Invited Article

A Brief History of Broadband Seismometry – Part I

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5.1 A Brief History of Broadband Seismometry – Part I

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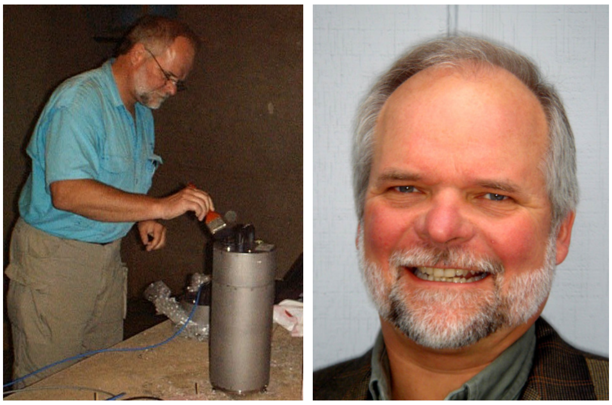

Horst Rademacher

5.2 Introduction

Almost five decades ago a new paradigm swept over the world of seismology like a tsunami. At a time when the theory of Plate Tectonics was still in its infancy and when the nuclear powers, engaged in a bitterly frozen Cold War, were testing atomic weapons several times a month, seismologists realised how ill equipped they were to measure the rumblings of the Earth, be they natural or caused by nuclear detonations.

No doubt, the data collected at that time by the World Wide Standard Seismograph Network (WWSSN) had considerably improved our abilities to record earthquakes and detect underground explosions (*Kerr*, 1985). But during its operation, which started as part of the Vela project by the US Department of Defense in the mid 1960's, it became clear that the WWSSN had major shortcomings. Each of the approximately 120 stations of the network was equipped with at least six separate seismometers, each one augmented by its own galvanometer. The data were recorded on light sensitive paper, requiring the equivalent of a darkroom at each station. Keeping such a complex system of equipment in running order became a maintenance nightmare (*Peterson and Hutt*, 2014).

Despite the words "World Wide" in its name, the WWSSN did not cover the complete globe by any means. Given the geopolitical situation at the time, no stations were deployed in what was then the

Soviet Union, in countries in the Soviet sphere of influence in Eastern Europe or in China. This led to a substantial gap in coverage. However, in 1965 the Council of Seismology of the former USSR began setting up its own network of identical seismic stations. By 1969 a total of 168 stations were deployed in the USSR and neighbouring countries. Each one was equipped with three sets of three component sensors covering the short, medium and long period parts of the seismic spectrum, thus recording in analogue form a broader frequency range than was possible with the standard WWSSN equipment (*Storchak et al.*, 2015). However, in contrast to the data collected by the WWSSN, the data from the Soviet network were not available in the rest of the world.

Despite its shortcomings the WWSSN was the top of the line seismic network of its time. The situation in most earthquake observatories around the world was worse. Operated mostly by universities and other research institutions, their equipment was often a mixture of different types and models of mechanical seismographs, each with different magnification and its own unique transfer function.

Many seismologists realised at that time that changes, even a completely new approach to the measurement of ground motion was necessary. But what was really needed?

Despite today's general perception that completely new seismic sensors were needed at the time, the most pressing issue was the way ground motion was recorded. For instance, the data of the stations of the WWSSN were recorded on photographic paper and later transferred in analogue form to microfilm. The analogue outputs of other sensors were quite often still recorded on sooted paper, posing a health hazard to the operators. In any case, these recordings were fixed and could not be manipulated further to improve their analysis. In addition, once the passband of a seismic sensor included the period range between 6 and 15 sec, the ocean microseisms dominated the recordings, masking most other seismic information. Hence making use of the rapidly developing computer technology four decades ago allowed the recording of seismic data in digital form, broadly opening the doors to the capacity to apply digital filtering and other computer-based analysis techniques.

Another item on the wishlist was the development of seismic instruments which would cover a wider frequency range, encompassing at least the same seismic band for which the stations of the WWSSN needed two separate sets of seismometers. In addition it was desirable to have the response of such a sensor be linear and flat across that broader frequency range.

In this two part contribution I will attempt to recount the development of what later became known as *modern broadband seismometry*. This technology is without a doubt the dominant tool in the world of seismology today. In the first part, I will describe the efforts of several groups of scientists and engineers in Europe and the United States who were working to implement some of the basic new ideas in the design of new sensors. Their endeavours led to the first operational broadband seismometers. In the second instalment I will describe the developments of digital recording methods, several subsequent technological developments in sensor design and the effects this new technique of measuring and recording ground motion had on the science of seismology.

Many of the original contributors are either no longer with us or are no longer working on these questions, while others are still pushing the frontiers of seismometry. New players have entered and with them new ideas have surfaced. Given the fierce competition in this field I will endeavour to stay as neutral as possible. Mention of specific instruments shall not be interpreted as endorsement. And in no way will

I judge the quality of the products developed and built by the various manufacturers referred to in the text. This call must be made by each seismologist planning to acquire and use broadband systems.

5.3 The Basic Concept of Seismometry

Ground motions associated with elastic waves can be measured in two ways, either with strain meters or with inertial pendulums. While the former allow a direct measurement of differential ground displacement, a complex transfer function has to be considered for the latter to gain meaningful information about the true movement of the ground in both amplitude and phase. This computational procedure is necessary because the actual output signal of an inertial pendulum seismometer is proportional to the relative motion between the internally suspended inertial mass and the frame of the instrument which should be well coupled to the ground. This important step is commonly referred to as the removal of the instrument response or in more mathematical terms as a deconvolution of the seismogram. Despite this complexity, inertial pendulum seismometers have been the dominant tool in seismology for more than a century.

Early instruments, like those developed by Ewing, Wiechert or Omori around the turn of the 20th century, were purely mechanical devices. The motion of their respective masses relative to the frame of the instrument - and hence the ground - was recorded on sooted paper by a system of levers and styluses (*Dewey and Byerly*, 1969). Such mechanical instruments, the seismographs, are not in operational use anymore. However many are still in working condition and can be found in museums or as exhibition pieces in seismic observatories.

It was *Galitzin* (1914), who in the early part of the 20th century first coupled the suspended mass of an inertial pendulum with an electromagnetic (EM) transducer, thereby creating the first seismometer. When its mass moves relative to the instrument frame, it induces an electrical current in the coil. This current is proportional to the velocity of the relative motion (see Figs. 5.1 and 5.2).

All seismic instruments used in the WWSSN were seismometers with electromagnetic transducers. Their

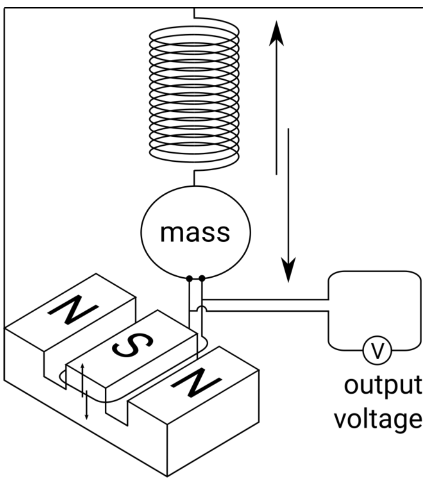

Figure 5.1: *Schematic depiction of an EM-transducer coupled to an inertial pendulum.*

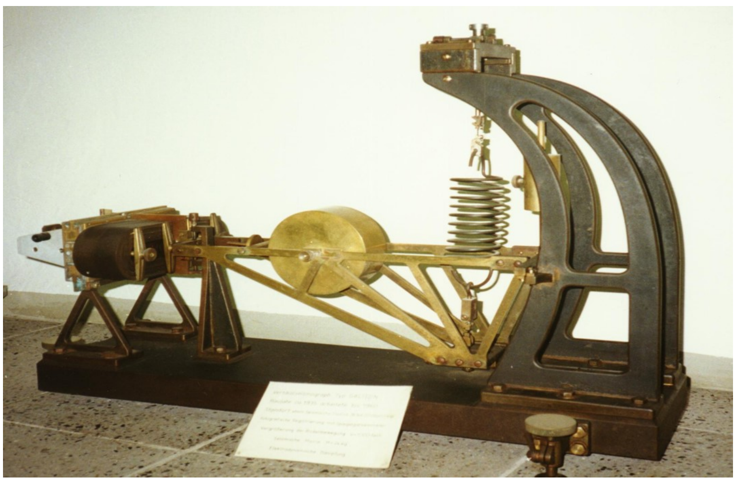

Figure 5.2: *Replica of Galitzin's instrument with the EM-transducer at the left end of the instrument. (Photo: Horst Rademacher)*

output current was fed into galvanometers, electromagnetic-optical devices, which act as very sensitive current meters. They converted the electric signal into the mechanical motion of a mirror, the movement of which was recorded as the deflection of a beam of light on light-sensitive paper or film.

Thus, recording the ground motion with a seismometer-galvanometer system is a complex series of conversions. Initially, the ground motion is converted into a mechanical displacement between the suspended mass and the instrument frame. The EM transducer converts this motion into an electrical current. The galvanometer reconverts the current into a mechanical motion and then via optical transmission into a record on light sensitive paper. In addition to the limitations mentioned in the introduction, this is another example of the complexity of seismic recording systems from past decades.

Each of these conversions is plagued by various shortcomings, which reduce the quality and fidelity of the seismic measurements. As galvanometers and optical recordings have been replaced by digital data handling and thus become obsolete, we will not discuss these aspects of the old instrumentation any further. Instead we focus on the shortcomings of inertial pendulum devices themselves. Their two main limitations are the non-linearity of the movement of the suspended mass, and clipping or saturation of the EM-transducer when the ground motion amplitudes are too large. *Wielandt* (2002) describes the causes of the non-linearity as *"imperfections in the spring and the hinges"* as well as the limited space inside a seismometer housing. The clipping has *"geometrical and electronic"* causes.

5.4 Open Loop vs. Forced Feedback Systems

Looking at an inertial pendulum seismometer through the lens of a cyberneticist we may say that it consists of two dynamic systems: the inertial mass and the transducer. The inertial mass (system A in Figure 5.3) reacts to the movement of the ground and the transducer (system B) converts this reaction into a measurable quantity. In seismometers such as those invented by Galitzin or used in the WWSSN, system A influences system B significantly, while system B has only a very minor effect on system A. Such an arrangement is defined as an open loop system (*Aström and Murray*, 2008). Modern geophones and many short period sensors operate under such an open loop arrangement.

If one could find a way to have system B also influence system A, i.e. by somehow passing the output of the transducer back into the moving inertial mass, one would get a closed loop arrangement. In

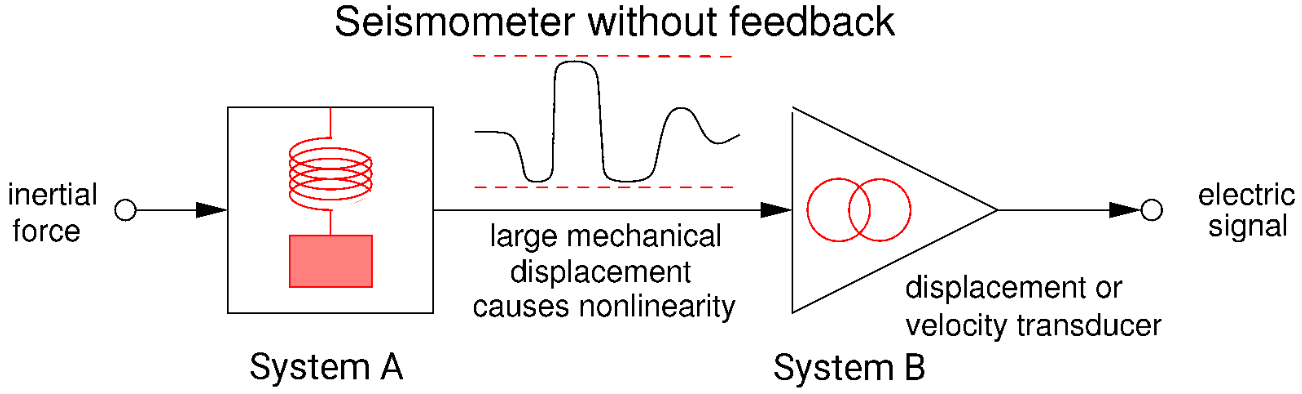

Figure 5.3: *Block diagram of the core elements of an open loop seismometer. Drawing by Erhard Wielandt* `http://www.software-for-seismometry.de/textfiles/Seismometry/BroadbandDesign.pdf`

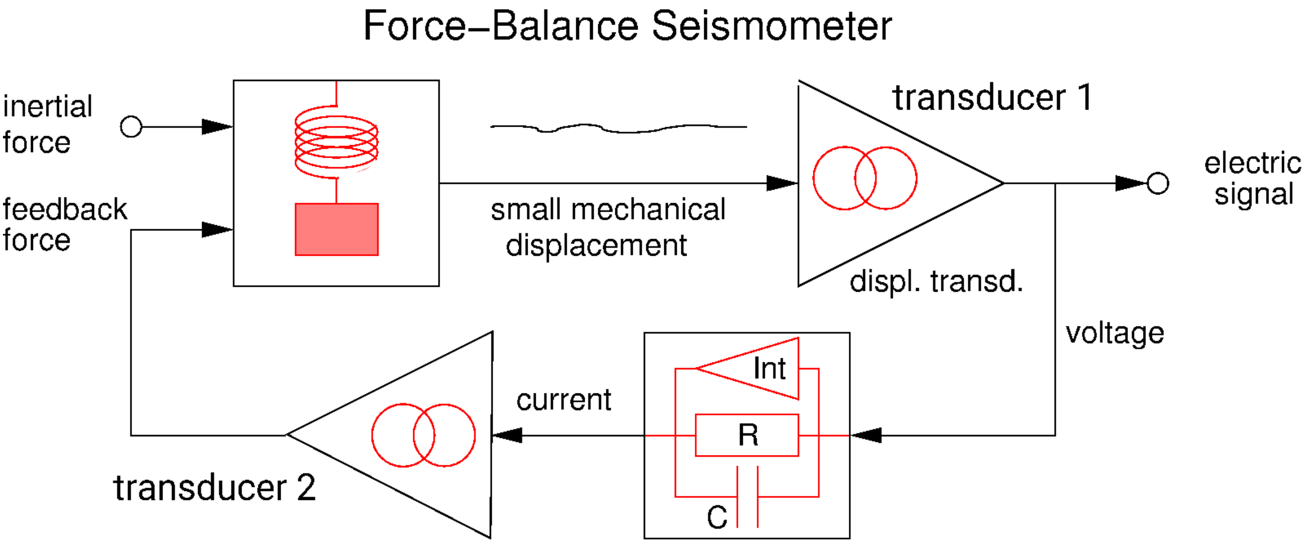

Figure 5.4: *Block diagram of a force-balance feedback seismometer. Drawing by Erhard Wielandt* `http://www.software-for-seismometry.de/textfiles/Seismometry/BroadbandDesign.pdf`

cybernetics this is called a feedback loop. If done right, such a loop can stabilise both systems. At least in theory, this concept opens the door to better seismometers, if one can find a good way to feed the transducer's output back into the system involving the inertial mass.

This becomes possible by equipping the inertial mass with a second transducer. While the first one converts the mechanical movement of the mass into an electric signal, the second transducer takes this electrical signal and converts it back into mechanical motion. If this force is exactly opposite to the amplitude and phase of the force of the original motion, one has created a negative feedback loop, also called a force-balance system.

According to the laws of cybernetics, loops with negative feedback are a necessary step to stabilise the entire system. But why would that lead to a better seismometer? The answer can be seen in the wiggly lines at the center of Figures 5.3 and 5.4. In the case of the open loop seismometer (Fig. 5.3), the amplitude of the relative motion of the mass with respect to the frame (mechanical displacement) can be very large. In contrast it is much smaller, even close to a flat line in the case of the seismometer with a feedback loop. Effectively, the feedback transducer forces the inertial mass not to move.

At first glance this is counter-intuitive. After all, we want to measure the motion of the ground. How can this be achieved, if the test mass is forced to remain still, while the ground is shaking? However, it confirms the statement of *Aström and Murray* (2008), that *"simple causal reasoning about a feedback system is difficult because the first system influences the second and the second system influences the first, leading to a circular argument. This makes reasoning based on cause and effect tricky, and it is necessary to analyse the system as a whole. A consequence of this is that the behavior of feedback systems is often counter intuitive, and it is therefore necessary to resort to formal methods to understand them"*.

Without going into these formal methods, the simple way to understand how a feedback sensor can measure ground motion even without the inertial mass moving, is to look at the forces involved. In most modern feedback seismometers, the first transducer is either a capacitive sensor or a linear variable differential transformer (LVDT). The second transducer is always an EM-transducer in a coil-magnet arrangement, which uses magnetic forces to balance the inertial motion of the mass. The larger the motion to be compensated, the stronger the magnetic force must be. A stronger current through the coil is necessary to increase the strength of the magnetic field that balances the force from the ground attempting to cause the relative movement of the mass – hence the strength of the feedback current is a direct measure of the ground acceleration acting on the inertial mass.

In order to get the actual output signal of a feedback seismometer, the current is passed through a resistor which causes a voltage drop that changes depending on the variation in the strength of the current. It is this voltage variation, which when digitised and recorded, gives us the representation of the ground acceleration in form of a seismogram.

But why would a seismometer based on a force-balance feedback system be better than a seismic sensor with an open loop arrangement? The main reason is the much reduced motion of the inertial mass in a seismometer with feedback. In order to understand why this has a dramatic effect, let's look at what we want to achieve with a seismometer. When an elastic wave travels through the ground, each small volume element can move in six different ways. These are the three perpendicular translatory directions and the three rotational motions (pitch, roll and yaw). As we are not describing rotational sensors in this paper, we will focus only on the translatory motions. In order to measure the full translatory ground motion in three dimensions, we usually deploy three independent sensors oriented orthogonal to each other. Theoretically, each sensor measures the movement of the ground in exactly one direction. A vector addition of the three measurements then gives us the truly three dimensional ground motion.

But because the inertial masses and their suspensions are mechanical devices, they are plagued by limitations. A few examples are the uniformity of the material of the springs which determines their internal friction, the friction in hinges (pivots), the linearity of motion within the transducer and way the inertial mass responds to ground motion over a wide range of frequencies. The larger the amplitude of the movement of the inertial mass, the more pronounced these limitations become, despite the best efforts of seismometer manufacturers to keep them small. In contrast, if the mass moves very little, these shortcomings remain less important and the seismometer records the ground motion with high quality.

5.5 The First Feedback Seismometers

Probably the very first feedback seismograph in the world was developed in the early part of the 1920's in Zürich by the two Swiss physicists Alfred de Quervain and Auguste Piccard. They built a mechanical three-component seismograph with a single mass of 21 tons with its position stabilised with water ballast (*de Quervain and Piccard*, 1927). As this "water feedback" was purely mechanical and was not recorded as described above, I will not consider it any further.

Instead it was Hugo Benioff, one of the grand masters of geophysical instrumentation in the 20th century, who first mentioned the use of an electronic feedback system to improve the performance of a seismometer. Without directly using the words feedback or force-balancing, *Benioff* (1955) described a *"pendulum stabilizing circuit"* in which he used magnetic forces to reduce the long period pendulum drift, particularly on horizontal seismometers. Benioff claimed this to be *"useful in applications such as portable installations where the pendulum drift may be large"*.

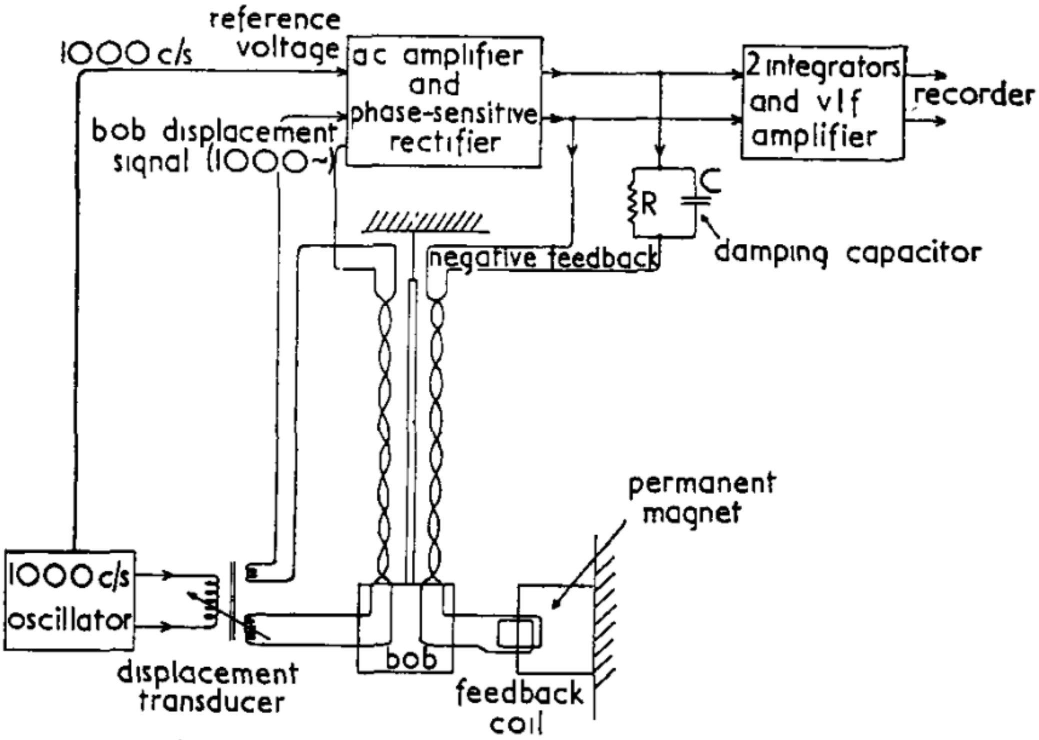

Figure 5.5: Schematics of Tucker's first feedback seismometer. From Tucker (1958) © IOP Publishing.

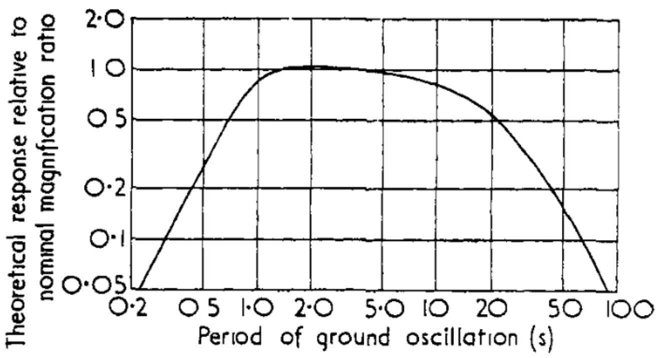

Figure 5.6: Frequency response of Tucker's sensor. From Tucker (1958) © IOP Publishing.

The first feedback seismometer based on this idea that I know of was built in the late 1950's at the British National Institute of Oceanography in Wormley (Surrey). Referring to Benioff's description *Tucker* (1958) constructed a long period pendulum which had several elements of modern feedback seismometers. The movements of the pendulum's bob were measured by a displacement transducer and then controlled by a feedback coil (Fig. 5.5).

The instrument was specifically developed for measuring the ocean microseisms. Hence its feedback loop was tailored for that frequency range. It gave the instrument a reasonably flat frequency response for periods between 1.5 and 12 sec (Fig. 5.6). It is not known if and where this instrument was ever deployed and if more than a prototype or two were ever built.

Shortly after Tucker's development, researchers at what is now the Lamont-Doherty Earth Observatory in

Palisades, New York, began using feedback loops to tackle a big problem which had plagued seismometry for decades: How could one build a compact, long-period seismograph to be deployed at remote sites? While long-period seismographs had existed for quite some time, they could only be used in a controlled observatory setting, where operators would adjust them when needed.

Such adjustments were necessary because any long-period elastic suspension is subject to long-term drift due to several causes. Among them are:

- thermal effects, which change the spring constant and the dimensions of the metal elements of a sensor,
- deformation of the structural elements of a seismometer over time due to fatigue or creep, and
- variations in the barometric pressure, which exert forces on the inertial mass of the sensor.

All of these influences can cause the mass to drift with amplitudes higher than those of the long-period seismic waves of interest.

To compensate for such long-term drift, the group at Lamont used a feedback loop and developed an *"integrated, triaxial long-period seismometer"* (*Sutton and Latham*, 1964). In it, the displacement of the inertial mass from its center position was measured by a differential capacitive plate, which generated a voltage proportional to the displacement of the mass. After some amplification and electronic filtering this output signal was fed into the coil of the coil and magnet assembly originally provided for the damping of the seismometer. The resulting magnetic force acted to restore the seismic mass into its electrical center position, where the output of the capacitive transducer is zero, thus completing the feedback loop.

This design was soon to be tested on a truly remote place, namely the Moon. The Apollo astronauts installed several of these seismometers – the space agency NASA called them *"mid-period sensors"* - on the lunar surface during most of their landings on the moon between 1969 and 1972. Many of them transmitted data back to Earth well into 1977 (*Nunn et al.*, 2020). However, the end of the Apollo program was also the end of the seismometer design efforts by the Lamont group. This sensor type was not developed further for use on Earth.

While the Apollo astronauts were busy on the Moon, several other groups of seismologists and engineers in Europe and in the United States worked independently on improving seismometers for use on Earth by applying feedback loops to various existing seismometer designs. Among them were *Block and Moore* (1966), at Princeton University, who applied a feedback system to a standard LaCoste-Romberg survey gravimeter and used the output to measure the extremely long period modes of free oscillation of the Earth.

Another example is Axel Plešinger and his group at what was then called the Czechoslovakian Academy of Sciences in Prague. In 1967 they outfitted several Russian built Kirnos seismometers with feedback loops (Figure 5.7). Compared to the original open loop Kirnos sensor, this endeavour led to a seismometer system with a flat amplitude response to ground motion over a large period range. The complete response curve of the feedback system is shown in Figure 5.8. Its response to ground velocity between 3 Hz and 300 sec was essentially flat with a fall off of ω^2 at even longer periods (*Plešinger and Horalek*, 1976).

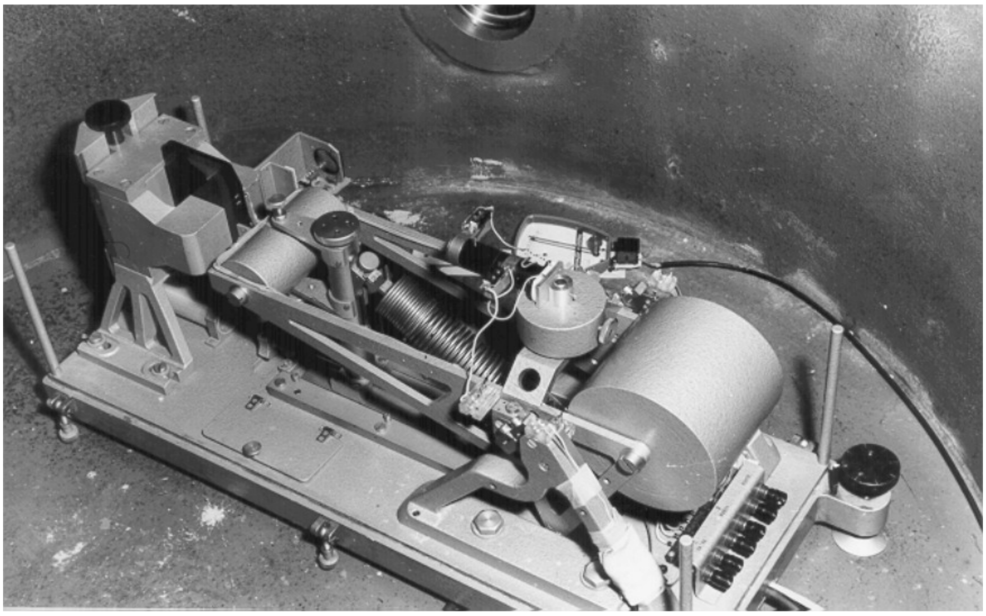

Figure 5.7: *Kirnos Seismometer with Plešinger's feedback loop (Photo: Plešinger)*

Dziewonski characterises this response as giving the instruments *"enough sensitivity to record not only the gravest modes of free oscillations of the Earth, but also the tides. At short periods, frequencies up to 5 Hz could be easily captured, and thus the entire band needed to record teleseismic signals could be accommodated"* (*Dziewonski*, 1989).

The first of these instruments was deployed in 1972 near Bishkek (then called Frunze) in Kyrgyzstan. A year later the group deployed another set at the very quiet Czech seismic station Kašperské Hory (station code KHC) in the Bohemian Forest. The signals of these three component (Z, N/S and E/W) stations were recorded locally on magnetic tape using FM modulation. The feedback-augmented seismometers at KHC operated continuously between 1973 and 1986, making it the very first broadband station in the world. A third set of these seismometers was deployed in 1976 at the station Ksiaz (station code KSP) in southwestern Poland (Fig. 5.9), about 270 km north-east of KHC.

While Plešinger's feedback sensors and other comparable alterations of existing open loop seismometers worked well and were successfully deployed at several locations, these instruments were never manufactured commercially. Hence, despite their - at that time - unique broadband performance they remain singularities in global seismometry.

5.6 Broadband Seismometry Goes Worldwide

While the Czech Group successfully operated their seismic broadband station in the Bohemian Forest for 13 years, their pioneering endeavours were barely recognised in the West. The Iron Curtain, which separated Europe during the Cold War, ran a mere 15 km west of the station KHC, effectively blocking any meaningful open scientific exchange between seismologists on either side of the line. Despite the political deep freeze, Plešinger had good personal contacts to seismologists in what was then West-Germany. Through their national science foundation, the Deutsche Forschungsgemeinschaft (DFG), the West Germans had inherited an old seismic array set-up and operated by the US Air Force in the southeastern corner of West-Germany near the small town of Gräfenberg, less than 180 km north-west of KHC. The original purpose of this array was to monitor underground Soviet nuclear weapons tests. But in the late 1960's, the station and most of its equipment was abandoned by the US military and turned over to German seismologists.

At the same time Hans Berckhemer, the long time chair of the Institute of Meteorology and Geophysics at the University of Frankfurt (Germany) proposed his concept of *"wide band seismometry"* at a meeting of the European Seismological Commission in Luxembourg. He made the case that having a seismometer that covered a spectral range of ground motion between at least 10 Hz and 300 sec was necessary to answer fundamental questions in seismology. He suggested several theoretical realizations, albeit without demonstrating the concepts with his own engineering solutions. However, his contribution was published (*Berckhemer*, 1971) in a small Belgian journal and therefore not widely read.

While the German seismologists were debating what to do with the abandoned array, Plešinger showed them seismograms collected with his broadband instruments - and the German group was impressed. In their discussion strongly influenced by Berckhemer's paper and Plešinger's data, it became very clear to the group that they wanted to rebuild the array and bring it up to the most modern standards of the time. That meant:

1. using highly sensitive broadband seismometers based on the feedback principle,
2. digitizing analogue outputs of the seismometers directly in the field and
3. transmitting the digital data in real time to a central location for recording, initial analysis and archival.

Given the state of seismometry in the world in the 1970s, these were indeed lofty and ambitious goals. In addition, this group of seismologists was just a loose federation of researchers from academia and government institutions which called itself "Forschungskollegium Physik des Erdkörpers" (Research Group for the Study of the Physics of the Solid Earth) - FKPE for short. It had no formal function within Germany's post World War II scientific hierarchy.

Nevertheless, the FKPE convinced the German funding agencies to finance a project which today would undoubtedly be labelled as truly high risk science. At the core of the uncertainty was the fact that, at that time no commercial broadband seismometer existed anywhere in the world. It was Erhard Wielandt, a German physicist who was then working in the Institute of Geophysics at the Swiss Federal Institute of Technology (ETH) in Zürich, who took on the challenge. Inspired by Plešinger's results, Wielandt and his student Gunnar Streckeisen set out to develop a completely new seismic sensor with an integrated feedback loop from scratch. The result of their work became the famous STS-1 (*Wielandt and Streckeisen*, 1982). After some initial tests of the new sensor, the German group decided to use the STS-1 as the heart of its new array.

Beginning with the first deployment in 1975 a total of 19 STS-1 seismometers were installed in the 13 stations of what became known as the Gräfenberg Array (station code GRF). Three of the stations were equipped with three components each, the rest had only vertical components as shown in the left panel in Figure 5.10. Initially the seismometers had a flat response to ground velocity between 20 sec and

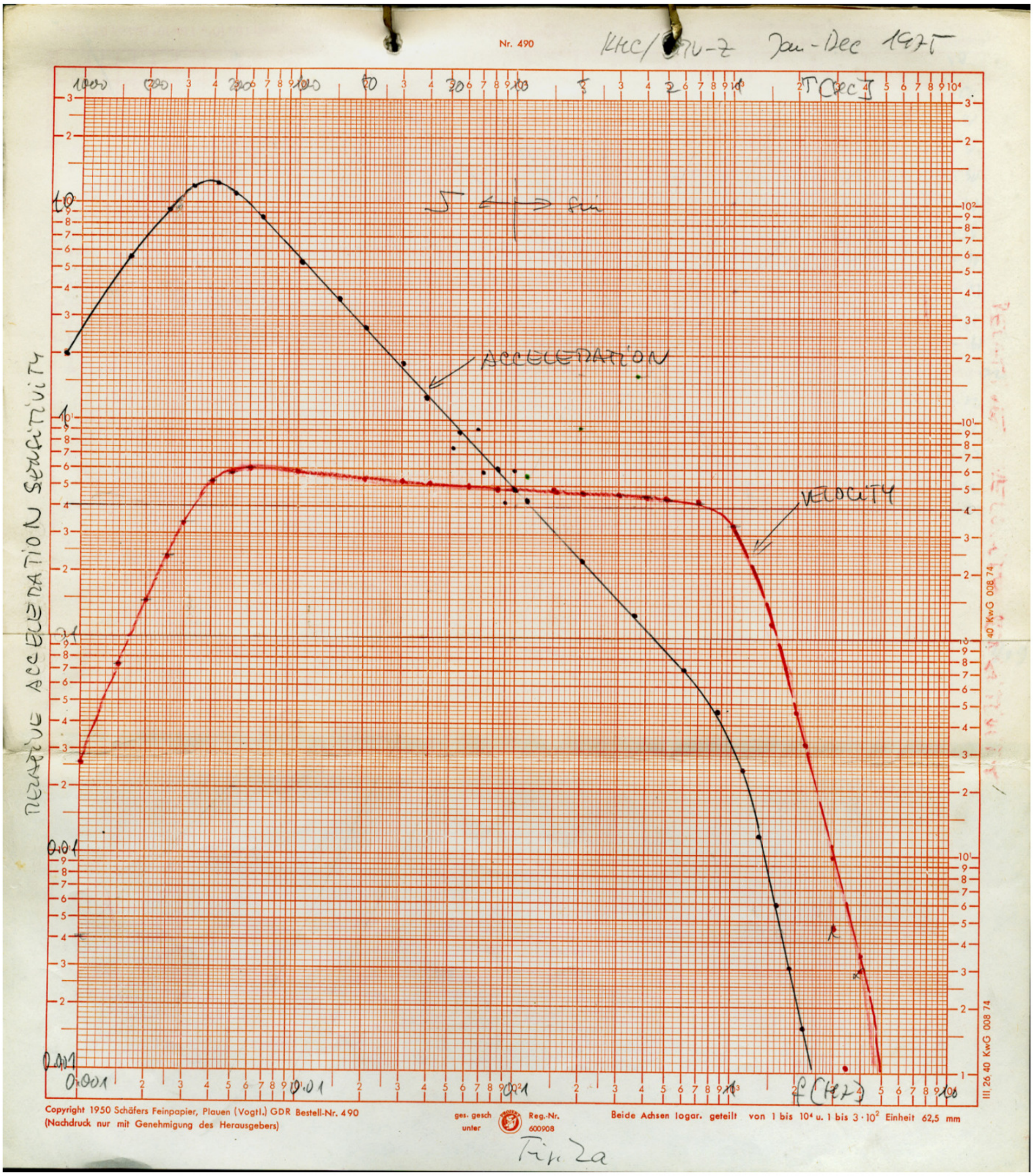

Figure 5.8: *Original measurements of the amplitude frequency response of Plešinger's complete system at KHC. The red line shows the nearly flat response of the system to ground velocities in the bandwidth of 300 sec to 3 Hz. Note that all data points were drawn by hand on log-log paper. From* Kolář, P., The KHC Seismic Station: The Birthplace of Broadband Seismology, Seismol. Res. Lett., *91*, 1057 – 1063, 2020, `https://doi.org/10.1785/0220190326` © Seismological Society of America.

Figure 5.9: *Three component Plešinger feedback sensors in sealed pressure housings in Ksiaz, Poland (Photo: Plešinger)*

5 Hz. Some of them were later upgraded to record ground motion at ultra long periods of up to 360 sec. The upper corner was eventually extended to 15-20 Hz. All data were digitised on site with a 16 bit AD converter with gain ranging. It gave the system a dynamic range of 138 dB, a value completely unheard of in seismology until then.

Finally, the digital data were telemetered over dedicated telephone lines to the central observatory site in the town of Erlangen (*Harjes and Seidl*, 1978). There, all data were archived continuously and are still available today through the German Federal Agency for Geosciences (BGR) in Hanover (`http://eida.bgr.de/fdsnws/dataselect/1/`); data from the station GRA1 is also available through the IRIS Data Management Center. After nearly thirty years of continuous operation, the STS-1 seismometers at GRF showed signs of ageing and in the early 2000's all 13 stations were upgraded with second generation, three component broadband seismometers from Streckeisen.

This unique set-up made the Gräfenberg Array the first continuously recorded, digital broadband array in the world. Because of its impressive results GRF became - at least for a while - the go-to site for seismologists from all over the world, who wanted to learn more about operating a complex array of these newly available broadband seismometers and about digital data acquisition and processing. It also helped Streckeisen, Wielandt's former student, to launch his own company manufacturing the STS-1, short for Streckeisen-Seismometer 1. Within a few years, these sensors became standard equipment for new, top of the line global networks, like the American operated Global Seismic Network (GSN) or the French GEOSCOPE and some of them are still operating today. More information on the Gräfenberg Array and the operational procedures of BGR can be found in their ISC Summary article (*Hartmann et al.*, 2018).

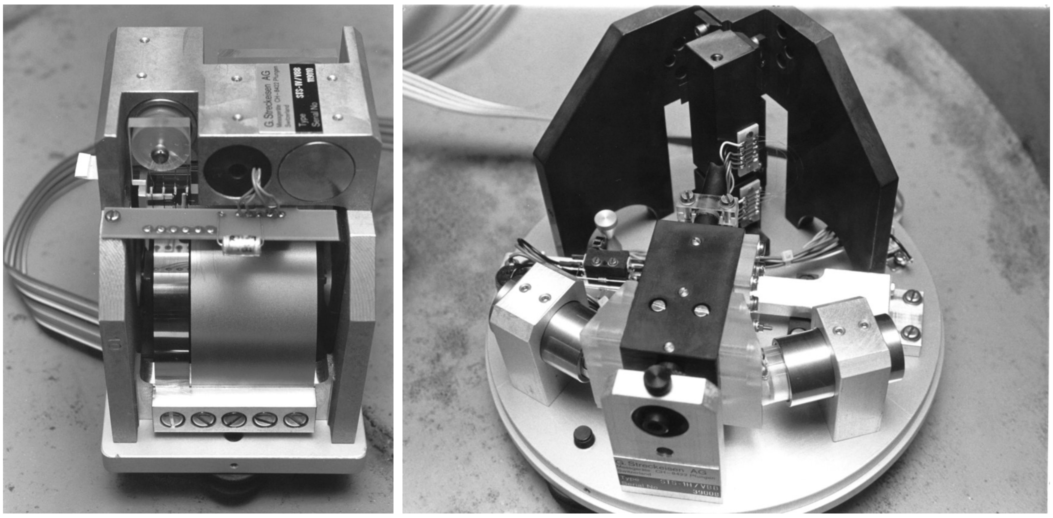

Figure 5.10: *The STS-1 seismometer. The vertical component with its famous leaf spring is shown on the left, a horizontal component on the right. (Photos: Rick McKenzie, UC Berkeley)*

5.7 A Broadband Borehole Seismometer

In the meantime scientists and engineers on the opposite side of the Atlantic were also busy developing seismic sensors with feedback systems. The most consequential work took place in the early 1970's at the Teledyne-Geotech Company in Garland, Texas. Under a contract with the Advanced Research Projects Agency (ARPA) of the US Department of Defense, the engineers at the company designed a broadband, three-component borehole seismometer with the goal of upgrading or replacing some stations of the WWSSN. The new concept was called Seismic Research Observatory (SRO) and in addition to using broadband seismometers, the plan was to record all data digitally. A borehole solution was chosen to help reduce the ever present long period seismic noise at the Earth's surface.

The new borehole seismometers contained three orthogonally oriented sensor modules and their associated electronics (see Fig. 5.11). It was mainly developed by two Geotech engineers, B.M. Kirkpatrick and O.D. Starkey. The mechanical configuration of the sensors was of conventional design; a LaCoste suspension was used for the vertical and "garden-gate" suspensions were used for the horizontal components. The sensors were of a force-balance type with capacitive transducers, based on the concept of *Block and Moore* (1966). As the signal of such capacitive transducers is proportional to mass displacement rather than mass velocity, their output was higher at low frequencies when compared to conventional seismometers (for a full description of the SRO stations see *Peterson et al.*, 1976). The instrument was named KS-36000, using the initials of the last names of the principal developers.

Despite the fact that each of the sensors in the KS-36000 had an output proportional to displacement over the frequency range from 50 sec to 1 Hz, this output signal was filtered at the wellhead to produce the short- and long-period signals, which were finally recorded (see Figure 5.12). While this arrangement had the advantage of almost completely blocking out the mostly unwanted ocean microseisms with periods of 6-8 secs, it also diminished the inherent "broadbandedness" of the seismometer. When compared, for example, to the amplitude frequency response of Plešinger's seismometer (Fig. 5.8) it is clear, that the filtering process prevented the SRO station from collecting the full information contained in the Earth's ground motions in the seismically relevant band.

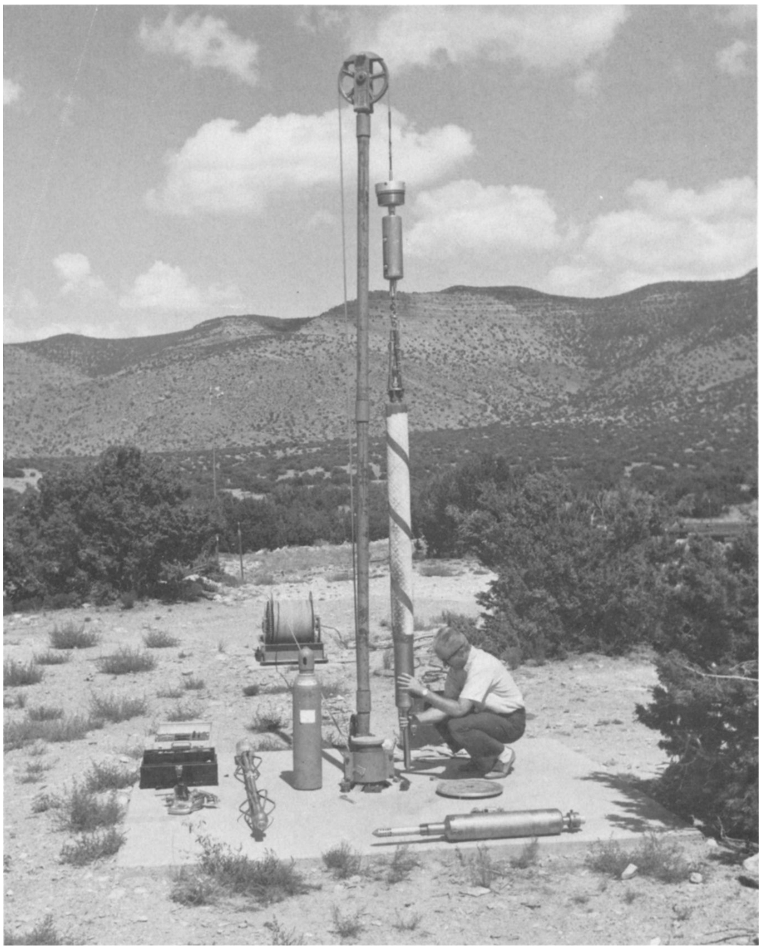

Figure 5.11: The first broadband borehole sensor, named KS-36000, was installed in a borehole at the Albuquerque Seismology Laboratory in July 1974. From Peterson et al., The Seismic Research Observatory, Bull. Seismol. Soc. Am., 66(6), 2049 – 2068, 1976, https://doi.org/10.1785/BSSA0660062049 © Seismological Society of America.

The initial preproduction SRO-System was deployed for testing at the Albuquerque Seismological Laboratory in New Mexico in July 1974 (Fig. 5.11, right). In the following years a total of 13 stations were installed globally, one of which was installed in a 150 m deep borehole at the main station of the Gräfenberg Array in the village of Haidhof (station code GRFO).

Both broadband sensors, the STS-1 and the KS-36000, brought seismological data acquisition to a completely new level. These sensors and their digital data recording systems made it possible to collect seismic data over a much wider frequency range using just one instrument. But both systems were extremely complex, very difficult to manufacture and hard to install, even by skilled personnel. For instance, each component of an STS-1 had be installed in an air tight arrangement under an evacuated glass bell. This vacuum was necessary to prevent pressure changes in the seismic vault from affecting the sensor's long period performance. They also had to be well protected from any temperature fluctuations and shielded against variations in the magnetic field. To reduce the effects of the dissipated heat generated by the feedback loop within the KS-36000, each borehole instrument casing was filled with Helium and wrapped with foam insulation before being lowered into the borehole. During the manufacturing process, each individual KS-36000 sensor was sealed in containers *"baked and evacuated to lessen the possibility of internal convections"* (*Peterson et al.*, 1976). In addition the systems were

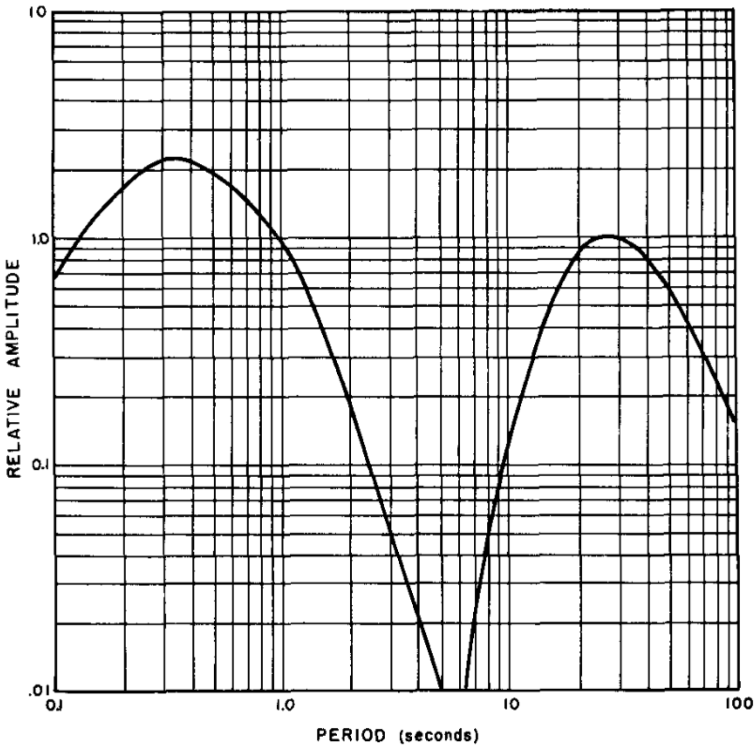

Figure 5.12: *The final output transfer function of the SRO stations. From* Peterson et al., The Seismic Research Observatory, Bull. Seismol. Soc. Am., 66(6), 2049 – 2068, 1976, `https://doi.org/10.1785/BSSA0660062049` © Seismological Society of America.

fairly big. The entire KS-36000 arrangement deployed in an SRO borehole was almost 4 m long, and the three separate components of the STS-1 each under its own glass bell needed several square meters of space on a seismic pier. In short, like Plešinger's seismometers, this first generation of commercial broadband sensors was anything but field worthy. They had to be carefully installed and maintained in boreholes or in seismic observatories in well constructed seismic vaults and on well built piers.

5.8 Small, Compact, Field Worthy and still Broadband

Most of the people whose contributions to the development of broadband seismometers controlled by feedback circuits described above were either seismologists or engineers with long experience with building seismic measuring equipment. While their equipment worked very well and certainly lifted seismology to new levels, it may take scientific outsiders to bring fundamentally new ideas into an established scientific field like seismometry. Two such outsiders to Earth science were Peter Fellgett and Mike Usher at the University of Reading in England. Fellgett had a lifelong interest in scientific instruments. He was however rather critical about the processes in which most of these instruments were developed, particularly about the widespread discrepancy between their performance "in theory" versus the actual results. He claimed this not to be *"good science, which demands that if theory and practice differ, then one or both must be improved"* (*Fellgett*, 1984).

With this premise in 1964 Fellgett became Professor of Cybernetics and Instrument Physics in Reading and the first director of the department. There, his interest in instrument science continued and he encouraged Mike Usher, one of the cyberneticists working in his department, to develop a rather small seismometer which should be able to record ground motions with very long periods.

Usher enlisted the help of R.F. Burch from the Blacknest Seismological Centre operated by the British Atomic Weapons Research Establishment in nearby Aldermaston to design and built a horizontal component "wideband miniature seismometer". This sensor was small indeed, measuring just a few centimetres across (see Fig. 5.13). The position of the small inertial mass of only 40 g was measured relative to the instrument frame by a differential capacitance transducer and controlled by a negative feedback loop using a coil-magnet arrangement (*Usher et al.*, 1977). Usher's graduate student Cansun Guralp took this design to a new level by designing and building a complete, three component, broadband miniature seismometer (*Usher et al.*, 1978).

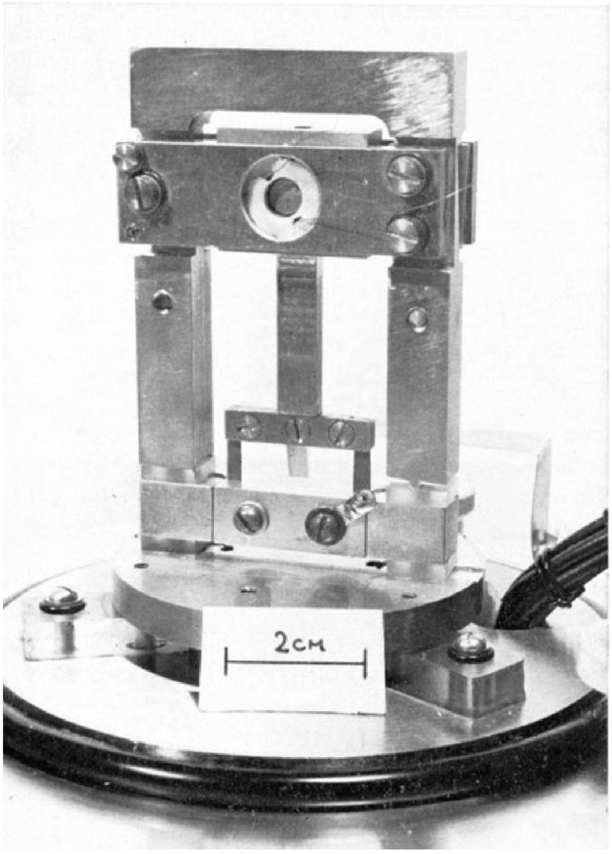

Figure 5.13: *The mechanics of Usher's horizontal miniature broadband seismic sensor. From* Usher et al., (1977) © IOP Publishing. Reproduced with permission. All rights reserved.

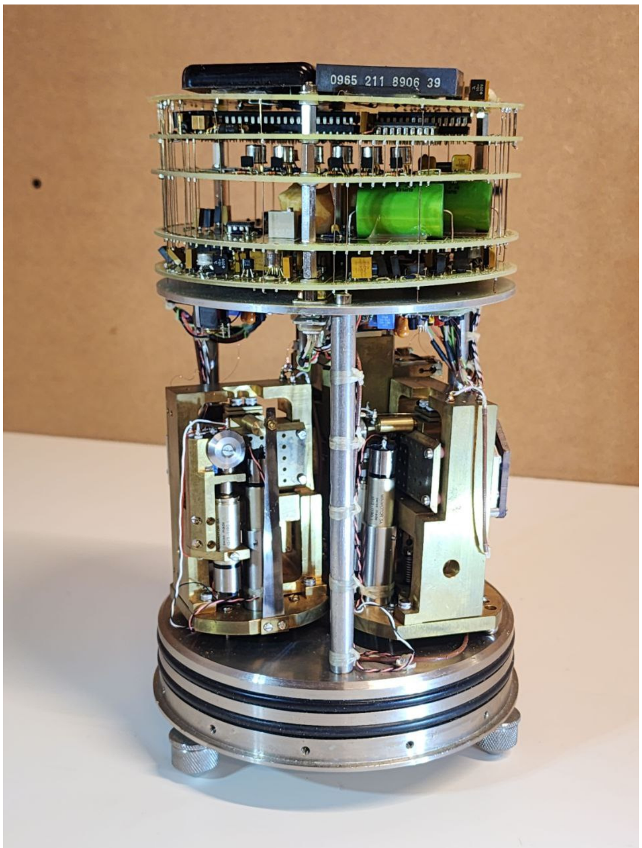

Figure 5.14: *The very first production model of the Guralp 3T seismometer without its casing. It was the first portable triaxial broadband seismometer. (Photo: Horst Rademacher)*

After obtaining his Ph. D. from Reading in 1980 with a thesis on designing a three component wideband borehole seismometer, Guralp founded his own company. There, he arranged the three components and the respective feedback electronics of the miniature wideband sensor into one cylindrical package with a diameter of just 17 cm and a height of less than 30 cm. The result was the Guralp 3T, the very first portable three component broadband seismometer (Fig. 5.14). It did not need to be installed in an observatory vault, but could be deployed even under rough field conditions. Its standard version had a flat response to ground velocity between 120 sec and 50 Hz. Over the decades, more than a thousand of these seismometers have been built in various versions, and as of this writing, the instrument is still in production.

5.9 An Initial Look at Broadband Seismograms

Despite the convincing theoretical underpinnings of the new developments and the technological advances described above, broadband seismograms were not accepted immediately in the broader seismological community. I will never forget the reaction of my former thesis adviser at the University of Cologne (Germany), when I showed him one of the first broadband seismograms we had collected at the Gräfenberg-Array in the late 1970's: This record is horribly noisy, he remarked, referring to the strong ocean microseisms dominating the seismogram. He was used to analysing only seismograms from short period seismometers, which did not record these microseisms with periods above six seconds - and also nothing else in the long-period range of the seismic spectrum. As previously mentioned, this criticism was the main reason why the initial output of the broadband borehole seismometers of the SRO stations was notch filtered to eliminate the ocean microseisms (Fig. 5.12).

Over time, however, the treasures hidden in the recordings of broadband seismometers became clear. In one of the first analyses of broadband data from the Gräfenberg Array, *Kind and Seidl* (1982) showed example records from medium sized earthquakes in the Chile-Bolivia border area recorded at GRF at an epicentral distance of almost 100 deg. Figure 5.15 shows three 15 sec long traces of the P-wave arrival of a M=6.5 quake in that region. The bottom trace depicts the unfiltered broadband recording of the vertical component at one of the GRF stations. The two traces above are digital simulations of how standard WWSSN seismometers would have recorded this P-wave train with the long period (LP) instrument (middle trace) and the short period (SP) (top trace) WWSSN sensors.

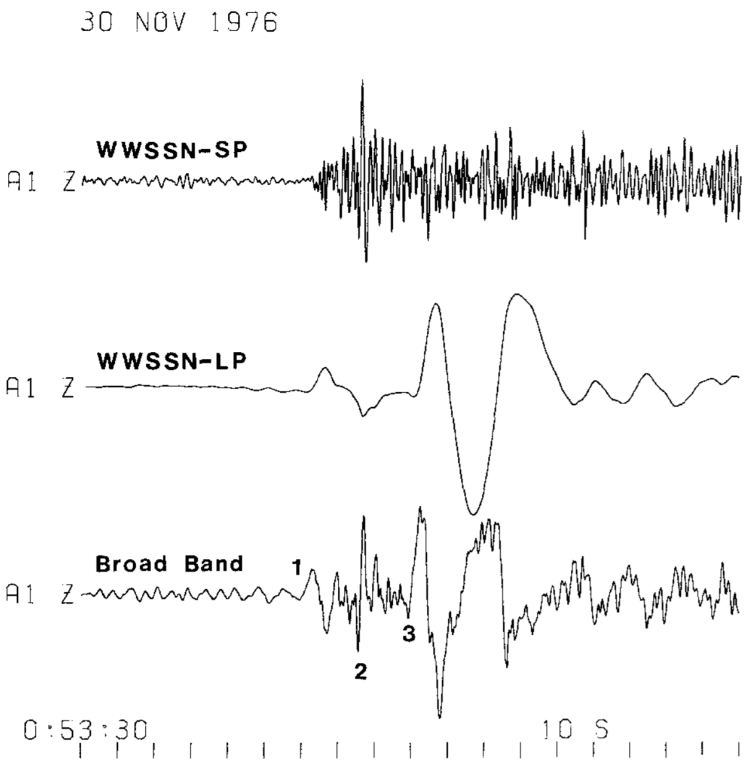

Figure 5.15: *15 sec long recording of the arrival of the P-wave of a M=6.5 earthquake in the Chile-Bolivia border region at the vertical component of GRF station A1. The bottom trace depicts the unfiltered broadband data, the traces above are digital simulations of WWSSN LP- and SP-seismometers, respectively. From* Kind, R. and Seidl, D., Analysis of Broadband Seismograms from the Chile-Peru Area, Bull. Seismol. Soc. Am., 72(6), 2131 – 2145, 1982, `https://doi.org/10.1785/BSSA07206A2131`, © Seismological Society of America.

There was of course no real WWSSN station in Gräfenberg. Instead the authors programmed bandpass filters which had the same characteristics as the transfer functions of the SP- and LP-WWSSN seismometers respectively. After applying these filters numerically to the broadband data, they were able to simulate the WWSSN recordings. With appropriate filters, almost any of the open loop seismometers existing at that time could be simulated. This, of course was only possible because of the inherent broadbandedness of the sensors and the digital recording of their outputs.

5.10 Summary

I have tried to recount the early development of broadband seismometry in the late 1970's and early 1980's. In this part, I focussed on the instrumentation, first by explaining the basic principles of feedback seismometers and then describing the work of various groups in Europe and in the United States in designing and building such sensors. In a second instalment I will focus on the digital recordings and describe some of the techniques used to apply broadband data to seismological analysis. I will also attempt to describe later technological development in the field of broadband seismometry and finally give an overview of how data from these instruments have contributed to the advancement of seismology in general and to our understanding of the Earth's interior and of earthquake source processes.

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The topics covered in this contribution were drawn from a graduate course on Seismic Instrumentation I gave in the Department of Earth and Planetary Science at the University of California, Berkeley. I thank Dmitry Storchak (International Seismological Centre, UK) for suggesting this expose. I am very grateful to Erhard Wielandt (Prof. em., University of Stuttgart, Germany), Axel Plešinger (formerly Czech Academy of Sciences) and Cansun Guralp (Gaiacode Ltd., UK) for critically reading the text. Their suggestions led to major improvements. I also thank Axel Plešinger and the staff of the Berkeley Seismological Laboratory (UC Berkeley) for providing me with photos of some of the early broadband instruments. Editor Kathrin Lieser (International Seismological Centre, UK) diligently pointed out inconsistencies in the text and secured all copyright permissions. Despite having such high level help, I am solely responsible for all errors - big and small - the reader may find in the text. If any reader has additional information about the early days of broadband seismometry, please drop me a note (`horst@berkeley.edu`). I always like to learn more...

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