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Radio Emissions From an Earthquake*

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Abstract—Earlier we associated radio emission preceeding the great Chilean earthquake of 1960 with the quake by virtue of the emission region's size (if its source were the subsequently observed rupture zone) and the required direction of arrival at the observation station in Boulder, Colorado. Through analysis of the power relations between the emission in total power and signal levels in the interferometer, which failed to observe the emission in phase power, it is possible to deduce the least source size, under the plausible assumption that the emissions propagated nearly horizontally. This size is 3.1 degrees; the next larger possible solution for sources at this azimuthal range is 6.2 degrees. For signals arriving from the azimuth of the center of the rupture zone as seen from Boulder, the least source size is 3.47 degrees; a solution of 6.94 degrees is also possible. The total span of the rupture zone in azimuth was 3.5 plus or minus 0.2 degrees. The agreement with the least source size for the azimuth of the rupture zone is excellent and is further evidence for the reality of the association.

I have been asked to talk to you about radio emissions from earthquakes even though I have not seen evidence from equipment I have operated that earthquakes do in fact produce radio emissions. Nevertheless, I have published one paper (Warwick, Stoker, & Meyer, 1982) on the possible connection between radio emission and a subsequent major earthquake. Not having done more in the intervening 10 years than request money to enlarge this database, a request that was denied, I feel it might be inappropriate to present, once again, my meager evidence here today.

During the International Geophysical Year the High-Altitude Observatory in Boulder, Colorado undertook to implement devices to detect solar flares via their prompt effects on Earth's ionosphere. These are produced, as was suspected at that time and is now well known, by flare emission of soft X-rays, which increase ionization in the lowest regions of the ionosphere. Ultimately, these flare detection devices were situated at stations around the world, but in May 1960 they were located at four places: southern Michigan, north central Colorado, southern New Mexico, and Oahu, Hawaii.

This equipment recorded the levels of cosmic radio noise power at ground level, where the power has been degraded by whatever absorption occurs in the ionosphere. It operated at 18 MHz where the cosmic background has a peak intensity close to that of a 100,000 K blackbody radiator.

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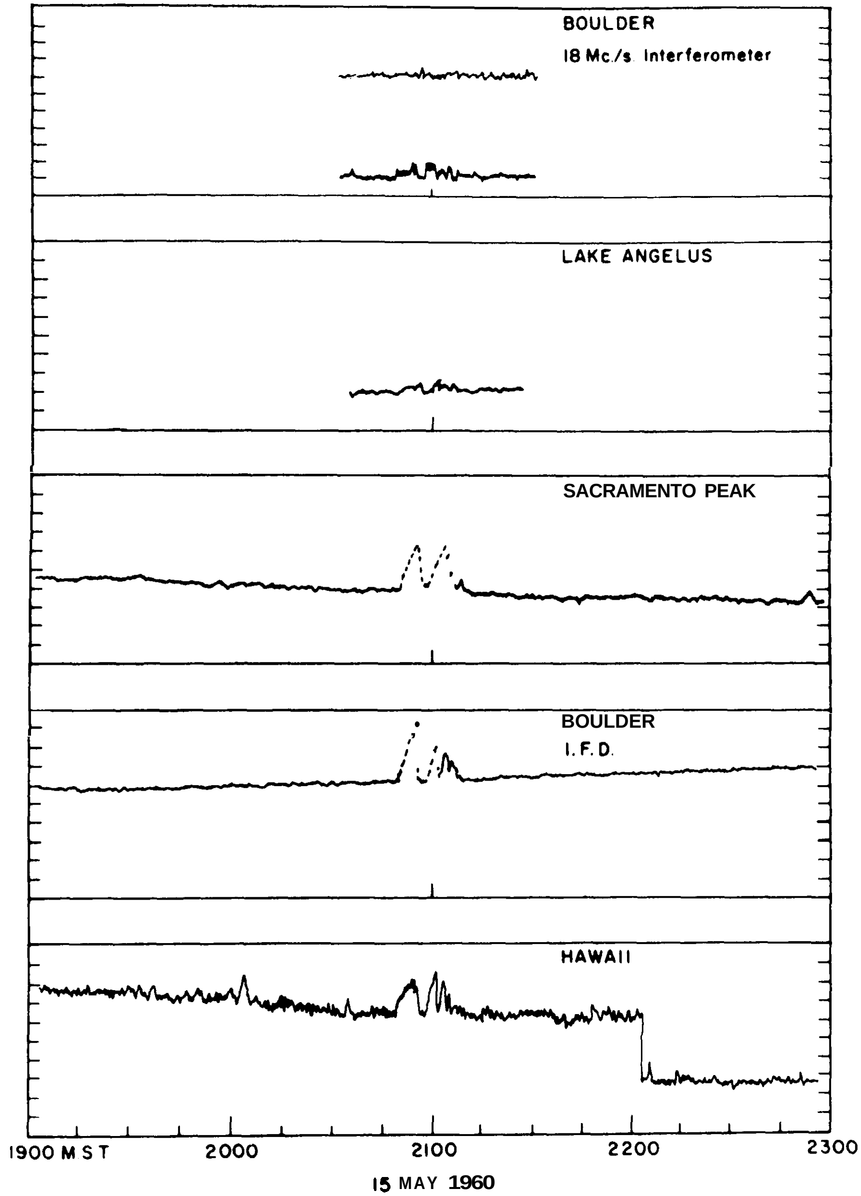

Fig. 1. The May 16, 1960 radio event as seen at stations in Boulder, Colorado; Lake Angelus, Michigan; Sacramento Peak, New Mexico; and Makapuu Point, Hawaii. The uppermost data pair are from the radio interferometer in Boulder. The upper trace is the phase power channel of the interferometer and shows no signal. The lower trace is the total power channel of the interferometer on which the signal appears. From Radio Astronomical and Satellite Studies of the *Atmosphere* (p. 419) edited by Jules Aarons, 1963, Amsterdam: Elsevier. Copyright 1963 by Elsevier Science Publishers. Reprinted by permission.

Radio receivers at such a low frequency are subject to continuous bombardment by intercontinental telecommunications signals, often many times more intense than the cosmic noise background radiation. These signals are typically quite narrow band, however, which in effect allows there to occur narrow, signal-free, frequency channels randomly throughout the radio spectrum in this range.

The flare detectors took advantage of this feature of the 18 MHz spectrum by scanning in frequency over a limited range, about 100 KHz, and by recording only the minimal levels detected in the range. This technique permitted the sky background radiation to be detected continuously and automatically, subject of course to the limitation that the precise frequency recorded, over the 100 KHz scanning range, was not known. On the other hand, the variation in sky radiations is minute within that range. The recorded radiations, therefore, are a good sample of 18 MHz broadband emissions probably not (because of the bandwidth scanned) of man-made origin.

In addition to these four flare detectors there was an interferometer in Boulder operating at the same frequency and with the same kind of minimum detection scheme. The interferometer used a pair of narrow-beamed antennas directed towards the zenith (like the flare detector antennas). Its output comprised two traces. One was identical in character to the flare detectors except for its recording the maximum levels of the putative seismic signals (see Figure I). The other could record the phase-sensitive fluxes of any small radio sources that happened to lie within the primary anenna beams.

For example it detected the daily culminations of the bright radio stars Cas A, Cyg A, Vir A, and Tau A. They provide unequivocal evidence that the interferometer trace was operating with high sensitivity both before and after the event in question, although at that exact time no strong radio star lay within the antenna beams. Furthermore, the equipment detected Sun and Jupiter when they were active. These planetary-system sources are quite characteristic in our records.

Figure 1 (from Warwick, 1963) shows the entire data set I wish to discuss: the four flare-detector records and the pair of traces for the interferometer. The time constants for the flare detectors are set at values that produce rapid fall to lower levels but slow rise to higher levels. This scheme is manifested by the saw-tooth shape of the radiations from the putative seismic event as recorded by the flare detectors. The total power side of the interferometer exhibits the same kind of structure with a somewhat more sophisticated time constant layouts but with a fast rise-time for signals not exceeding anominal level. In this way, we hoped to be able to detect solar and planetary signals faithfully and still gain the advantages of minimum detection when strong interferences were present.

That layout proved important for the event at 2100 MST on May 15,1960 (Figure 1). The sensitivity of the total power side was set so that full scale was four times cosmic background. The scale is roughly linear in power. The maximum flux levels in the event were equal in magnitude to the cosmic noise level. We do not know the zenith distance of the event. There remains an unknown pattern correction that must be applied to the data. Its upper limit is 10 dB.

The event occurred at 2100 hours local time in Boulder, after sunset, but during late twilight. Night had fallen at the time the Michigan record was taken. It was late afternoon in Hawaii. This is a range of about five hours in hour angle as perceived by the various stations. The range of zeniths covers more than 20 degrees in declination on the celestial sphere. The large range of viewing geometries implies that we are not recording an astronomical source. That is, the observing conditions differ radically and yet the source is recognizably similar among all stations.

Perhaps the most remarkable aspect of these records is the absence of any trace of the emission from the phase-sensitive side of the Boulder interferometer chart. The gain is set so that the flux of **Cas A,** passing directly through the center of the antenna beam, produces about one-half full scale on the chart as displayed. Cas **A** increases the total power side of the chart by an amount too small to indicate on the chart, namely about 20 dB less than the cosmic background flux recorded with this antenna.

The mystery source must be present, although it is suppressed on the phase-sensitive side.

We need to discuss briefly how this remarkable situation can occur. The interferometer creates two antenna patterns, each comprising many narrow, sinusoidal (in voltage), antenna lobes, called "fringes." The two sets of fringes are virtually identical, differing only insofar as their voltages are relatively inverted. The two sets of lobes are like the interdigitated fingers of your clasped hands.

The "phase" side of the record is produced automatically by the interferometer, which switches between the two antenna patterns and stores the powers recorded by each. Instead of plotting each separately, it subtracts one from the other (always in the same order). The cosmic noise background power, virtually identical in the two patterns, cancels out. The difference power, plotted with much higher gain than the total power, is called the interferometer output. To allow recovery of the actual powers present in each antenna configuration, we also plotted the sum of the powers in each. That is the total power side of the interferometer record.

The total power is essentially identical to the power seen by the flare detectors at all four stations, but there is no difference power. For this to happen, the source of this radiation must lie distributed identically over the two different lobe systems.

The only way in which this can reasonably happen is if the source of the radiation is at least as large as the interferometer lobes. Suppose that it is a uniformly intense linear source that crosses the lobe pattern perpendicular to the fringes and therefore, if its altitude is small, essentially parallel to the horizon. We assume that each point on this source radiates independently of the other points. The different points produce either positive or negative output. These add to make up the source power observed in a given position of the phase switch. If the source covers an integral and equal number of positive fringes and negative fringes, the summation of the independent powers from different parts of the source will add up to zero power.

"Zero power" needs to be made more precise. I think that I can just see what might be residual traces of the total power source on the phase-sensitive side of the record. I could be argued out of this, but it may ultimately be unimportant how precisely this cancellation does in fact occur. This residual visibility amounts to about 10% of full scale on the record, which corresponds to about one-fifth of the flux density of Cas A in the zenith. This is, in turn, about one one-hundreth of the unknown source's amplitude on the total power side of the record. The length of the phase-sensitive source fails to cover an integral number of fringes by about one part in 500. If the source covers two complete fringes almost (but not quite) exactly, then its integral deficit may be only one part in 250.

The source might cover many more fringes. If it covers a great number of fringes, the required precision of fringe covering decreases. The maximum number is 37, which requires that the integral deficit be about one in seven. The length of the source is therefore about 0.14 of a fringe separation less or more than a precisely integral number of fringes. This is still a coincidence to a high degree and therefore remains an uncomfortable conclusion.

I believe that a literal interpretation of the fringe vanishing is the only plausible solution to this dilemma, despite the degree of coincidence it requires.

In my previous discussion of the possible relation of this event to the Chilean quake on May 22, 1960, I compared the ends of the rupture zone of this quake as defined by seismology to the view of these ends as perceived by my interferometer in Boulder Colorado. That comparison is shown in Figure 2 (Warwick et al., 1982).

The measured ends of the quake are plotted on a map of the southern sky, near the Boulder horizon. The map also shows the interference fringes, labelled positive or negative, and gives their azimuths in degrees and tenths of degrees. The quake ends are spaced 3.5 degrees apart along the horizon. In this azimuth range, the interferometer fringe spacing is 3.47 degrees.

It is daring, perhaps even outrageous, but I suggest that these two independent measured quantities agree within 0.03 degrees out of a total of 3.50 degrees is not an accident, but definitive proof that the source of radio waves recorded by our interferometer was of almost precisely the same size as the Chilean rupture zone.

What is daring about this suggestion is manifold. First, do we know the interferometer system this accurately? The brief answer to that is yes, because it is a matter of survey and electrical measurement, both of which we tried to accomplish as accurately as our equipment and skills permitted.

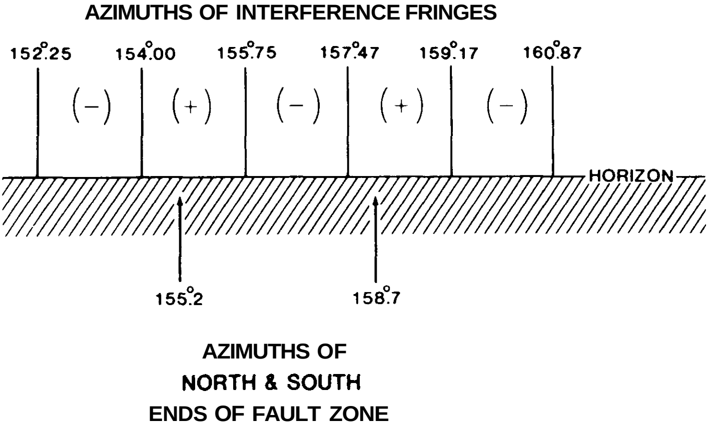

Fig. 2. Fringe geometry of the Chilean shock of May 22, 1960, as seen in Boulder, Colorado.

Second, do we know what happens to angles of arrival (in the plane of the horizon) to precisions of hundredths of degrees? I'm not certain that we do, although it is more likely that the differential deflections in the horizontal plane are small than that the deflections in a vertical plane are small. Whether "small" is measured in hundredths of degrees is, for the time being, a moot point.

Third, do we know the ends of the rupture zone sufficiently accurately? I would like to think that they are probably pretty well defined, although whether this is to within 10% of the overall length of the rupture is probably questionable. Allowing for errors on either end of the fault, I estimate that we know its perceived length (in Boulder) to lie in the range 3.3–3.7 degrees. Fringes (positive to negative and back to positive) have widths 3.3–3.7 degrees in the azimuth range (along the southern horizon) from about 147 to 165 degrees.

Basing our azimuth measurement solely on the coverage of just one fringe with zero integral deficit, I conclude that the emissions might have arrived from almost (ranges of 15.8 degrees centered on the east point and 8.3 degrees centered on the west point are excluded) anywhere around the horizon. But, the source size could range from a minimum of 3.165 to a maximum of 15.42 degrees. In other words, the hypothetical Chilean fault zone source is about as small as the source can be and satisfy the interferometry.

Finally, even if we accept all of the above interpretation, how do we know that the source of the emission is identical to the subsequent rupture zone? We, of course, do not know that. I would prefer to turn the question around: it seems that we have *prima facie* evidence that the source of radio emission was identical, within the errors of observation, to the section of the fault zone that ruptured six days later.

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