unmanned Geophysical Observatory located on Arrival Heights above McMurdo Station. One aspect of this system was continuous data telemetry back to the continental United States via synchronous satellite. The system utilized an Intelsat channel at 5000 BPS with a power of 20 watts into an 8 foot dish with a 3 degree elevation angle (M. J. Sites, personal communication, 1981). Despite the fact that a 3 degree elevation angle is the normal extreme limit for accessing the satellite, and that the path was over water, system performance was excellent. The results of this experiment provide proof that a dependable synchronous satellite telemetry link can be established from that site. During the past few years quite compact ground terminals for use in transmitting digital data via synchronous satellite have become available. At least one of these (the Motorola MODET/3) appears to be quite capable of performing this function at reasonable cost. The antenna for this system would probably need redesigning to enable it to withstand the severe icing and wind loads expected at that site, but this modification could be easily implemented.

Two configurations of satellite telemetry should be assessed. The terminal could be located at the borehole site in the Dry Valleys or at McMurdo Station in conjunction with a VHF link as discussed above. The choice between these two possibilities must be based on power budgets, reliability versus re-repair tradeoffs, and timing considerations. If a synchronous satellite is used and a two-way telemetry link is available, timing could be conducted on the telemetry and the satellite telemetry equipment could be located at the borehole site in the Dry Valleys. This option would be the simplest and most straightforward to implement from the standpoint of field operation. It would eliminate VHF telemetry to McMurdo and the maintenance of a facility at that station. The operation would be completely self-contained requiring only a once-a-year maintenance and refueling visit. Reliability would be a prime consideration because the site would be completely isolated for over 8 months out of the year.

The satellite to Dry Valleys site, half of a two-way link, may not be feasible because the satellite transmit power is fixed; therefore, increasing antenna size is the only means of beefing up the down link at low elevation angles. Antenna size might become prohibitive. If so it still may be possible to locate the satellite telemetry system at the Dry Valleys site by allowing the field equipment to free-cycle independent of real time. A local, unsynchronized clock would govern the A-D conversion rate and the telemetry transmission rate in the field. Real time could be associated with the seismic data after receipt at the receiving station. The power requirements for a ground-based satellite terminal such as the MODET/3 are rather high (approximately 1200 watts) for a thermoelectric power source. This would be a problem which would have to be addressed in a final design. Possibly this unit's power requirements could be reduced by redesign as has been done for the Sandia unmanned system (the low-power versions cost about twice as much) or the standard unit could be located at McMurdo where sufficient power is readily available as proposed below.

Maintenance requirements may dictate that the satellite telemetry be placed at McMurdo where it could be serviced as needed. If a reliability comparison analysis of the satellite system versus the VHF telemetry link indicates higher reliability with this configuration, then it would be preferable. This is also the lowest field-site power-budget configuration, and it would facilitate Antarctic timing of the seismic data (the VHF telemetry link is two-way, thereby introducing a manually set and calibrated clock located at McMurdo Station). This configuration also allows the inclusion of manned magnetic tape recording, if desired. Overall, a minimal Dry Valleys equipment design consisting of the borehole seismometer, A-D converter synchronized over telemetry, digital data transfer via a two-way repeater linked VHF telemetry system to McMurdo Station, at which is located both manual digital tape recording of the data coupled with real time synchronous satellite telemetry of the data to ASL, is the ideal Dry Valleys seismic system configuration.

4. INTEGRATION INTO THE GLOBAL TELEMETERED SEISMIC NETWORK

Since the recommendations of this study itilize technology very similar to that being proposed for the USGS-sponsored Global Telemetered Seismic Network (GTSN) project (borehole seismometer, digital, real-time telemetry, etc.), it would be desirable from the initial design and subsequent maintenance standpoints to utilize as much common equipment as possible. In fact, the GTSN project is at such a stage that an Antarctic upgrade could be easily integrated into it for the initial planning. This would reduce total system costs by designing a common system for both the GTSN application and the Antarctic upgrade. The Dry Valleys station would require some added design considerations due to the wind and cold environment, but the uniqueness would be minimal. A full-time power supply would be the only additional major component over and above those required for the rest of the GTSN Stations (assuming the final GTSN design utilizes ground satellite terminals located at the seismic station installation).

5. COST ESTIMATES AND IMPLEMENTATION SCHEDULE

The cost of implementing an upgrade of the USGS Antarctic seismological capability will be relatively high as compared to those encountered in the SRO program during the mid-1970's. Inflation has drastically boosted the cost of all equipment and services. In addition, the Antarctic environment necessitates higher cost, and more rigorous design. The one-of-a-kind aspect of this upgrade means that the engineering costs cannot be distributed over more systems. If this proposed project could be integrated into the GTSN project, at least part of the design costs could be spread over several systems.

Block diagrams of the three proposed upgrade options are shown in Figures 2, 3, and 4, and Tables 1, 2, and 3 contain itemized estimates for the three options (South Pole, Dry Valleys, and Dry Valleys plus McMurdo). The chief costs at the South Pole (total estimated cost 705K) are tied up in the specially designed KS-36000 borehole seismometer and the borehole itself. This system should provide high quality digitally recording short- and long-period data, but the raw data would not be accesible during extended portions of the year. The Dry Valleys option (total estimated cost 751-811K) provides the most appealing configuration for upgrading USGS Antarctic seismology. It is a compact, unmanned concept which should provide high quality short- and long-period data in real time. The chief drawbacks are the danger of system failure during the inaccessible winter time period and the lack of magnetic tape recording backup. The third option (total estimated cost 936K) provides magnetic tape recording backup to the real time telemetry channel for the Dry Valleys installation.

Anticipated subsequent maintenance costs should be approximately the same as SRO stations with the exception that a yearly resupply of propane fuel will be required for the thermoelectric power generators.

The costs contained in Tables 1, 2, and 3 do not contain any estimates of shipping costs for the equipment or personnel to and from the Antarctic.

All shipping for the U.S. Antarctic Research Program is funded internally through the National Science Foundation. As a rule of thumb, there are a fixed number of operating hours for the ships and aircraft involved in the Antarctic program as determined by the number of vehicles on hand, restricted fuel allotments due to budget requirements, down time for maintenance, etc. Scientific projects for a given year are evaluated and assigned a priority rating which is then used to allocate the fixed transportation cost to the individual project. There is the possibility of not receiving any transportation allotment at all if higher priorities arise.

Implementing any or all of these recommendations would require an extended period of time to carry out since all field activities must be scheduled around the short (approximately 4 month) window of the Antarctic summer. Assuming a prompt start for the project, a possible scenario might schedule site surveys for the summer of 1982-83, followed by construction of the boreholes during the 1983-84 summer, with final station installation being completed the summer of 1984-85. This could allow two years to plan, procure, and ship all essential items for borehole construction and three years to design and fabricate the remaining items for the systems as well as implement any required modifications to the seismometer.

6. RECOMMENDATIONS

The author recommends that the unmanned Dry Valleys option be the first option to be implemented because it is the simplest system which can provide real time telemetry. Reliability would be of primary consideration to this option because if it is unmanned, but with good engineering, the system should perform satisfactorily. Admittedly, the

Dry Valleys are not as centrally located as is the South Pole, but they are not that much further from the rest of the world than is the Pole (see Figure 5 for a comparison of the relative locations of the two proposed sites). If the South Pole itself is believed to have an advantage as far as a seismological site is concerned, it is recommended that both the Dry Valleys option and the South Pole options be implemented; the Dry Valleys would provide real time primary information, the delayed Pole data could provide better resolution of certain interesting events at a later date. The third option (VHF telemetry to McMurdo) would be implemented in place of the Dry Valleys option if a reliability analysis of the Dry Valleys configuration indicates problems or if magnetic tape-recorded backup is desired, or if the Dry Valleys only option power budget becomes unmanageable.

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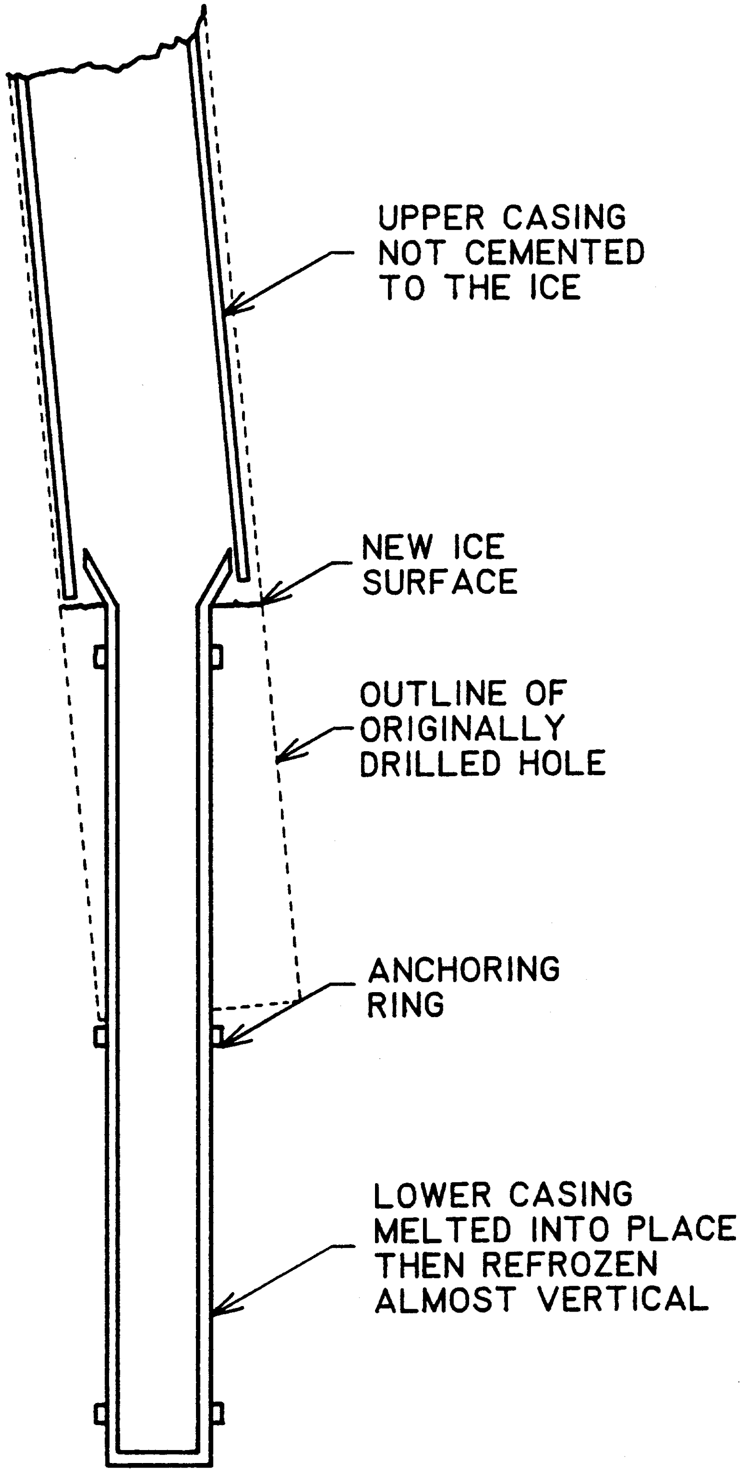

Figure 1. Illustration of lower portion of specially designed borehole for use at South Pole Station.

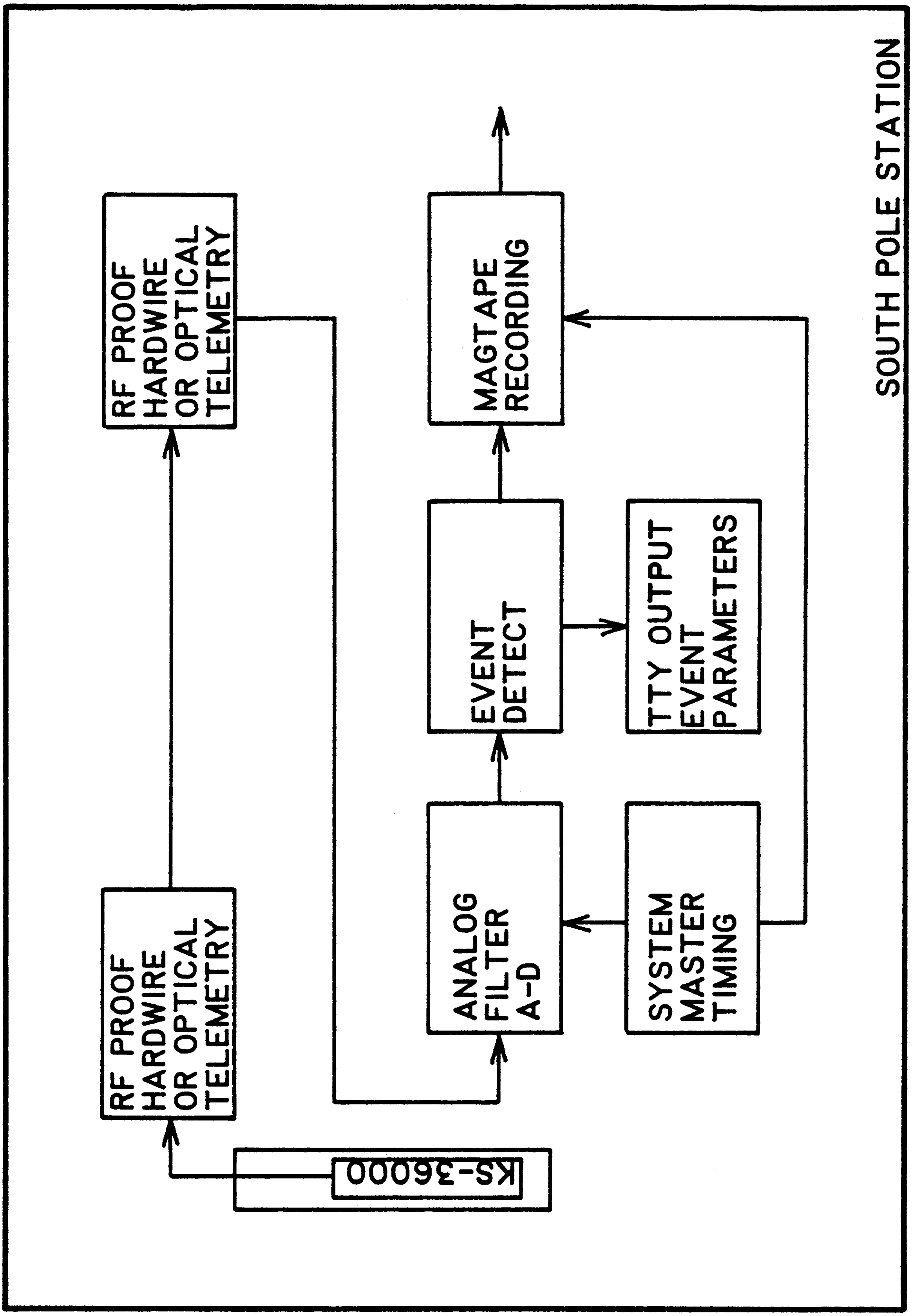

Figure 2. Block diagram of the upgraded seismological station proposed for installation at South Pole Station utilizing the ice borehole depicted in Figure 1.

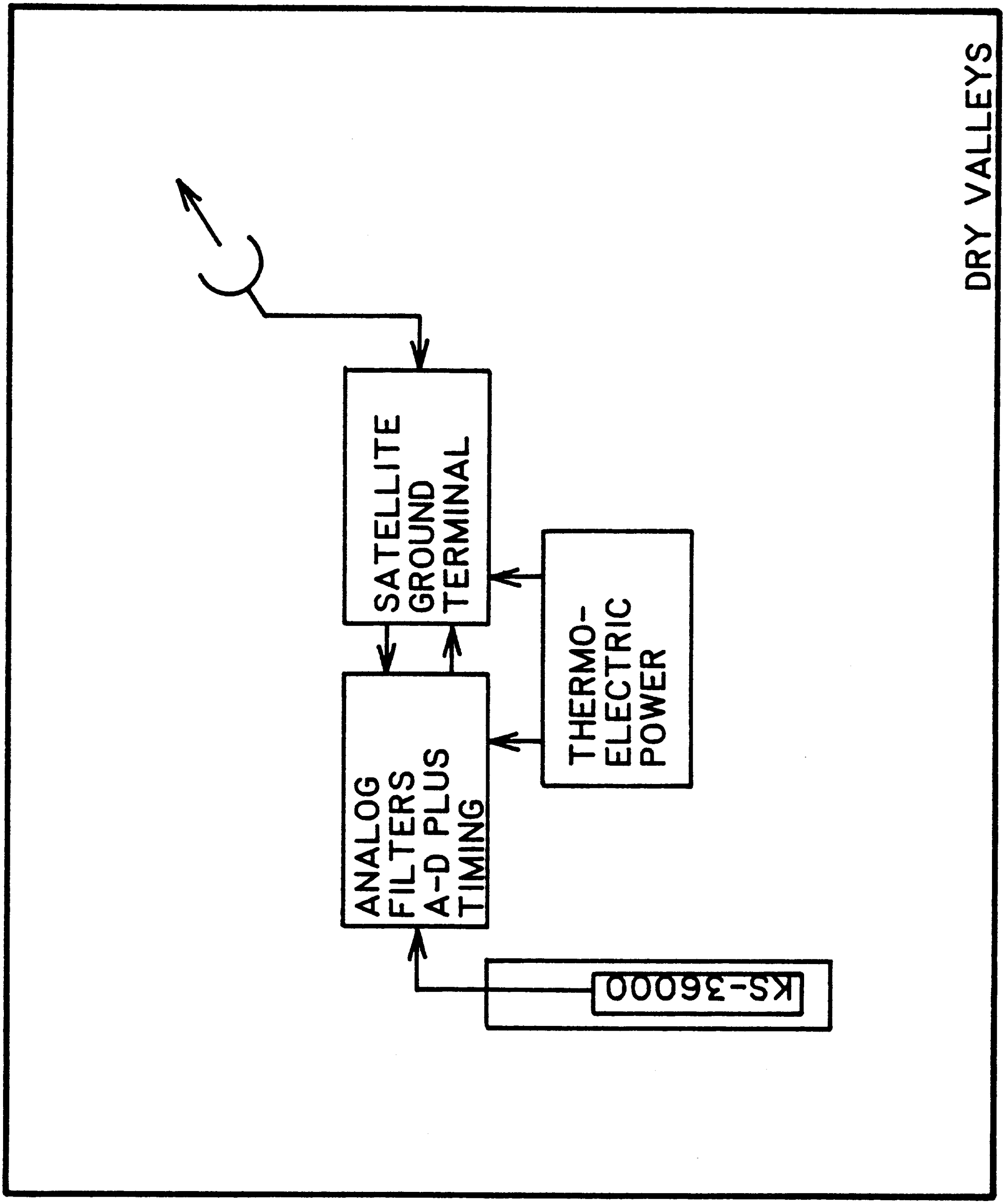

Figure 3. Block diagram of the unmanned seismological station proposed for installation somewhere in the Dry Valleys of Antarctica approximately 100 kilometers west of McMurdo Station.

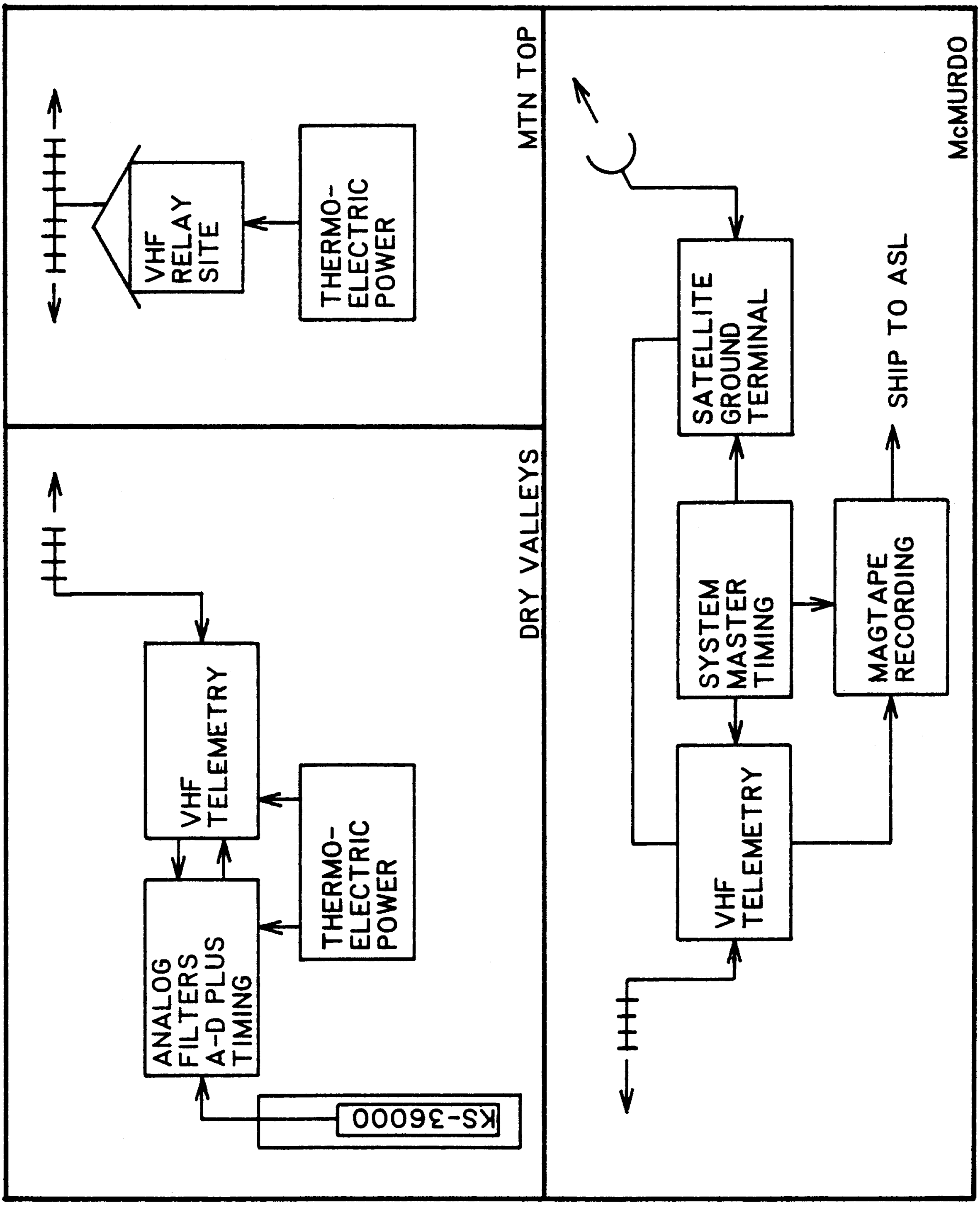

Figure 4. Block diagram of alternate Dry Valley seismological station which provides backup manned magnetic tape recording at McMurdo Station.

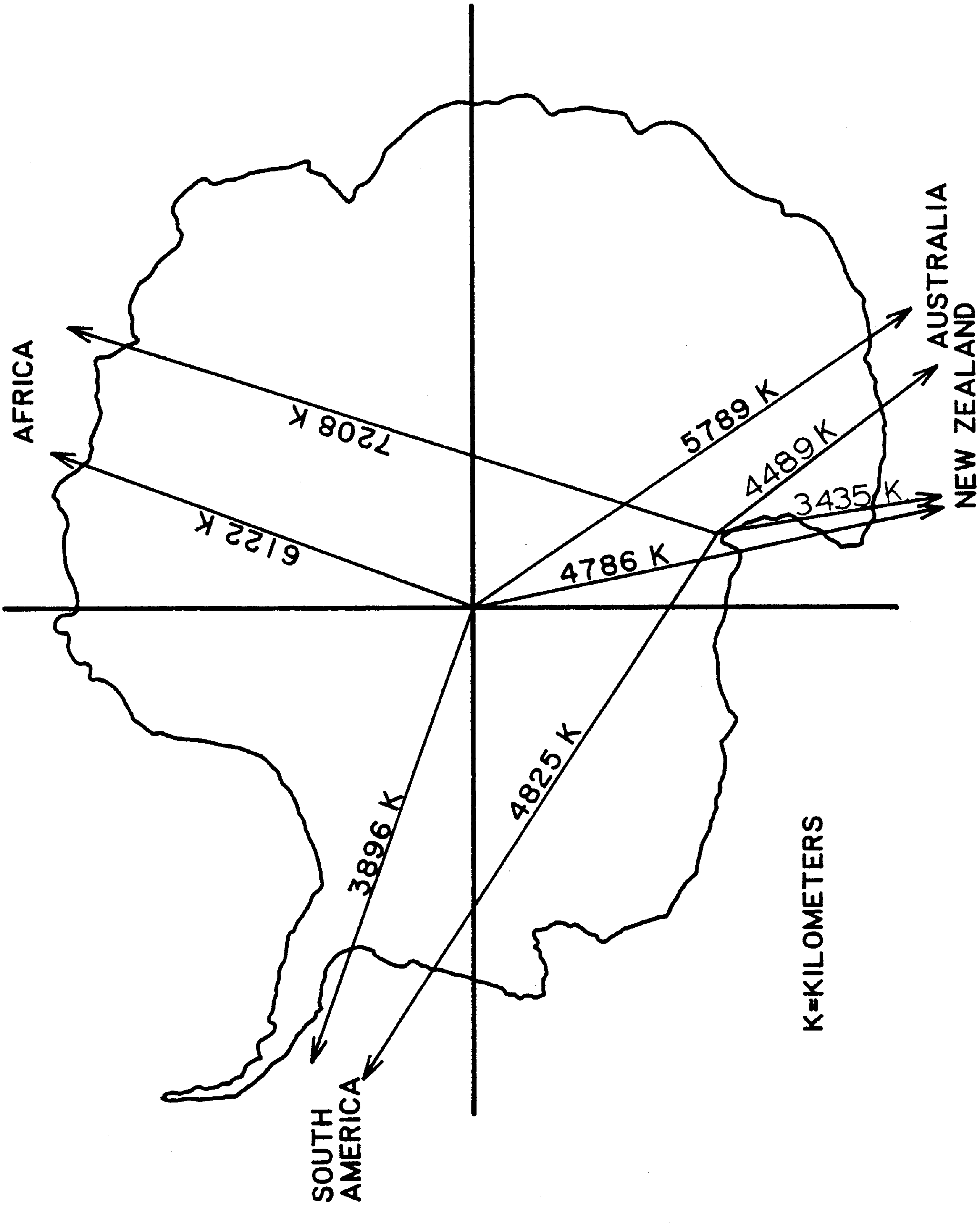

Figure 5. Azimuths and distances to large adjacent landmasses from two proposed upgrade locations (South Pole Station, and the Dry Valleys).

TABLE 1 -- ESTIMATED COSTS OF THE SOUTH POLE STATION OPTION

Site Survey	10K
Remote Site	
1. Cold Regions KS-36000	150K
2. RF proof 1 mile analog telemetry	10K
3. Borehole	300K
4. Packaging	5K
South Pole Station	
1. Digital Magnetic Tape Recording System	90K
2. RF Proof Telemetry	10K
System Integration, Engineering, Assembly, and Test	100K
Field Deployment	40K
Total	705K

NOTE: This estimate assumes that space for housing the bulk of the equipment will be available within the existing South Pole Station complex.

TABLE 2 -- ESTIMATED COSTS OF THE DRY VALLEY SATELLITE TELEMETRY OPTION

Site Survey (seismic plus satellite)		25K
Remote Dry Valleys Site		
	1. KS-36000	90K
	2. A-D converter plus control	26K
	3. Thermoelectric Power	35K
	4. Packaging (building, etc)	25K
	5. Borehole	300K
	6. Ground Satellite Terminal	60K-120K
System Integration, Engineering, Assembly, and Test		150K
Field Deployment		
Total		751K-811K

TABLE 3 -- ESTIMATED COSTS DRY VALLEY TO McMURDO VIA
UHF PLUS SATELLITE TELEMETRY OPTION

Site Survey (seismic plus satellite)	25K
Remote Dry Valleys Site	
1. KS-36000	90K
2. A-D converter plus control	26K
3. VHF Telemetry	15K
4. Thermoelectric Power	35K
5. Packaging (building, etc)	35K
6. Borehole	300K
VHF Repeater	
1. VHF Telemetry	15K
2. Thermoelectric Power	35K
3. Packaging	10K
McMurdo	
1. VHF Telemetry	15K
2. Digital Magnetic Tape Recording System	60K
3. Ground Satellite Terminal	60K
4. Packaging	25K
System Integration, Engineering, Assembly, and Test	150K
Field Deployment	40K
Total	936K

NOTE: This estimate assumes that space for housing the bulk of the equipment will be available within the existing McMurdo Station complex.