A TELEMETRY LINK FOR AN EARTH PENETRATOR

THURLOW W.H. CAFFEY
Sandia Laboratories
Albuquerque, NM

Summary. The design and field-testing of a telemetry link to send signals to the surface of the earth from an earth penetrator are described. The link uses a PCM/FM format at a frequency of 10.5 kHz, dissipates 8 watts, and fits within a cylinder with an inside diameter of 100 mm. A bit error rate of less than 10^{-5} was achieved from a depth of 52 meters at a bit rate of 10^3 bits per second.

Introduction. Interest in a variety of geologic and volcanic parameters near the surface of the earth such an soil moisture, conductivity, and temperature has generated a need for the implantation of probes to depths of 50 meters. Such probes are typically fired from a gun pointing vertically downward, and often the measurement of the deceleration load upon the vehicle and the monitoring of some internal functioning parts is required. Previous attempts to provide this information have taken the following three forms:

1. Recover the penetrator and extract the contents of an on-board memory. This method is expensive at best, and some penetrators have been abandoned at depths of less than 50 meters with a total lose of information.

2. Deploy a fine wire from the penetrator to the surface. This method had to be abandoned for impact velocities above 300 m/s due to breakage of the wire.

3. Drill a hole parallel to the intended descent path and emplace a receiving system for lateral transmission through the soil from a 220-MHz telemetry system within the vehicle. The cost of hole-drilling, together with the fact that a penetrator does not necessarily either descend or come to rest vertically, discourages this approach.

The method described in this report is that of transmission between two vertical magnetic coils, one upon the rear of the penetrator and the other upon the surface of the ground offset from the descent path. This article first describes the choice of transmission scheme based upon considerations of signal-to-noise ratio. The design and results of a typical field experiment are presented. Further details of the work summarized here are available [1] as

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is the description of another approach to the penetrator telemetry problem due to Galbraith [2].

Choice of Transmission Scheme. Because the earth is a conducting medium, a source of atmospheric noise generates a wave which propagates, at a large distance from the source, with a predominately vertical polarization and which is slightly tilted in the direction of propagation. A shielded receiving coil is required to eliminate the effect of the two E-field components, and the coil axis should be perpendicular to the surface of the earth in order to eliminate the effect of the H-field noise. The receiver noise is thus set, neglecting man-made sources of noise, to the thermal noise level of the antenna-preamplifier combination.

The vertical orientation of the receiving coil would permit its use with the vertical H-field component from a buried coil with either a horizontal or vertical orientation. The vertical H-field from the buried vertical coil is much stronger than that for buried horizontal coil, so that transmission between two vertical coils emerges as the best choice.

In the formula for the induced voltage, the transmitting coil is assumed to be buried a distance z = -h below the origin of a cylindrical coordinate system located at the air/earth interface with the coil axis along the z-axis. It is also assumed that displacement currents are negligible with respect to conduction currents in the earth. The formula for the voltage induced in a receiving coil located near or upon the surface of a semi-infinite, homogeneous earth is due to Wait [3] and given below:

$$V = \frac{\mu_o \omega (NA)_r (NAI)_t}{2\pi h^3} \int_0^\infty \frac{x^3 \epsilon^{-\frac{xz}{h}} \epsilon^{-(x^2 + j\mu_o \sigma \omega h^2)^{1/2}}}{x + (x^2 + j\mu_o \sigma \omega h^2)^{1/2}} J_0\left(\frac{x\rho}{h}\right) dx \quad \text{volts.} \qquad (1)$$

In Equation (1) the symbols have these meanings:

V = voltage induced in a vertical coil by vertical H-field
N = number of coil turns
A = cross-sectional area of a coil turn, m^2
r,t = subscripts to denote receiving or transmitting coil
I = current in rms amperes
z = height of the center of the receiving coil above the surface, m
h = depth of the center of the transmitting coil beneath the surface, m
ρ = radial distance in a horizontal plane between the centers of the two coils, m
x = h times the separation constant, λ, of Bessel's equation of order zero which results from solving the wave equation with azimuthal symmetry
μ_o = permeability of free space, Hy/m

ω = angular frequency, rad/sec
J_0 = Bessel function of the first kind of order zero.

The terms outside the integral in Equation (1) describe the voltage induced in a coil whose axis coincides with that of the source coil located an axial distance h away in free space. The integral is the modification of the free space field due to both the semi-infinite conducting earth and the radial offset. The system design is based upon the formula for a homogeneous earth, and the choice of the parameters (ρ,z,σ,ω) in indicated below.

Choice of Design Parameters. The soil conductivity, σ, varies over a considerable range of values and because it is difficult to measure σ at every possible test site, it was desirable to find a value of σ which would conservatively apply to most locations in the continental United States. A detailed conductivity map of the U. S. prepared by the FCC from data supplied over the years from radio station licencees is available but is too large to include here [4]. The major area of highest conductivity is the central third of the U. S., and the major area of lowest conductivity roughly corresponds with the Appalachian mountain range. Keller and Frischnecht [5] have also compiled a conductivity map based on the rate of decay in field strength from about 7000 radio broadcast stations. Their map agrees with the main features of the FCC map, but there are many differences in detail. The accuracy in either map is limited by the fact that the relatively few observation sites were determined by the commercial aspects of siting commercial broadcast transmitters rather than by a requirement to provide a national conductivity map. Figure 1 is a distribution curve adopted from [5] which shows that a design value of 100 mmhos/meter should be a conservative choice since all of the data suggest that it should seldom be exceeded.

Because of the shielding and orientation of the receiving coil, the noise level is set by thermal processes within the receiving system so that the maximum signal-to-noise ratio as a function of frequency will occur at the frequency for which Eq.(1) is a maximum. Choosing ρ = 10 m, h = 50 m, and z = 0.25 m results in Figure 2 which shows a broad relative maximum near 8500 Hz. A frequency of 10 500 Hz, a standard IRIG frequency, was chosen because of the availability of hardware. The reduction in received voltage due to this choice is less than 1 dB. Figure 3 shows the effect upon the induced voltage as each of the parameters ρ, h, and σ are separately varied with respect to the design values which are marked with a dot on each curve.

Coil Designs. Examination of Equation (1) shows that it only remains to choose the quantities $(NA)_r$ and $(NAI)_t$. It is preferable to make $(NA)_r$ as large as possible to reduce $(NAI)_t$. The receiver coil was finally sized so that it could be readily transported between the wheel wells of a station wagon or 1.18 meters square. The coil consists of 6 square planes, 109 centimeters on a side, each of which supports 40 turns of 24SF wire wound in a basketweave pattern to reduce capacitance between turns. A 6-millimeter spacer was used between planes, and between the end planes and the slotted shield. The inductance and resistance between each side of the balanced assembly and the output common was 50.3 mHy and 320 ohms measured at 10 500 Hz. The $(NA)_r$ was 239 square meters and the weight of the coil, including the 6-mm thick aluminum shield, was 63.5 kg.

The choice of $(NAI)_t$ was based upon both the receiver noise and the desired quality of transmission, namely a bit error rate of 10^{-4}. The IF bandwidth was established as 1600 Hz due to the availability of IRIG ±7½% discriminators, and the anticipated maximum bit rate was 1000 bits per second. The product of the IF bandwidth and bit period was 1.6 so that the required SNR in the IF became 20 dB [6]. The receiver noise in the IF bandwidth, including the effect of the antenna impedance upon the preamplifier noise contribution, was 290 nV so that a minimum signal of 2.9 µV was required. The use of this value and $(NA)_r = 239 m^2$ in Eq.(1) leads to a $(NAI)_t$ of 0.57 amp-m^2. The possibility of winding the coil within a narrow groove upon the outside of the penetrator was prohibited by structural considerations, so that an aft-protruding coil was required. The transmitting coil van wound with 126 turns of 23SF wire on a 93-mm diameter cylinder, and was driven with 1.0 ampere rms from a Class-D amplifier [7] to provide a $(NAI)_t$ of 0.86 amp-m^2.

A Typical Experiment. The experiment described here was performed at Edgewood, New Mexico, and the observed transmission quality is typical of other experiments performed at six widely scattered sites in the western U. S. and Canada. At each site a vertical hole was drilled and then cased with 150-mm rigid PVC tubing which was plugged at the bottom. The finished depth for this experiment was 52.3 meters.

The soil conductivity was measured using a right-angle array [8] at a frequency of 150 Hz. The apparent conductivity, as measured with two arrays rotated 90 degrees with respect to each other, is shown in Figure 4. The curves lie close to each other which shows that the conductivity was independent of azimuth angle. The peak in the conductivity curve suggests three layers with the middle layer having a relatively large conductivity. A lengthy analysis of the data led to these estimated values of the soil conductivities and interface depths: c$\sigma_1 = 24$, $\sigma_2 = 165$, $\sigma_3 = 46$ mmhos/m, and $d_1 = 9.1$, $d_2 = 49.4$ meters.

As a preliminary to conducting the PCM/FM bit error tests, a cw transmitter was lowered to the bottom of the hole in small incremental spacings to check the signal level. The results of such a test together with computed values using a 3-layer earth model are shown in Figure 5. The induced voltage from the bottom of the hole was about 3.5 µV rms which was close to the minimum required value.

Following the cw tests, a 127-bit pseudorandom code generator was added to the test package to simulate an NRZ-L/PCM data stream into the transmitter VCO. Figure 6 is a diagram of the receiver system upon the surface of the ground. The discriminator output is the NRZ-L stream which is fed into the bit synchronizer. The clock pulses are reconstructed by the bit synchronizer from the NRZ-L pulses and toggle an 8-stage shift register and feedback combination similar to that used in the transmitter for the pseudorandom code generator. When the switch is in the “Load” position, the NRZ-L data is loaded into the shift register after which the switch is moved to the “Run” position which introduces the feedback elements. This process causes the NRZ-L data to circulate continuously through the receiver shift register whose output can be compared with the NRZ-L output from the synchronizer. Any disagreement between the two data streams is accumulated as a bit error by a counter. The bit error rate, or BER, was defined as the number of errors divided by the total number of transmitted bits. The goal of the PCM/FM tests was to find the maximum bit rate at which a BER of 10^{-4} or less could be provided. Optimum performance would be obtained if some combination of peak deviation and lowpass filter could be found which would further decrease the BER. The bit rate could be varied from 200 to 1000 bits/second and the peak deviation to 425 Hz. Low-pass filters were limited to 220, 500, 1000, and 2000 Hz with Butterworth characteristics. Twenty-nine tests, each involving at least 10^5 bits, were run for various combinations of the parameters. At the maximum rate of 1000 bits/second the BER was no worse than 10^{-5} for (375 < peak deviation < 425) Hz and (500 < low-pass filter < 2000) Hz. At the maximum rate, the sample size was at least 2 x 10^5 bits. The results of this experiment exceeded the design goals but the order of magnitude improvement in BER could have been eliminated by only a 2 dB increase in noise.

System Improvements. An easy way to improve the system noise margin was to increase the $(NA)_r$ by using a larger coil while keeping the coil resistance constant. The new coil design is mounted on a two-wheel trailer and has an $(NA)_r$ of 478 m^2, twice the previous value. The antenna coil on present TM packages is mounted on the rear and it is desirable to minimize the axial winding length to reduce the possibility of breakage by passage through the earth. This was easily done by using much finer wire and winding several banks in parallel such that the resistance and inductance remained substantially constant. For example, the first TM coil had a single-layer wound over a length of 7.6 am, while present coils have 8-bank windings over a length of only 1.5 cm.

It should be noted that, for a required magnetic dipole moment, the power varies inversely with the cube of the winding diameter. For example, an increase in winding diameter by only 25 percent reduces the power by 50 percent. An upper bound to winding diameter is set not only by the vehicle diameter but also by the radome thickness required for protection.

Equation 1 obviously applies for transmission in either direction, and a two-way link using a common buried antenna for simultaneous transmission and reception is currently being developed. The present one-way link is in frequent use in current penetrator programs.

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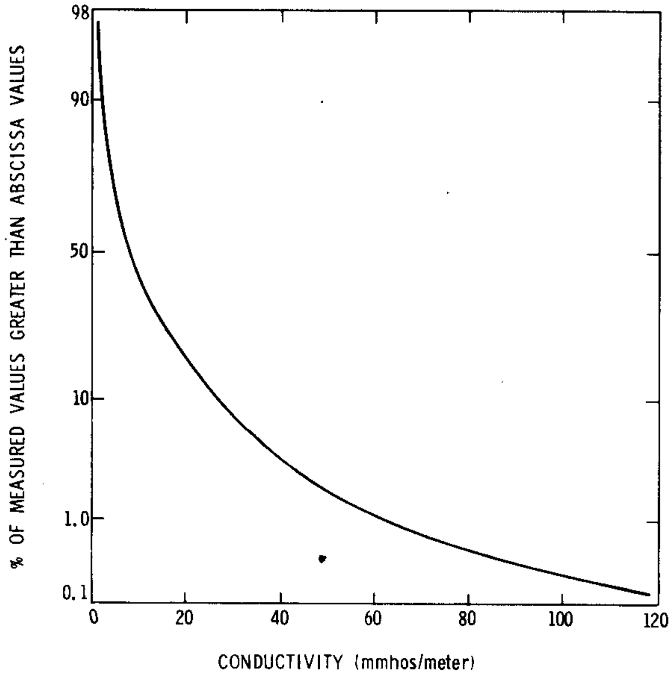

Figure 1. Distribution of U. S. Soil Conductivity

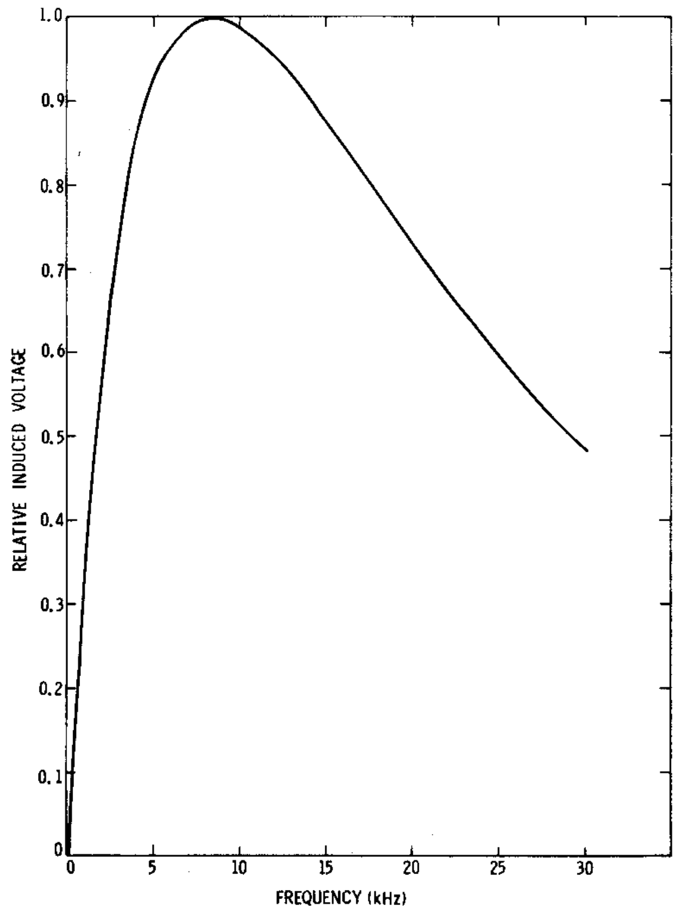

Figure 2. Induced Voltage vs Frequency
σ = 100 mmhos/m z = 0.25 m h = 50 m ρ = 10 m

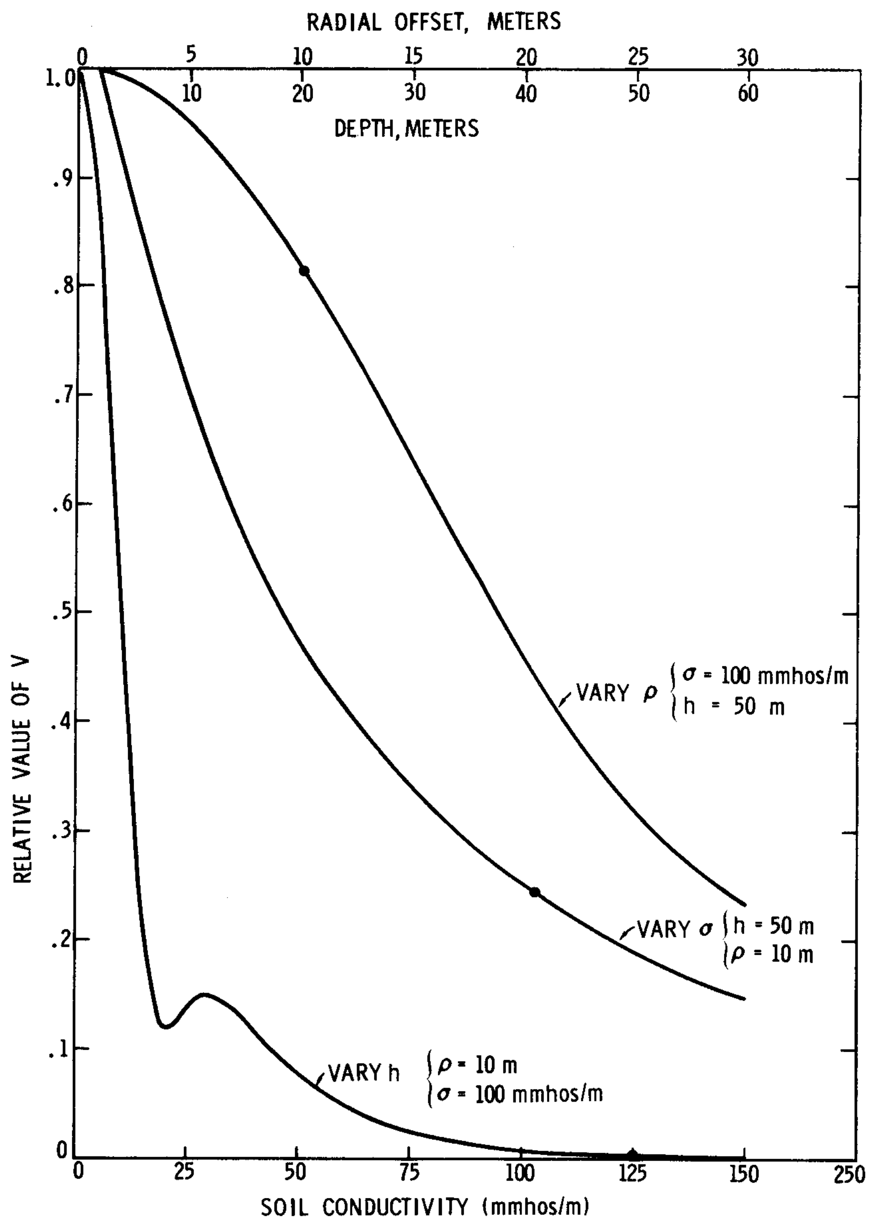

Figure 3. Induced Voltage vs Parmeters, ρ, h, σ

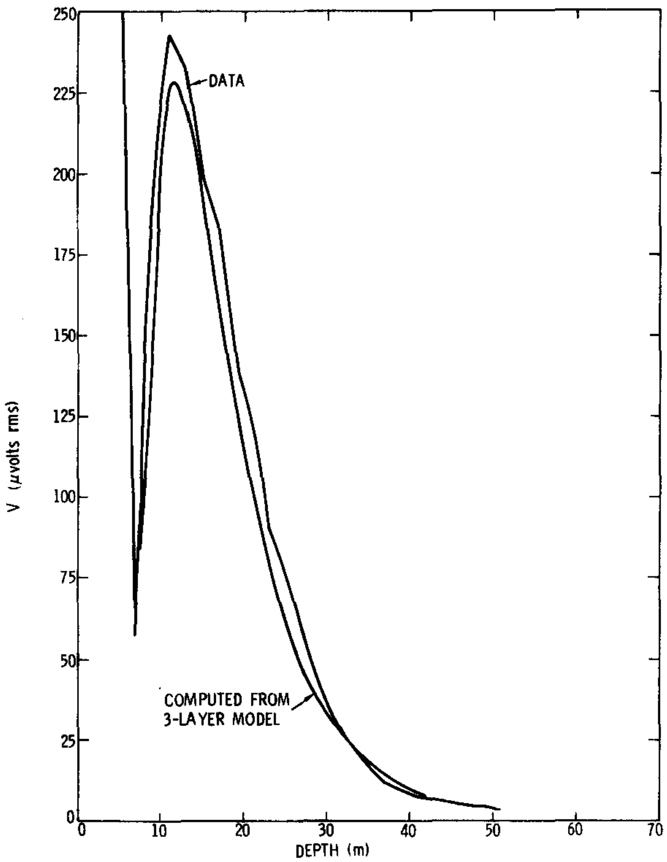

Figure 4. Apparent Conductivity vs Electrode Spacing

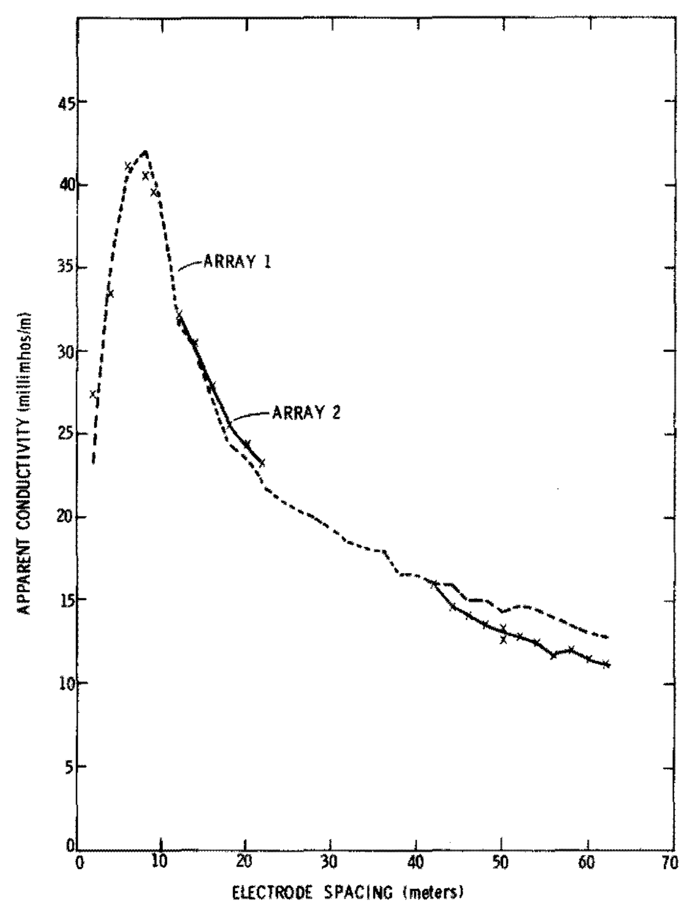

Figure 5. Induced Voltage vs Depth
ρ = 10 m   z = 0.25 m

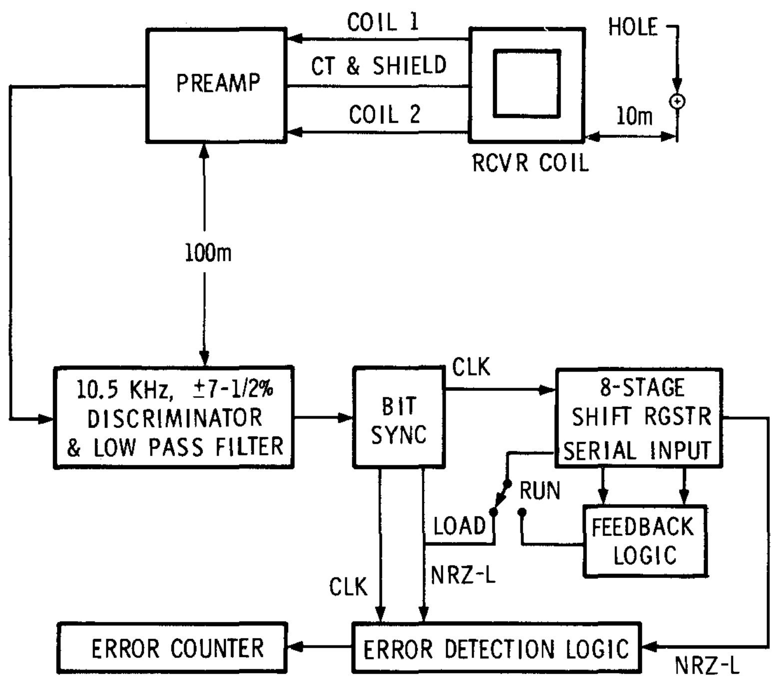

Figure 6. Diagram of Receiving System