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Specification Goals for a Mars Seismic Network

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Abstract

A seismic network on Mars should: 1) have enough stations (e.g., 24) to characterize the seismicity of the planet for comparison with a diversity of structural features; 2) be comprised of low noise stations, preferably underground, 3 to 4 orders of magnitude more sensitive than those used on Viking; 3) record over a sufficient band-width (DC-30 Hz) to detect micro-earthquakes to normal modes; 4) record for a sufficient duration (10 years) and data rate (10^8 Mb/day/station) to obtain a data set comparable to that from the Apollo mission to the Moon so that locations of major internal boundaries can be inferred, such as those in the Earth, i.e., crust - lithosphere - asthenosphere - upper - lower phase transitions - outer - inner core. The proposed Mars Global Network Mission provides an opportunity to sense the dynamics and probe the interior of the planet. We discuss the seismic objectives, the availability of the instrumentation and trade-offs to meet them.

Introduction

The science objectives of the Mars Global Network Mission include installation of a seismic network on Mars in order to measure the seismic activity of the planet and to characterize its structure for comparison with Earth. Preliminary specifications for the mission call for installation of up to 24 penetrators or hard-landers on Mars, in pairs, at 12 widely dispersed locations. Landers making up each pair will be installed hundreds of meters to several kilometers apart, thereby achieving some redundancy. We review here the science objectives of the seismic experiment, the instrumentation specifications required to meet these objectives, and report on some recent progress on construction and testing of a prototypical hard-lander seismometer.

Science Rationale for Seismic Network on Mars

Seismology has told us more about the Earth's interior than any other geophysical method. Such information from Mars is vital to progress in understanding the evolution of the solar system. The Viking spacecraft landed on Mars in 1976. The seismometer on Lander I failed to uncage whereas that on Lander II provided 0.24 Earth years of observational data (Goins and Lazarewicz, 1979). The Lander II data contained mainly wind

noise and possibly one marsquake but even that is doubtful. The seismic part of this mission was of secondary importance to the search for life experiments. We are not yet sure that marsquakes exist.

Apart from the uncaging problem on Viking I, wind noise on Viking II was extreme because the instrument was located high up on the Lander near antennae, which vibrated or rocked the structure in response to the wind forces. Also, because only one instrument operated on Mars, it was almost impossible to tell if a given event was a wind burst or a marsquake. The seismometer was less sensitive than the Lunar (Apollo) instruments due to size, weight and power constraints. However the experiment did place bounds on noise levels. It has been estimated that a network of "seismometers more sensitive than the Viking instrument by at least a factor of 10^3"... " emplaced by penetrators or deployed as small packages can operate on the planet without being affected by typical Martian winds" (Anderson et al., 1977).

Science Goals of Mars Seismic Network

Scientific questions that a seismic network on Mars can address depend on whether the instruments are short period (10 seconds to 10 Hz) long period (DC to 10 seconds) or broad-band (DC to 30 Hz) and whether they are 1-component or 3-component. Ideally they should be 3-component, broad-band, but this places severe constraints on installation, and volume and weight of the instrument package, but has the return that the science goals will be met faster than if the performance is restricted. Table 1 lists the seismic science goals separated into those achievable with short period instruments and long period instruments.

Short Period Seismometers

1. Are there marsquakes?

2. How do their locations compare to structural features such as rift zones, volcanoes, and uplift zones?

3. How does the attenuation of seismic waves compare with Earth and the Moon where an order of magnitude difference was observed?

4. Are there major internal boundaries in Mars similar to those within Earth and the Moon, i.e., crust-lithosphere-asthenosphere-upper-lower phase transitions-outer-inner core?

5. Is there sub-surface structure that yields information on the Martian hemispheric dichotomy (e.g. l=1 convection)?

6. What are the dynamics of impacts on Mars from meteorites?

7. What are the focal mechanisms of marsquakes and how do they relate to inferred stress fields, e.g., from isostatic imbalance?

Long Period Seismometers

8. Do large impact events or marsquakes generate measurable normal modes which can be used to estimate velocity and density distribution?

9. Can we detect surface wave dispersion?

10. What is the Love number of the Planet?

11. Can we detect annual or Chandler wobble generated by internal changes of the moment of inertia?

Table 1 Scientific Questions for Mars Seismic Array

Science Goals of Mars Seismic Network

If we knew Mars as well as we know the internal structure of the Earth from seismology, not only would would we be exploring a new planet, we would also be adding fundamentally to our understanding of the evolution of the Solar System including the formation and composition of both Mars and Earth. Solar Nebular theories of the compositions of the planets predict that the volatile content, oxidation state and silicate iron ratios increase with distance from the Sun. The distribution of elements within a planet is determined by the temperatures during formation. For Mars we know only the mean density and moment of inertia (and there is still considerable debate on this, Kaula et al., 1989, Bills, 1989). Further progress is hampered because models satisfying these constraints allow trade-off between mantle and core densities, and core size. Direct determination of the size of the core and density profiles, by seismic means, would constrain the overall composition of the planet. Models of the thermal evolution of Mars (Schubert et al., 1989) since formation differ as to whether the core is solid or molten. An important factor in this regard is the amount of Sulphur in the core, which if it is the 15% as inferred from the SNC meteorites, results in a completely molten core, but if much less, can result in a solid core. Attenuation of S-waves would tell us about the fluidity of the core.

We assume that Earth's core is mainly iron but with a substantial amount of lighter element, or elements, based on estimates of uncompressed density, shock wave data, and consistency with meteorite (type I carbonaceous) compositions. There are nonetheless uncertainties associated with this view. Are the finite strain theories used for decompression of the density truly applicable? What is the light element, or elements? Are the meteorites a relevant geochemical reference frame? Comparison of Earth with another planet will allow us to test the hypotheses used on Earth.

Installation of Mars Seismic Network

Various methods to install seismometers on Mars include implantation by penetrator, deployment on the surface from a rover, or by hard, rough or soft-landers. The g loads on the instrumentation range from thousands of g for a penetrator and hard lander, hundreds of g for a rough lander and tens of g for a soft lander.

Penetrators

Penetrators offer an attractive way to implant a seismometer because the seismometer is firmly coupled to the planet, and is unlikely to experience the wind generated rocking motions that were thought to have generated noise on the Viking instrument (Anderson et al., 1977). Penetrator technology is well advanced. Approximately 18,000 penetrators were dropped in Southeast Asia and radioed information on troop movements from seismic and microphone sensors which was detected by planes at 20,000 feet. The idea of a penetrator mission to Mars dates back to reports by JPL (Briggs et al., 1975) and Sandia (Lumpkin et al.,1974). Other studies made in the mid seventies include those by Westphal et al., 1976, Blanchard et al., 1976, and Greely and Bunch, 1976.

Burial of the seismometer beneath the surface by a penetrator will reduce wind noise. Also remoteness from a lander will eliminate internally generated spacecraft noise, both electrical and mechanical, as well as wind generated vibrations of the superstructure. Burial will also keep the seismometer thermally insulated from diurnal and other surface temperature changes. This is critical for long period seismometers which, if installed at the surface, record strong signals generated by thermoelastic strains, both in the surrounding rock and in the instrument itself. At short periods, thermoelastic changes are buffered by the thermal inertia of the instrument.

Presently we expend much effort digging pits to install sensors 1.5 m into the ground in our field installations on Earth. For short period recording, it suffices to cover the pits. For intermediate period recording, the pits are filled with insulation. However, first class seismic observatories are usually located in vaults deep underground such as mine shafts, tunnels, or in bore-holes. A penetrator installation on Mars is a practical compromise.

Surface Versus Penetrator Installation

A surface installation, though attractive because of its simplicity, compromises the quality of the seismic data obtainable. Ground coupling can not be assured. Proximity to wind and temperature changes would probably limit the instrumentation to short period only. However surface installations worked on the Moon, though they did not have to deal with winds. There are, however, advantages to designing two types of landers, a surface one for the seismic package and a sub-surface penetrator for short-lived (1 month) experiments such as soil properties, mass spectrometry etc. It would remove the need for a small RTG, since the short term experiment in the penetrator could run on lithium batteries. It also removes the possibility of contamination of the chemical analyses by radioactive products from the RTG. A softer surface lander for the seismometer would reduce the shock tolerance requirements for the RTG and seismometer system. This may be critical for the RTG since, because of its extreme temperature (1000°C) the thermocouples can not be bonded; it may not survive shocks greater than a few hundred g.

Although it should be tested, it is probable that a large proportion of seismic short period information on Mars could come from instruments installed on the surface. The trade-off in simplifying the installation would be the loss of long period signals. Also, the low end of the short period band would be noisier than that at depth. We ran a series of tests in the alluvium in the caldera at Long Valley, California, in which a short period sensor was buried and the background noise measured as a function of depth in a wind of about (4.0 m/s) 8 knots. In the frequency band tested, 5 Hz - 30 Hz, there was no perceptible difference in background noise. Such tests need to be performed over the full frequency range and for different wind and surface conditions, before effects of burial can be quantified. Shedding wind vortices from obstacles can generate noise in the seismic band dependent on wind speed and obstacle shape.

Viking mission data showed that mean seismic amplitude increased as the wind velocity squared (Anderson et al., 1977) for winds ranging from 3 m/s to about 10 m/s. Optimal design of a surface installation will require the instrument package to be of a streamlined shape . It will need to have the capability to attach to the surface securely. It will also need to be kept isothermal (gradients less than $10^{-5\circ}$C/m) and at constant pressure (to within 10 mbar).

Table 1 shows the science objectives (1-7) that could be achieved with a short period seismometer installed at the surface. We could measure the seismicity, the travel times, fault plane solutions, invert travel times for radial structure, including detection of the Martian core. We would miss out on (8 - 11), in particular, surface waves and normal modes, which would be regarded by most seismologists as an extremely high price to pay.

Normal modes will give an independent check on the radial structure determined from travel time analysis of body waves. One large marsquake which generated a wide spectrum of normal modes would allow inversion for internal radial structure; that would take years using short period travel-time data alone. Measurement of lateral variation in the excited modes, at multiple stations, can be used for determination of global heterogeneity. Surface waves measured at multiple stations provides a method to measure upper mantle lateral heterogeneity, which will be particularly interesting beneath the Tharsis plateau region.

Detection of lateral heterogeneity means all stations should be broad-band. We conclude that too much science is lost if the seismic installations are restricted to (surface) short period installations. All instruments should be broad-band, installed either in penetrators at depth or, if on the surface, they should have good coupling, preferably to bedrock, and be insulated from temperature and pressure fluctuations.

Data Acquisition Specifications

Mars' seismic activity is thought to lie between that of Earth and that of the Moon (Kaula, 1984). If Mars' seismicity obeys a Gutenberg Richter law, with b value = 1, such as is observed on Earth, with instruments a factor of 10^3 more sensitive than Viking, 3 orders of magnitude more earthquakes should be detectable. As well as marsquakes, landslides of over steepened crater walls and meteorite impacts will generate seismic signals. On Earth, installations of comparable sensitivity to that proposed for Mars, detect about 1 earthquake of magnitude=5.5 per day world-wide. A marsquake of this magnitude would probably not have been observable had it occurred further than 90 degrees from the Viking instrument.

If Mars seismograms are similar to those on Earth in order to capture the important phases, P,S, ...multiple ScS etc., recording at 50 samples/second should continue for several hours after initiation of a moderate sized event. After this time a low sampling rate (1 sample/second) could be used to detect normal modes. In areas of seismic swarm activity, for example active volcanic regions, the local earthquake activity can be as much as 100 events per day, requiring continuous recording.

On the Moon, an average of 4 events per day were detected comprised of: unclassified events (2.4/day), deep moonquakes (1/day), meteoroid impacts (0.6/day). Events on the Moon persisted for several hours, because of the high Q (4000) of the Lunar mantle (Dainty et al., 1976; Nakamura et al., 1976). For a Lunar-type activity it would be necessary to save data for several hours per day, at 50 samples/second, to record the full wave trains of the seismic signals.

These considerations indicate that the daily data budget of a seismic station can be calculated as 3 components at 50 samples per second for 24x3600 seconds at 30 bits per sample (24 bit A/D and 6 bit gain range) = 3.88×10^8 bits/day. With data compression, such as event detection, this number can be reduced; 10^8 bits/day per station would provide an adequate coverage. If 2 transmissions were made to an orbiter per day, this amount of data would require an on-board 6 Megabytes of RAM.

Investigation of seismicity requires setting up a network of at least 3 stations since this is the minimum needed to locate an event. However to measure local, regional and global seismicity at least 9 should be installed, that is, a 3-station local network with stations separated by about 20 km, a regional network of separation 200 km and three stations distributed across the planet. We propose that the local array be installed in the Tharsis region where earthquakes are expected from the associated stresses due to inferred isostatic imbalance. The regional and global networks would extend out from this base. To measure seismicity at diverse structural settings, several local networks should be installed. The proposed network of 24 seismometers at 12 different locations with closely separated pairs will achieve these goals.

Seismometer Specifications

There is currently no seismometer available that would withstand the shock associated with penetration. Either presently available ones, with the desired sensitivity, will have to be modified, or a new design implemented. The seismometer design should be predicated on considerations of ruggedness and simplicity. Leaf spring seismometers such as the Ranger (Kinemetrics, Pasadena, California) have the required ruggedness.

In 1962 Lehner et al.,(1962) report (2000') drop tests from a helicopter of the Ranger seismometer which was clamped with all moving parts immersed in fluid (150 cc of n-heptane). Decelerations were in the range 3000-7000 g. After cushioning the various components, the final design survived a series of 7 drops with no degradation of performance.

Coil spring designs such as the Mark products (Houston, Texas) L4C or the HS10 (Geospace, Texas), are also rugged but have less tolerance to non-verticality. The response of a damped inertial seismometer depends on the mass, the spring constant and the damping factor. The low frequency response of a velocity transducer is critically dependent on the value of the resonant frequency. Since the response to ground displacement falls off as about 1/(frequency squared) the useful bandwidth is about a decade above and below resonance. With high signal to noise ratio and wide dynamic range, the useful bandwidth can be extended to 3 decades, e.g., 0.01 Hz to 10 Hz, for seismometers of resonant frequency 0.5 Hz. However a typical range for an L4C, as used in the USGS network in Southern California, is 0.1 to 10 Hz.

One way to extend the dynamic range and linearity of an inertial seismometer is to use force-balance feedback in the form of either a magnetic or electrostatic restoring force proportional to the ground acceleration. The former consumes power whereas the latter, while consuming negligible power, provides a weak force and is typically used on long period instruments (such as the LaCoste gravimeters of the IDA array). Alternatively addition of a displacement transducer, sensitive to sub angstrom displacements, can provide a low frequency channel output with flat response to ground acceleration with a minimal power requirement.

The final position of the penetrator may be well off vertical. The seismometer must either work at any angle or have a levelling mechanism. Seismometers with the mass suspended from coil springs have little clearance and so jam if they are not close to vertical. For example, the L4C jams at 17^o off vertical. The mass of the Ranger seismometer is attached to leaf springs at either end so that when it is tilted the transverse shear strength of the flat springs prevents lateral movement which would otherwise cause it to jam against the casing. In fact it can be converted to a horizontal seismometer merely by rezeroing the mass to the position of greatest sensitivity. The commercially available Ranger from Kinemetrics has a diameter of 11.1 cm excluding casing. This is too large to be directly transferred into a penetrator (diameter 9 cm). A seismic sensor is required that has the versatility and ruggedness of the Ranger but is small enough to fit in a penetrator and has a broad-band transducer.

In 1977 the Bendix Corporation (Perkins 1977) presented a design for a multi-instrument penetrator including a 3-axis seismometer. The seismometer was attached to a levelling table pivotted on a monoball bearing. Two motor drives 90 degrees apart, attached to the table via spherical bearings and flexures, are used to level to within 1 microradian. The transducer consists of a vertical geophone and a North American Rockwell biaxial bubble tiltmeter which can both be used as a two axes horizontal seismometer and also as the levelling transducer. However this apparatus was not built. Levelling to within 10^{-6} is difficult. We favor a simpler design which does not have such stringent levelling requirements.

Number of sites	**12**
Number of landers	**24**
Number of channels/lander	**3**
Number of samples/s	**50 sp/s**
Bandwidth	**DC-30 Hz**
Sensitivity	**10^{-11}g**
Displacement Resolution	**10^{-12}m**
Free period	**0.6 seconds**
Power	**100 milliwatts (sensor)**
	1.0 watts (signal acquisition)
Data rate	**1000 b/s or 10^{8} b/day**
A/D	**24 bit**
Gain Ranging	**6 bit**
Dynamic Range	**140 dB**
Clip Level	**10^{-4}g**
On Board RAM	**6 Megabyte**
Clock Accuracy	**10 millisec**
Calibration	**1/day**
Shock	**10,000g for 2 millisecs any axis**
Weight seismic mass	**3x0.16 kg**
Weight sensor (exclusive of housing)	**3x0.5 kg**
Diameter	**9.0 cm**
Height	**3x15.0 cm**
Temperature control	**10^{-5}°C/m**
Vacuum	**10 mbar**
Spring resonances	**$\geq$ 80 Hz**
Mass Centering	**+- 90 degrees; 6 volt motor**

Table 2.
Specifications for Mars Global Seismic Network

Specifications for the Mars Network Seismic stations are listed in table 2. Seismometer specifications are based on presently available force balance seismometers, including the

Guralp (Guralp Systems, Reading, England) seismometer and the Strekeisen seismometer (Wielandt and Strekeisen, 1982) which have the sensitivity required but, owing to the Bendix hinges that support the boom, they do not have the required ruggedness. Specification of the digital acquisition system is based on systems currently in use by IRIS (Incorporated Research Institutions for Seismology) for the permanent and portable networks.

Brassboard Prototypical Penetrator Seismometer

One of the most popular modern broad-band seismometers is the recently developed Guralp force-balance feedback seismometer, the mechanical part of which resembles, in many ways, a leaf spring micro-gravimeter designed by R.V. Jones (Jones and Richards, 1973). The difference is that the Guralp employs Bendix hinges to pivot the boom with a leaf spring supplying a restoring torque whereas in the R.V. Jones design, the leaf springs also perform the function of the hinge. The Bendix hinges are too weak to withstand the high deceleration impacts.

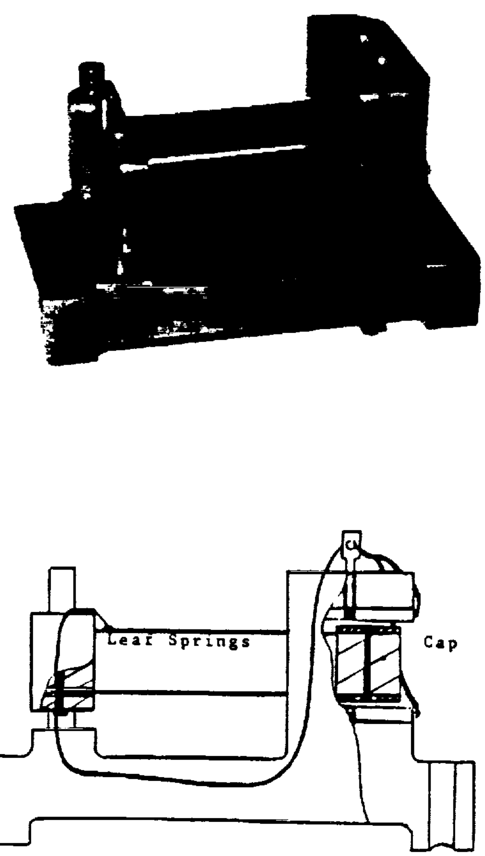


Figure 1 Leaf spring seismometer designed to be shock tolerant.

We have constructed a leaf spring seismometer based on the R.V. Jones design. This design has an advantage that it works 13^o off-vertical without post-implantation adjustment and fitted with an adjustable re-zeroing mechanism would work in any orientation. Therefore a three component set could be installed in a penetrator for which the default would be no post impact adjustment, if the penetrator ends up close to vertical, and minimal rezeroing adjustment if it ends up well off vertical. Even then, if the rezeroing system fails, some data would be achieved, albeit at reduced sensitivity. Basically the ruggedness of leaf springs is achieved by employing 2 parallel Beryllium Copper springs on which the mass is suspended. A photograph and schematic of our sensor is shown in figure 1. Although it is more rugged than the Guralp seismometer, the trade-off is that it is about 1/3 as sensitive.

The position of the mass is detected by capacitance micrometry. Eventually a magnet-coil assembly will be used to provide force feedback as in the Guralp seismometer. By adjusting the filters for the force feedback output a wide dynamic range can be achieved.

Implementation of a Laboratory Impact Tester

In order to test the prototype, we assembled a laboratory impact simulator (Kewitsch, 1989). This has enabled us to conduct impact tests in the laboratory at UCLA to eliminate obvious design flaws before going to the more extensive testing at Sandia National Laboratories, Albuquerque, or from helicopter drops. Validyne Engineering (Chatsworth, California) donated a drop tower to the project. We added 8 bungee cords stretched over a pulley system, allowing 100% stretch of the cords to accelerate the drop, to give an effective drop of 40 feet (figures 2 and 3). An accelerometer/charge amplifier system measures the deceleration; the output is recorded on a signal analyzer (see figures 2,3,4). The system was calibrated at Environmental Associates, Chatsworth.

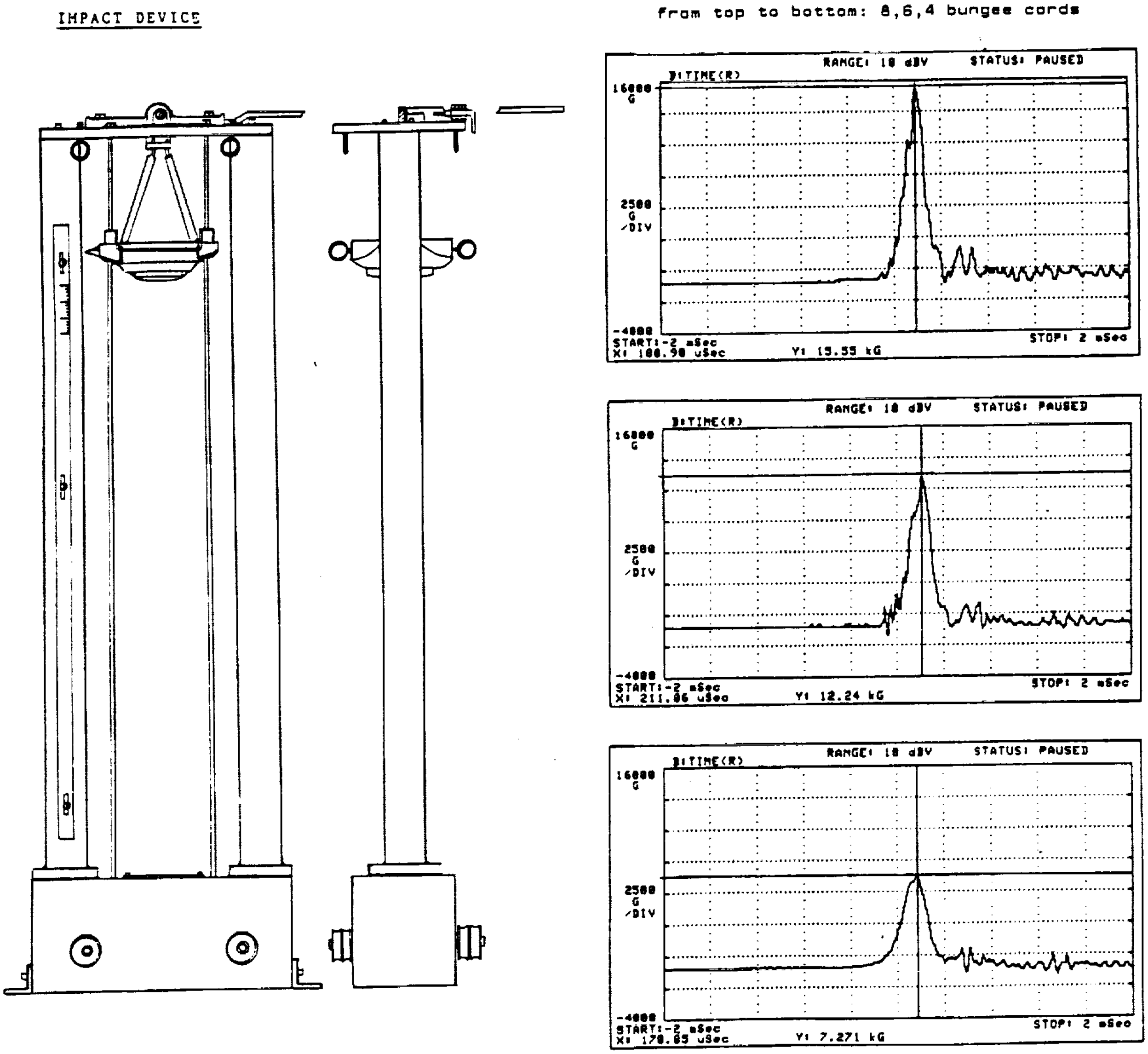
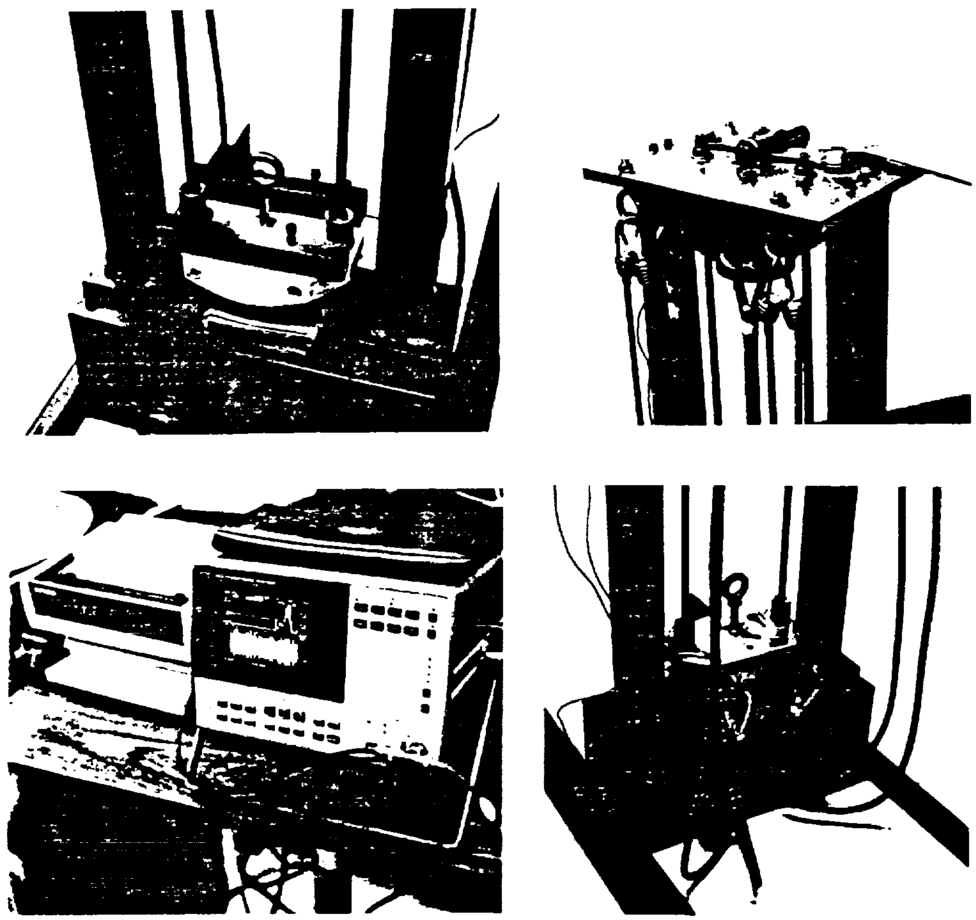


Figure 2,3 Schematic of Bungee assisted drop tower for Lab testing seismometer and examples of deceleration pulses.

Addition of weight to drop table to simulate future seismometer

Release mechanism



Signal analyzer

Drop table and bungee cords at point of impact

Figure 4 Photos of Bungee assisted drop tower.

We subjected the leaf spring sensor to impact impulses of 3 g secs (15,000 g at 0.2 ms, figure 3) for a variety of combinations of peak pulse and duration. It survived longitudinal shocks well but lateral shocks caused distortion of the frame supporting the springs. Components must be modified and the design changed until performance survival is guaranteed.

conclusion

Seismometers, many orders more sensitive than those on Viking, emplaced on Mars, will detect marsquakes, meteorite impacts and, possibly, landslides. To identify the locations of events, and to correlate phases, at least 4 stations are required, 3 for location and a fourth for redundancy. To examine diverse geological sites, several different regions should be instrumented; A total of 12 sites with 2 stations per site would achieve these goals.

Emplacement by penetrator, with detachable forebody, achieves good coupling, isolation from surface temperature and wind pressure effects; but the high g loads risk the seismometer and probably rules out using an RTG.

Emplacement by hard-lander on the surface, could achieve fair coupling, if post-emplacement mechanisms are employed (such as driving in a spike or drilling). It will need special provision for isolation from temperature and wind pressure effects, which if only partially successful, will result in a short period narrow band station only. High g loads can be minimized, to less than several hundred g's, if a rough-lander is used.

Leaf spring, force-balance feedback, seismometers have the wide band-width, dynamic range, shock tolerance and sensitivity to be used in penetrators or surface landers. They are light but consume more power than narrow-band magnet-coil velocity transducers. We have tested a brass-board suspension design, which approaches the necessary ruggedness, but has about 1/3 the sensitivity of a state-of-the-art instrument.

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6.2 SESSION B SUBMITTALS

Session B, Submittal No. 1

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A POLAR ORBIT FOR THE MARS GLOBAL NETWORK MISSION

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JPL