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A ten-element array of short period seismometers and a broadband instrument will be installed in early 1995 at Blue Mountains Observatory (BMO) in northeastern Oregon. BMO operated as a VELA array from 1962 to 1975. It is being reactivated to provide a high-quality data base on regional crustal phase propagation through varying geologic provinces. In particular, BMO data will be used to identify crustal phases useful in determination of event focal depth. Numerous crustal events occur annually at regional distances around BMO, and the depths of many of these events are well-constrained by virtue of occurring within regional telemetered networks. We will use BMO data in assessing how well a small-aperture array performs in discriminating blasts from earthquakes on the basis of focal depth determined from regional phases. This document provides an overview of BMO and its instrumentation, including means of access of the digital data by interested users.

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A REGIONAL CRUSTAL PHASE OBSERVATORY

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14 February 1995

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INTRODUCTION

Focal depth determination of seismic events recorded at regional distances is potentially an important means of discriminating between small explosions and earthquakes. In the United States, relatively little attention has been paid to depth determination using crustal phases, since most U. S. earthquakes occur within dense station networks and the depth is easily computed along with the epicenter and origin time from observations of times of first arrivals. In the sparse network scenarios that are likely to be applicable in global monitoring of a comprehensive nuclear test ban, however, station density is inadequate for accurate depth determination from times of first arrivals. A number of techniques exist for determining depth from other seismic information, for example P_{nl} waveforms or surface wave radiation patterns. Unfortunately, most such methods cannot be employed unless an event has a magnitude of at least 3.5 to 4 because of global signal-to-noise characteristics at seismic wave frequencies greater than 0.05 Hz, and a lack of sufficiently detailed crustal models. Identification of different crustal phases whose time differences at a given station may be functions of focal depth is possible down to fairly small magnitudes, of the order of 2 to 2.5. Methods of routine focal depth determination based on such identifications would seem to offer the wide applicability. Crustal phases can often be difficult to identify from records of a single station, however. Moreover, the maximum accuracy of depth determination possible using crustal phases is not known, nor is the frequency with which any given station can make such determinations.

The problems inherent in identifying crustal phases at a single station can be diminished if that station is an array which includes one or more 3-component elements. With such data it is possible to determine slowness of each observed phase, as well as wave polarizations and angles of incidence. To test potential accuracy of regional phase focal depth determinations and applicability of the methodology to propagation paths through mixed or unknown structure, it would be desirable to locate an array in a region meeting the following criteria: (1) as many geologic provinces as possible located at regional distances; (2) known gross features of regional velocity structure; (3) widespread crustal seismicity with a good range of focal depths; and (4) well-determined hypocenters due to dense regional seismographic coverage. The northwestern United States meets these criteria. Figure 1a shows located seismicity at the magnitude 2.5 level

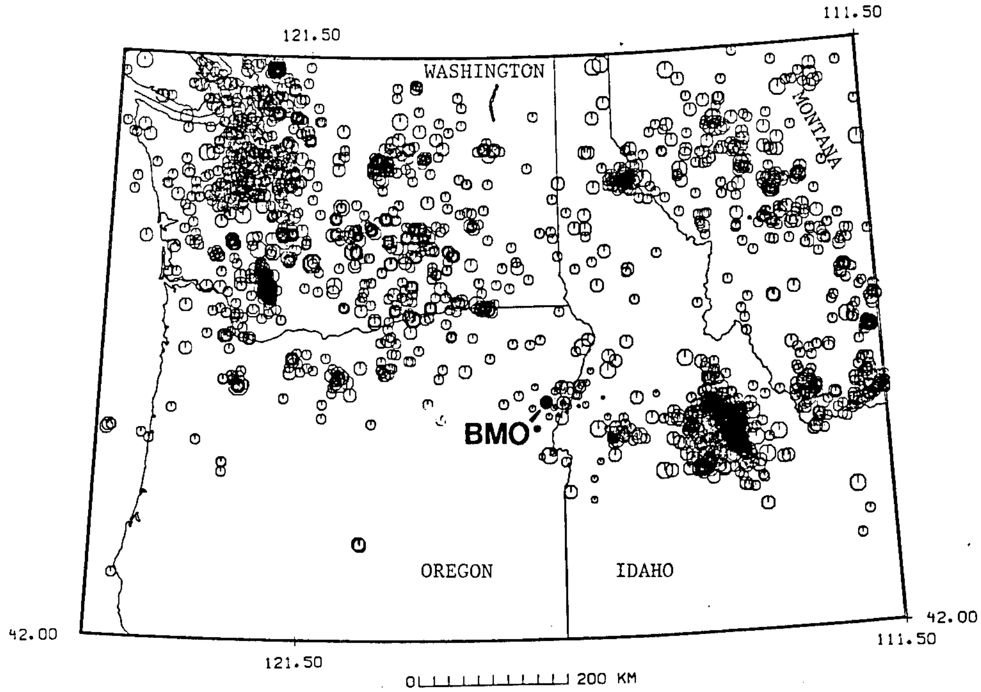


FIGURE 1a. Regional seismicity, magnitude 2.5+.

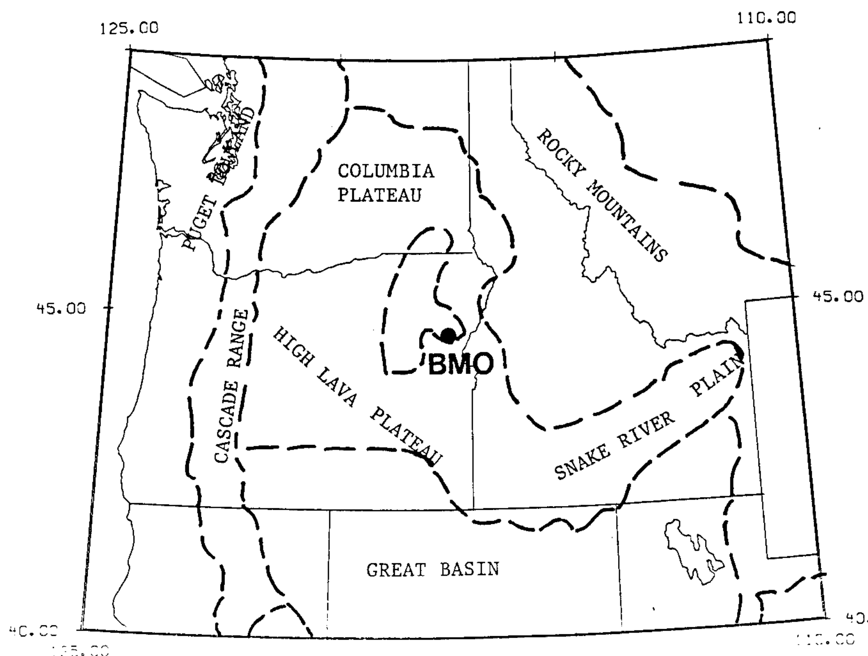


FIGURE 1b. Geological provinces. BMO is in the Blue Mountains Uplift.

from catalogs maintained by the University of Washington and Boise State University, while Figure 1b shows the geologic provinces recognized in the northwest. Figure 2 shows the present configuration of telemetered networks of seismograph stations operated by the University of Washington and Boise State. Earthquakes and blasts occur at depths of 0 to greater than 80 km in the Puget Sound Basin and between 0 and about 15 km throughout most of the rest of the northwest. It would seem that the northwest is one of the best places in the world for development of methodology for using regional phases in depth determination because of the very large number and wide geographic distribution of "calibration" events with well-determined focal depths.

In 1962, the United States Air Force established 5 small arrays in the U. S. to test array design. One of these was Blue Mountains Observatory (BMO) located near Baker in northeastern Oregon. Although operation of the BMO array was terminated in 1975, from the point of view of the four criteria listed in the preceding paragraph BMO is located in an excellent place to test depth discrimination techniques based on regional crustal phases. As part of a regional seismicity study, Boise State University reinstalled a single element at BMO in 1991. It remains a very quiet site, and crustal phases are regularly observed. Figure 3 shows crustal phases recorded at BMO for several recent events at distances of 150 to 250 km. DEPSCOR funding through the Air Force Office for Scientific Research was obtained in late 1993 for installation of a small array of short-period vertical elements, with a broadband 3-component seismograph located at one element. We have exceeded the original design specifications of an eight-element array with 16-bit data acquisition; we will install a ten-element array with 24-bit data acquisition. Such instrumentation is adequate for a research observatory focused on recording of regional phases at various distance ranges. Experience gained with such an observatory may prove important in routine blast/earthquake discrimination monitoring and in selecting station sites and instrumentation for such monitoring.

Equipment for BMO has been obtained or is on order and will be installed in the spring and summer of 1995. The remainder of this report is a description of BMO, its equipment, and the data flow procedures we are establishing. The last section of this report discusses the problems encountered in obtaining and installing the equipment.

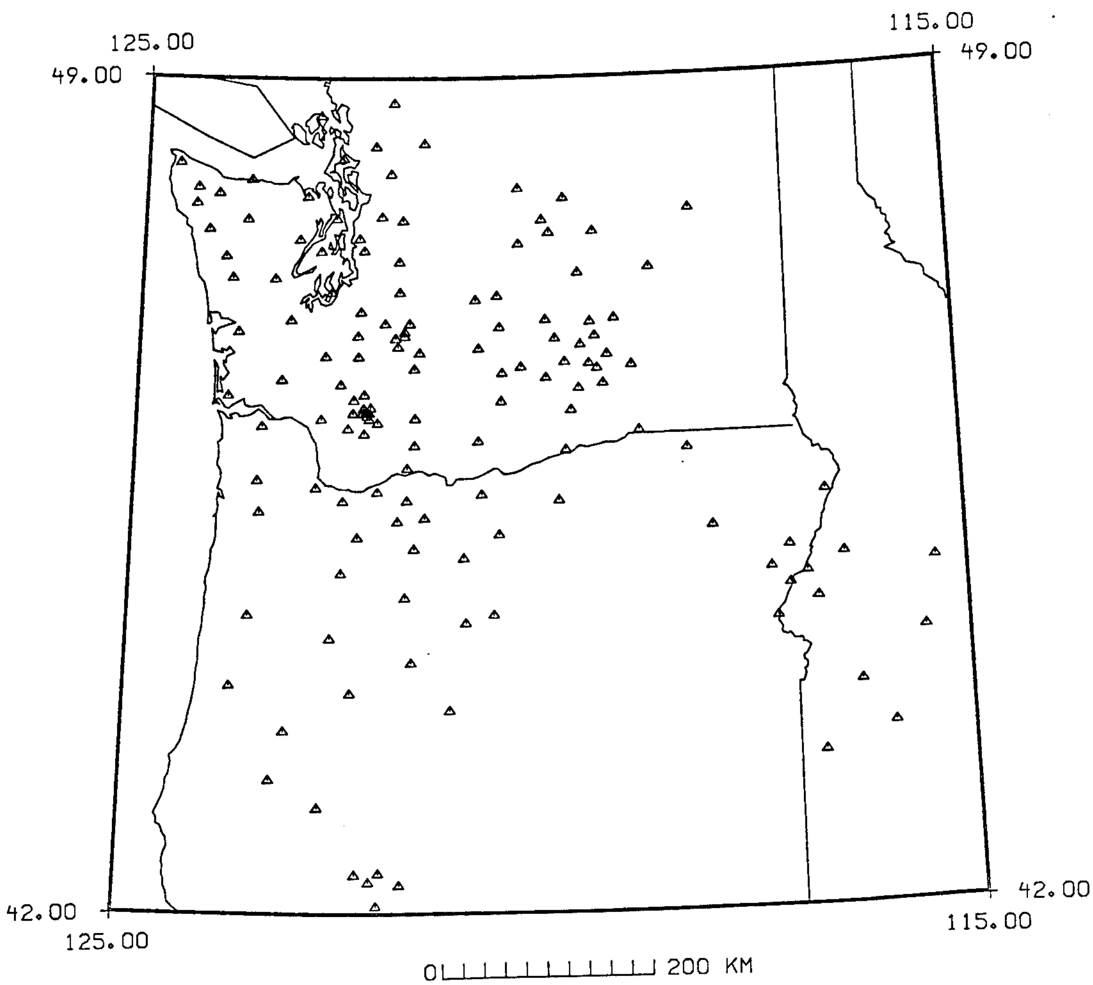


FIGURE 2. Regional telemetered seismograph stations operated by the University of Washington and Boise State University. The station distribution allows good resolution of focal depth for many events.

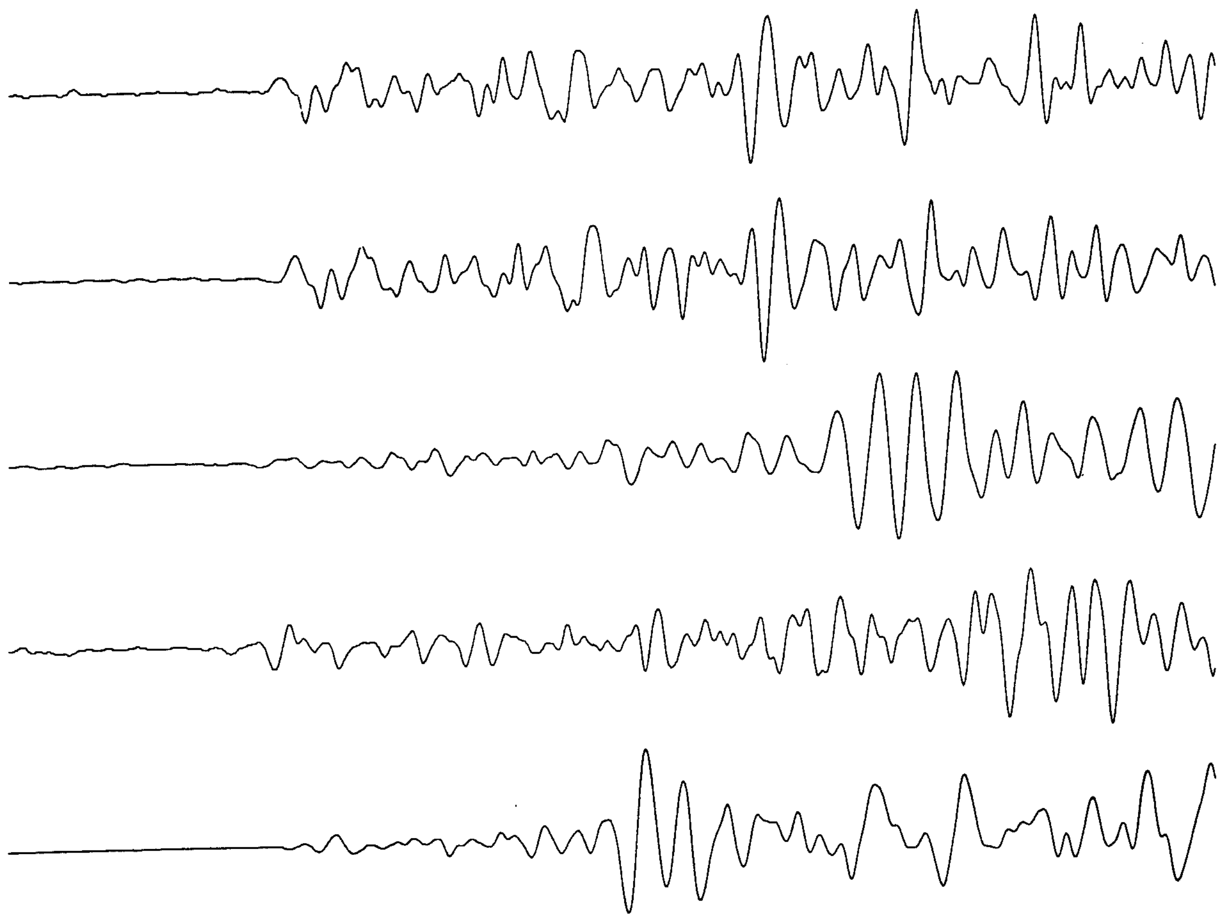


FIGURE 3. BMO short-period vertical seismograms (element Z3) for 5 recent regional earthquakes. Magnitudes are 2.8 to 2.9 for the first four events and 4.8 for the fifth. Epicentral distances are 150 to 250 km. Seismograms are 10 s in length and are filtered with a 3-pole Butterworth filter with corners at 1 and 5 Hz. Multiple *P* phases are observed at BMO for nearly all regional events.

BLUE MOUNTAINS OBSERVATORY

Blue Mountains Observatory is located near Sparta, Oregon. The geologic foundation is albite granite, the surface exposure of a small laccolith (Seymour, 1965). The average climate is cold and semi-arid, with average annual temperature extremes near -5 and 105 degrees Fahrenheit. The immediate area of the BMO array is characterized by low hills. Vegetation is largely confined to sagebrush and cheat grass, although some trees are found in sheltered ravines and along the courses of small creeks. The area of the array is used primarily for cattle grazing. There are no permanent habitations within at least 2 km from any element of the original array, and no paved roads within at least 5 km. A network of unimproved and 4-wheel drive roads provides access to array elements.

The original BMO array was an equilateral triangle of 10 short-period vertical elements at 1.0 km spacing (Figure 4). Short-period horizontals were operated at element Z3, along with intermediate-period, broadband, and long-period 3-component seismographs. Each seismometer was located in its own vault. The vaults at Z3 were regularly spaced in a quadrilateral with 50 ft spacing between seismometers. Each vault was excavated to bedrock and a concrete pad poured onto the bedrock. Following the closing of the array in 1975, all seismometers were removed and the vault access pits were backfilled and graded to contour. We have located several of the original vaults using a handheld Global Positioning Satellite (GPS) receiver and/or a magnetometer, and we opened 3 of the 12 vaults at Z3 in 1990 and 1991.

Followill and Harris (1983) proposed an array geometry based on concentric rings spaced at distances R related in a log-periodic manner:

$$R = R_{min} \cdot a^n, n = 0, 1, 2, ...$$

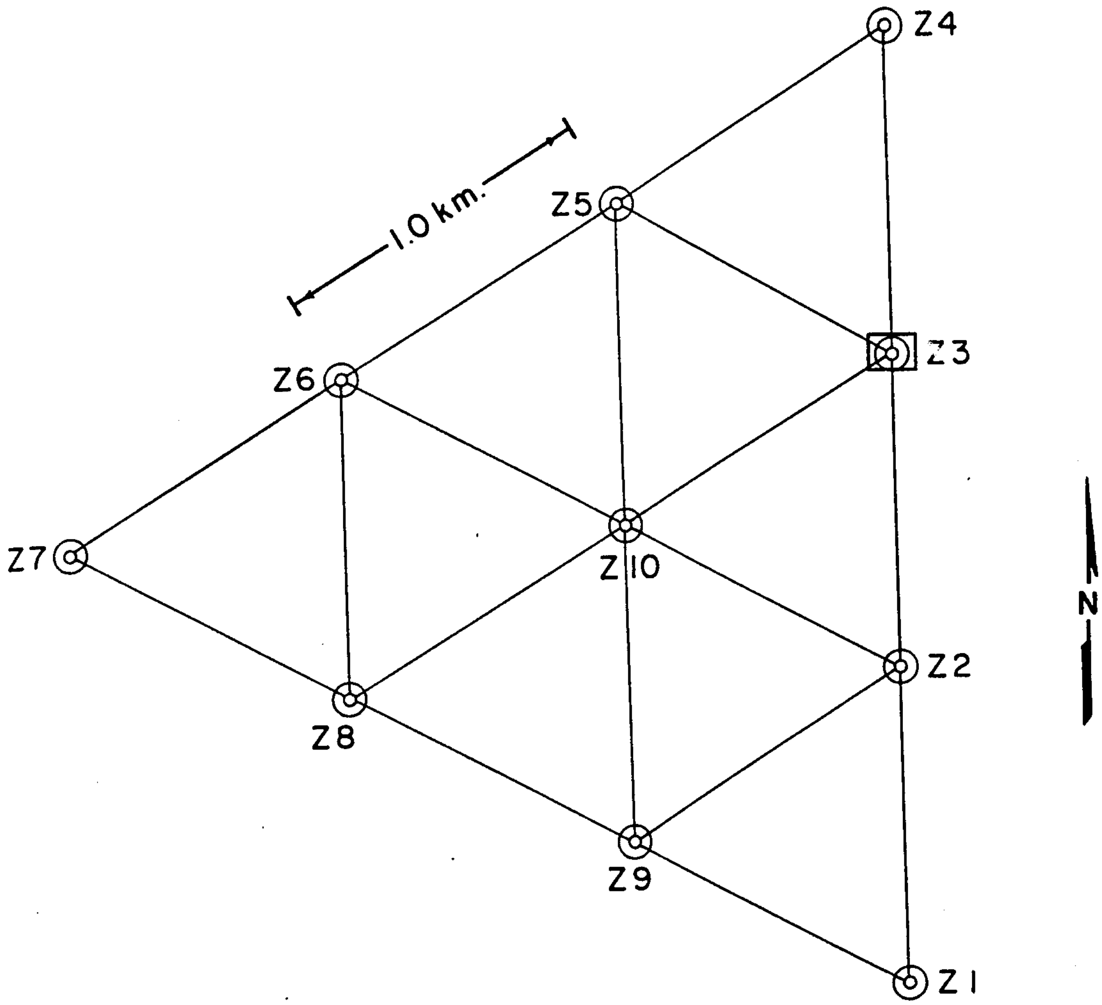
Mykkelveit *et al.* (1990) confirmed the advantages of such a small, tuned array with the NORESS installation. The original BMO array design does not have a particularly good response in frequency-wavenumber (f-k) space. While our objective in installing a research array is not detection *per se*, the usefulness of f-k plots to extract slowness and backazimuth is compelling.

We decided to make the new BMO array more closely correspond to the log-periodic geometry, while at the same time utilizing as many of the existing vaults as possible. Figure 5 shows the adopted geometry, which corresponds to rings 0, 1, and 2 of a NORESS-style array with R_{min} = 250 m and a = 2. The elements in ring 1 are all new to this installation. Ring 2 has 6 rather than 5 elements, the result of the original array layout. The array diameter is 2 km. All elements except Z3 utilize a single short-period vertical seismometer. Z3 operates a 3-component broadband seismometer as well as a short-period vertical instrument. Z3 was selected for the broadband installation to provide continuity with the original array, which operated all its three-component seismographs at that location. It is also the most accessible element.

SEISMOMETERS

The short-period vertical seismometers are Teledyne Brown S13 instruments. The natural frequencies are adjusted to 0.80 Hz and damping is 0.70 critical. Three of the S13s are owned by Idaho Power Company and are on long-term lease to Boise State; three others are being borrowed from Lawrence Livermore Laboratories. S13 seismometers have self-noise below that at Lajitas, Texas at frequencies lower than about 10 Hz. While BMO is a very low-noise site and may approach the Lajitas model at high frequencies, project funds were not sufficient to purchase the quieter, more expensive GS13 seismometers. All S13 seismometers have been or will be shake-table calibrated before installation. We have not attempted to normalize the individual seismometers' responses.

The broadband seismometer is a Guralp CMG-3T instrument with the U. S. National Seismic Network (USNSN) response. This response was chosen to match that of the two nearest broadband stations. The nominal noise characteristics of the CMG-3T seismometers presently in production indicate that instrument self-noise is below the USGS low-noise model between approximately 0.011 and 12 Hz. Since the broadband instrument will be located in a shallow vault at a depth of about 2.5 m, we do not believe the site conditions warrant better low-frequency response. At high frequencies our observations indicate the ground noise approaches the low noise model. The broadband seismometer will be shake-table calibrated before installation.



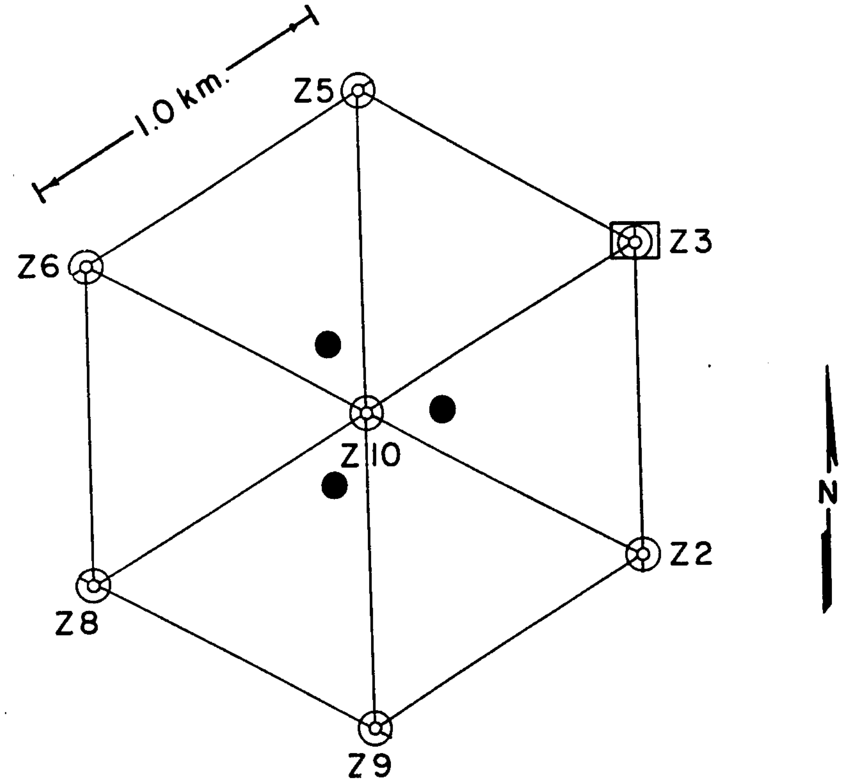
ARRAY CONFIGURATION BMO

LATITUDE - 44° 50' 56" N
LONGITUDE - 117° 18' 20" W
ELEVATION - 3908 FEET

SPZ element

SP, LP, & BB site

FIGURE 4. Original BMO array geometry.



ARRAY CONFIGURATION BMO

LATITUDE - 44° 50' 56" N
LONGITUDE - 117° 18' 20" W
ELEVATION - 3908 FEET

New SPZ element ●

Old SPZ element reoccupied ◎

Old Broadband site

FIGURE 5. BMO geometry for present installation.

DIGITIZERS

The digitizers for all components are Guralp CMG-DM24 24 bit units. The manufacturer reports between 22 and 23 bits actual resolution. Preamplifiers are built into the digitizers being used with S13 seismometers. We have incorporated an analog input filter to reduce the "ringing" effect commonly observed with impulsive arrivals on non-causal instrument systems. We intend to use a sampling rate of 100 Hz per component. The digitizers are near-real time units to allow data compression and, potentially, triggered transmission. Timing is received and data transmitted via a duplex radio link to be described in the next section. In normal operation, all units have synchronized sampling based on GPS time received from the array control site at Boise State. In the event GPS timing is lost, the digitizer clock free runs with an accuracy of 2×10^{-7} (a few milliseconds per day).

DATA TRANSMISSION TO BOISE STATE UNIVERSITY

Most seismometers transmit data in near-real time to concentrators located at two array elements. Local RS232 radio links are used for most of the elements, but ring 1 seismometers transmit data over land lines using the RS422 protocol. Data from the concentrators are re-transmitted utilizing two 9600 baud radio links. Because data compression is used, up to five components are time-division multiplexed onto a single radio link. The Z3 element has 4 components (one short-period vertical and three broadband) concentrated within the digitizing module and is transmitted on a radio link by itself. Because of the distance to Boise State and the non-line of sight path, a repeater is necessary at Iron Mountain, Idaho. A total of four repeaters is located at Iron Mountain: three repeat BMO array data into Boise, while the fourth repeats GPS time and control signals from Boise into BMO. The GPS time/control link allows limited changes of digitizer parameters to be performed remotely. It is also used for handshaking purposes to insure that any corrupted data packets received in Boise are re-transmitted until correct data are received. We do not yet know what the actual error rate will be, but assume that several re-tries within a period of 60 to 90 seconds should ordinarily suffice to correct data garbled in transmission.

RECEIVE SITE AT BOISE STATE UNIVERSITY

The digital data from BMO are received on the roof of the 8-story Education Building at Boise State. Boise State's analog telemetry stations are also received there. A room on the 8th floor is devoted to receiver site hardware and computers. BMO data will be input to serial ports on a multiport board in a 66 MHz 486 PC, on which software is resident for separating individual channels out of the data streams, verifying the integrity of the received data and requesting re-transmissions if necessary, and performing continuous and triggered data logging. Actual logging will be done on a 2 Gb hard drive on a Sun IPC workstation, to which the PC acts as a client. Both computers are backed up by uninterruptible power supplies (UPS). The PC is an energy efficient model which draws less than 15 W with the monitor off, and will run several hours off the UPS. The Sun IPC draws more power, but should still have a few hours' reserve. We are considering writing data to both the PC hard drive and the Sun workstation as an added precaution against data loss.

A D/A converter will be used to produce analog signal output suitable for use on an available drum-type recorder. Such a record is useful for making rapid assessments of seismicity and selecting potentially interesting events for research purposes, as well as being a quick check on the state of health of the system.

DATA ACCESS

Data will be logged to disk in both event-triggered and continuous formats. The 2 Gb hard drive is sufficient to ensure that several days of continuous data (target is 5) are available online for other users' needs. We do not plan to archive continuous data as our research purposes do not require them. Availability of the continuous data online for several days should allow sufficient time for interested users to download data segments of interest.

We are discussing continuous forwarding of the broadband data to the USGS for use with the USNSN. We expect that continuous (although possibly decimated) broadband data will be available from the USGS through the USNSN archiving scheme. This procedure would assure that data from the broadband system will always be available to other users separate from our local archiving system.

The BMO data will be available via anonymous ftp. The internet node is sisyphus.idbsu.edu or 132.178.10.238. Data should begin being available in late summer or early fall of 1995.

DATA PROCESSING

Array data processing procedures have been developed by the Joint Seismic Program Center (JSPC) and will run on Sun workstations. Full-scale routine processing of continuous data in real time requires a Sparc 10 or equivalent machine. We do not have a computer that is capable of such real time processing. However, the data required for our studies are events with magnitude 2.5 or greater. Therefore, our analysis will primarily concentrate on interpretation of triggered events. All event triggers will be saved and archived. We have a 500 Mb magneto-optical drive for storage, and the Boise State Department of Geosciences is purchasing a drive capable of making CDROMs. CDROM storage media are cheaper than magneto-optical disks and it is expected that most storage will ultimately be done on CDROM media.

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Mykkelveit, S., F. Ringdal, T. Kvoerna, and R. W. Alewine (1990), Application of regional arrays in seismic verification, *Bulletin of the Seismological Society of America* **80**, 1777-1800.

Seymour, F. (1965), *Gravity of the Area Surrounding the Blue Mountains Seismological Observatory*, M. S. Thesis, Southern Methodist University, Dallas, Texas.

ACCOMPLISHMENTS AND PROBLEMS

The original proposal called for an 8-element array with 16 bit data acquisition. Attention to economy, falling prices on some digital equipment, and careful design have allowed us to assemble the components of a ten-element array with 24 bit data acquisition. We are installing the entire array for a cost lower than most seismic equipment companies quoted for digitizers, data concentrators, and software. We believe BMO may be the least expensive 24 bit array of its size ever acquired.

The acquisition phase was lengthier and more complicated than anticipated. Consultations with several seismologists and instrument manufacturers led to several redesigns of the array, with the most important changes being in the array symmetry (and number of elements), the duplex radio communications links, and the design of analog filters useful for reducing the ringing response common to non-causal digital systems. The redesigns required extensive technical research by the principal investigator and certainly lengthened the acquisition process, but we believe the ultimate product is a better scientific resource than that originally proposed. It will also be useful in other investigators' research and will benefit the USNSN coverage of the western United States.

We experienced considerable difficulty obtaining the system through the State of Idaho's Purchasing Division, which we were unfortunately obliged to use for purchases in excess of $10,000 from a single vendor. In essence, we were unable to write sufficiently detailed specifications to both satisfy the Purchasing Division and keep the bidding competitive. With the assistance of the Boise State Purchasing Department we were eventually able to prod the Purchasing Division to issue the requests for bids, but the outcome was ludicrous: the State Purchasing Division rejected the low bid for the system on technical grounds. Since the accepted bids all greatly exceeded total project funds, we were forced to reject all bids and start a new round of acquisition procedures. This time, the Boise State Purchasing Department was allowed to control matters and we were finally able to place all the necessary orders. We have learned a great deal from this experience and now have the necessary procedures in place that the more efficient Boise State Purchasing Department will be able to perform most or all future acquisitions for us.

Long product delivery times were bid by the manufacturers, and we are still awaiting delivery of the digitizers and the data concentrators. They are expected in March, 1995. An early and fairly harsh winter closed our field work in late October of 1994, and so work on installation of the BMO array is expected to begin with the spring thaw in early April, 1995.