# LOW FREQUENCY TELEMETRY FROM TERRADYNAMIC VEHICLES

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**Summary.** A telemetry system has been designed and built which transmits digital data from a buried earth-penetrating vehicle to the surface by magnetic induction. The transmitting package is a cylinder 10 cm in diameter by 30 cm long and draws 5 watts of dc power while transmitting. Error rates of $1.16 \times 10^{-4}$ have been obtained at a range of 52 meters through soil at a data rate of 50 bits/second, utilizing only the 0-50 Hz region of the electromagnetic spectrum. Projected performance of the system in high-conductivity media indicates useful ranges exceeding 50 meters in media as conductive as sea water (4 mho/meter). System improvements are discussed which should allow severalfold increases in data rate or range over the experimentally obtained values.

**Introduction.** Terradynamics is the science of high velocity projectiles which penetrate the earth to depths of tens to hundreds of feet.(1) Reliable telemetry of on-board generated data to the surface is presently a serious problem. Direct data transmission along a trailing wire pair is sufficiently reliable for operations utilizing small expendable vehicles(2) but not for the more costly operations involving larger, more fully instrumented projectiles. Real time radio data transmission through dry soil has been accomplished from a high-speed penetrator at a 260 kHz carrier frequency.(3) Under more general field conditions, however, terradynamic media are found to vary at least five orders of magnitude in conductivity, from about $10^{-5}$ mho/meter for dry granite to several mhos per meter for sand or mud saturated with salt water. In the latter materials, deep penetration ranges and high media conductivity rule out the use of kilohertz frequencies because of excessive signal attenuation.

This paper will describe a successful low-frequency telemetry system which was designed to perform equally well through any terradynamic medium likely to be encountered. The basic design approach was first to set a minimum system range of 50 meters to cover the expected distribution of penetration depths. Next, the operating frequency of the transmitter was chosen on the basis of this minimum range and the maximum earth medium

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conductivity expected (4 mho/meter). Finally, the transmitter modulation format was chosen to maximize the data rate with the limited bandwidth available.

**Determination of Operating Frequency.** Figure 1 shows the geometric variables in the underground-to-surface to telemetry link. The transmitter is shown as an oscillating magnetic dipole (electric dipole moments are poorly coupled to soil in physically small antenna structures at low frequencies) with a dipole moment amplitude P in weber-meters. If the axis of the dipole (transmitting coil) is at an angle θ with respect to the vertical, the magnetic field components $B_H$ and $B_V$ at the ground surface directly above the transmitter are given by:

$$B_V = \frac{2PQ(\theta,H)\cos\theta}{r^3} \quad \text{weber/m}^2 \tag{1}$$

$$B_H = \frac{PD(\theta,H)\sin\theta}{r^3} \quad \text{weber/m}^2 \tag{2}$$

where r is in meters and the functions Q,D are dimensionless attenuation factors; $H = (\sigma\mu\omega)^{1/2}r$ where σ = soil conductivity in mhp/meter, μ = permeability and ω is the operating frequency. H is also √2 times r expressed in skin depths for an electromagnetic wave of frequency ω propagating into the conductive medium.

Both Q and D approach unity as H→0. At a given burial depth r, therefore, the expression for the fields at the ground surface become equivalent to the free-space values as operating frequency or medium conductivity go to zero, provided $\mu = \mu_0$, which is true for most earth materials. Wait(4) has derived an integral expression for Q(0,H), equivalent to the case of a vertical magnetic dipole. The amplitude and phase components are plotted in Figure 2. It is clear that the loss of amplitude and phase shift do not become prominent until H exceeds about 2.5, at which the amplitude is 59% of the dc value and the phase shift is 67°. For a maximum anticipated medium conductivity of 4 mhos/meter and r = 50 meters, the operating frequency at H = 2.5 is 50 Hz. This frequency was chosen as the upper limit of the operating band for our terradynamic telemetry system, particularly since it allows the use of a 50 Hz sharp-cutoff low-pass filter in the receiver system to minimize interference from 60 Hz power line noise.

**Receiver System and Background Noise Limitations.** Although in principle a magnetometer can be used to detect the time-varying field produced by a buried oscillating magnetic dipole, a simple inductive pickup coil can be fabricated to provide four or five orders of magnitude more sensitivity. The receiver coils employed in our work generally have several hundred turns enclosing on the order of 1 square meter of area. The coil is connected to a low-noise transformer to step up the coil voltage by a factor of 100 and then fed into a Princeton Applied Research low-noise preamplifier, law-pass filter and strip chart recorder.

In order to determine whether the 50 meter system range would be attainable with a practical transmitter package, the characteristics of natural and man-made background noise first had to be evaluated at representative test sites. Measurements with a 456 turn, 0.81 $m^2$ coil were first carried out at the Sandia Laboratories experimental test range near Tonopah, Nevada (TTR). This site is relatively uncontaminated by 60 Hz paver line interference; atmospheric noise was the predominant noise component intercepted by the coil in the 0-250 Hz region. With the receiver coil axis horizontal and oriented in azimuth for maximum atmospheric noise pickup, the atmospheric noise-induced coil output voltage was 0.2 µv rms in the 0-50 Hz band,,with occasional short bursts of ~ 1 µv rms. The data of Maxwell and Stone(5) taken during the summer in Colorado indicate that the horizontal magnetic field noise spectrum is relatively flat from 3 Hz to 50 Hz. Assuming this to be true of the atmospheric noise picked up at TTR by our coil, our measurements correspond to an atmospheric noise density of 0.34 µ amp/meter/√Hz. This is within 1 dB of the values measured by Maxwell and Stone between 3 and 50 Hz.

When the receiver coil was oriented with its axis vertical, the noise voltage appearing across the coil terminals was 0.02 µv, or 20 dB below the value measured with the coil axis horizontal. The noise also appeared to be Gaussian in nature without the short high amplitude bursts characteristic of atmospheric noise and was probably mostly thermal and amplifier noise. Evidently atmospheric magnetic field noise in the 0-50 Hz region is oriented predominantly in the horizontal plane.

60 Hz noise from power lines must be taken into consideration in a general low-frequency telemetry system design, since this man-made noise component may have substantial vertical magnetic components and not all potential terradynamic test sites are as remote from habitation as TTR. For instance, at the Edgewood Test Site (ETS) near Edgewood, New Mexico, a small power line runs about a mile away from an area where terradynamic experiments are done. The same coil which picks up 0.02 microvolts of random noise when oriented vertically at TTR has more than 30 µv of 60 Hz noise across its terminals at ETS. A low-pass filter was constructed which combined a 10-pole active 0-50 Hz Butterworth filter and an active twin-T notch filter tunable around 60 Hz. When this filter (which was also used in the TTR test to define the system bandwidth) was connected to the low-noise amplifier output at ETS, the 60 Hz noise component could be nulled out completely, leaving a much smaller random component.

**Transmitter Design Considerations.** For preliminary tests, an oscillating magnetic dipole transmitter had to be designed within the requirements of a practical terradynamics package. Basically, this amounted to getting the highest possible dipole moment with

5 watts of power consumption in a cylindrical volume 10 cm in diameter and about, 30 cm long. An air-core cylindrical coil has a dipole moment given by:[6]

$$P = \frac{\mu_0 NIA}{4\pi} \quad \text{weber-meters} \tag{3}$$

where N = number of turns in the coil, I = coil current in amperes and A is the average effective area in square meters of each turn. In an air core coil, A is the area enclosed by each turn projected along the coil axis. However, if a core of high permeability material is provided, the effective area of each turn, and hence the total dipole moment, is multiplied by a factor of $\mu_{rod} > 1$, whose exact value depends on the core permeability and length-to-diameter ratio.[7] For L/D ratios of ten or above, the values of Belrose[8] for $\mu_{rod}$ in rod-type loop antennas are roughly proportional to $(L/D)^2$. If L is chosen to be the maximum transmitter package length, the dipole moment per unit current per turn, which is proportional to the product $A\mu_{rod}$, is almost independent of the rod diameter (since $A \propto D^2$). Since the core diameter is not very critical, a laminated silicon steel rod 32 cm long and with a square cross section 3.3 cm on a side was fabricated for a prototype transmitter, allowing ample room for coil driver electronics and the coil winding (see Figure 3). The latter consisted of 450 turns of #16 copper wire with a winding length of 15 cm and situated at the midpoint of the core. The length-to-diameter ratio of the core gave a projected $\mu_{rod} = 40$, and with a winding resistance of 0.948 ohm and $A = 15\ cm^2$, a sinusoidal current dissipating 5 watts in the winding should produce a dipole moment $P = 0.21 \times 10^{-6}$ weber-meters. If this antenna is buried 50 meters below a receiver coil in a nonconductive medium and both coils are oriented vertically, the signal induced in the receiver coil used at TTR with a 50 Hz sinusoidal transmitter current should be 11.5 microvolts rms, or 55 dB above the measured noise level at 0-50 Hz for a vertically-oriented receiving antenna. Even if one subtracts 30 dB for worst-case conditions (a medium conductivity of 4 mho/meter and the transmitting antenna axis horizontal, necessitating a horizontally-oriented receiving coil), the remaining 25 dB signal-to-noise ratio in a 50 Hz band should be ample for low-error rate digital data transmission.

**Choice of Transmitter Modulation Format.** The overall voltage transfer function of the transmitter coil-receiver coil-low-pass filter system is flat within 3 dB from 4.4 to 45 Hz. The system response falls off to zero at dc because of the nature of inductive coupling, hence direct application of an NRZ pulse train to the transmitter coil was ruled out because of the large baseline shifts produced by lack of system dc response. Biphase coded data at 50 bits/second was considered next, since its dc component can be made zero without disturbing data fidelity.

It was initially not clear that 50 bit-per-second biphase data could be successfully reproduced after propagating through the low-pass filter with its nonlinear phase versus frequency characteristic near 50 Hz. A simulated telemetry system was therefore built and tested in the laboratory with biphase-modulated data (see Fig. 4). The simulated data signal was a 31-bit pseudorandom sequence coded in biphase format at 50 bits/second using equal positive and negative voltage levels so that the average dc level was zero. This signal was applied through a power amplifier directly to the transmitter coil. A couple of meters from the transmitter coil was situated a receiver coil having the same inductance and resistance as the coil designed for field use, and connected to the 100:1 stepup transformer, low-noise preamplifier and 50 Hz low-pass filter used in the noise surveys.

Random white noise could also be injected into the preamplifier input through an attenuator to add to the coil signal and allow the system bit error rate to be found as a function of signal-to-noise ratio (measured at the low-pass filter output). The signal was decoded into digital form with a laboratory prototype, matched-filter type biphase demodulator. A strip-chart record of the transmitter input signal and demodulator output signal indicated about 8% time jitter in the output signal and an overall system delay of about two clock periods. When the transmitter input signal was delayed two clock periods with a two-stage shift register and sent into an exclusive-or gate with the demodulator output, no bit errors could be detected (the gate output was sampled at the midpoint of the clock period) until noise was added deliberately to the preamplifier input. Bit error rates were then measured as a function of signal-to-noise ratio of the filter output. The results are plotted in Figure 5. It is apparent that the low-pass filter adds a 1.5-bit period delay to the data (the remaining 0.5-bit period delay is inherent in the demodulator) but does not by itself set a lover limit for the bit error rate.

**Fun System Field Test.** When the various subelements of the system were shown to be working up to theoretical expectations, the complete system was felt to be ready for a simulated telemetry test under actual field conditions. The tests were carried out at Edgewood Test Site, since it was anticipated that power-line induced noise would be the limiting factor in system performance. The transmitter coil was driven by a switching-mode pulse amplifier driven by a biphase signal derived from a 127-bit pseudorandom generator. The transmitter coil driver circuit (Fig. 6) operates from a single 28 volt dc supply derived from rechargeable nickel-cadmium batteries. Since the driver transistors operate either in the fully off or fully saturated mode, most of the inductive energy stored in the coil is returned to the battery pack during data transmission. At 50 bits per second, the transmitter draws an average power of 5 watts from the batteries despite peak battery currents of several amperes at 28 volts.

The transmitter and battery pack were hermetically packaged and lowered to the bottom of a 52 meter deep, 15 am diameter hole cased with plastic pipe. The receiving coil of 240 turns and 1 $m^2$ area lay on the surface 10 meters from the well and with the coil axis vertical. The coil was connected to the 100:1 stepup transformer, low-noise preamplifier and 50 Hz filter used in the TTR noise tests, and the filter output was recorded on an analog FM tape recorder at 1-7/8 inches per second. The tests were run long enough for 432 kilobits to be transmitted, and the tape record was taken back to the laboratory for signal recovery and processing.

When the tape was played back into an Elpac bit synchronizer, the latter would not lock onto the signal at first. A strip chart record of a portion of the taped signal indicated large base-line level shifts during the longer strings of ones and zeros. Putting the signal through a differentiator circuit removed the baseline shifts and enabled the bit synchronizer to lock onto the signal. Comparison of the synchronizer output with a laboratory-generated 127-bit pseudorandom sequence indicated an overall error rate of 50 bit errors in 432,000 transmitted bits or a bit error rate of $1.16 \times 10^{-4}$. This bit error rate was somewhat larger than would be expected from the measured system signal-to-noise ratio of 18 dB. The background noise, however, was not Gaussian in nature but was characterized by large spikes of 20 dB or more above the mean noise level. Strip chart records of both the raw tape signal and the bit error detector output indicated that errors occurred in groups of two to four within a second, followed by long periods (up to 20 minutes) with no errors at all. The bit error groups coincided with large noise spikes in the raw signal. Since the background noise was nearly 30 dB greater than the atmospheric noise measured at TTR, it may have been man-made in origin. A possible explanation is that power line current surges, which would not be eliminated entirely by the 50 Hz low-pass filter, were being inductively coupled to the receiver coil. Nevertheless, the system met the overall requirements of a practical through-the-earth low frequency telemetry system, producing a bit error rate low enough for practical telemetry, especially with error-detecting data codes.

**Outlook for System Improvement.** The biggest area of potential improvement is in the system signal-to-noise ratio in cases of high natural or man-made noise backgrounds. Both types of noise sources can be expected to produce relatively small field gradients compared with those characteristic of the oscillating dipole transmitter. If, for instance, two identical receiver coils are positioned so that one is directly above the transmitter and the other at least three burial depths away from the first, connection of the two coils in series opposition would result in a less than 10% reduction of the received signal. Cancellation of inductively coupled background noise should be 20 dB or more, leading to a greatly improved signal-to-noise ratio under high noise conditions such as were encountered at ETS. A 20 dB improvement in signal-to-noise ratio would enable the system range to be doubled to at least 100 meters.

The main limitation to data rate in the available 50 Hz bandwidth is the large nonlinear phase shift at the upper band edge produced by 60 Hz rejection filters (or by the medium itself for conductivities on the order of 4 mho/meter). Digital filtering with linear transversal filtering techniques,[9] however, are capable of linearizing phase response to the extent that multiphase or combined phase-amplitude modulation techniques could multiply the data rate severalfold. This would still not allow the system to be used for real-time terradynamic data transmission, which requires a capacity of several thousand bits/second, but it would substantially reduce battery requirements for a system using on-board data storage and later playback.

**Conclusion.** We have shown that a magnetic induction telemetry system can be designed to transmit at least 50 bits/second of data through a minimum of 50 meters of highly conductive earth media. The system can be used with practical terradynamic vehicles in conjunction with on-board data storage. Although the data rate is limited compared with most other telemetry systems, it has the capability of working under conditions where no other telemetry system will perform adequately. The potential exists for extending the system range at least twofold and the data rate by a factor of three or four, using state-of-the-art signal processing techniques.

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*Available from National Technical Information Service.

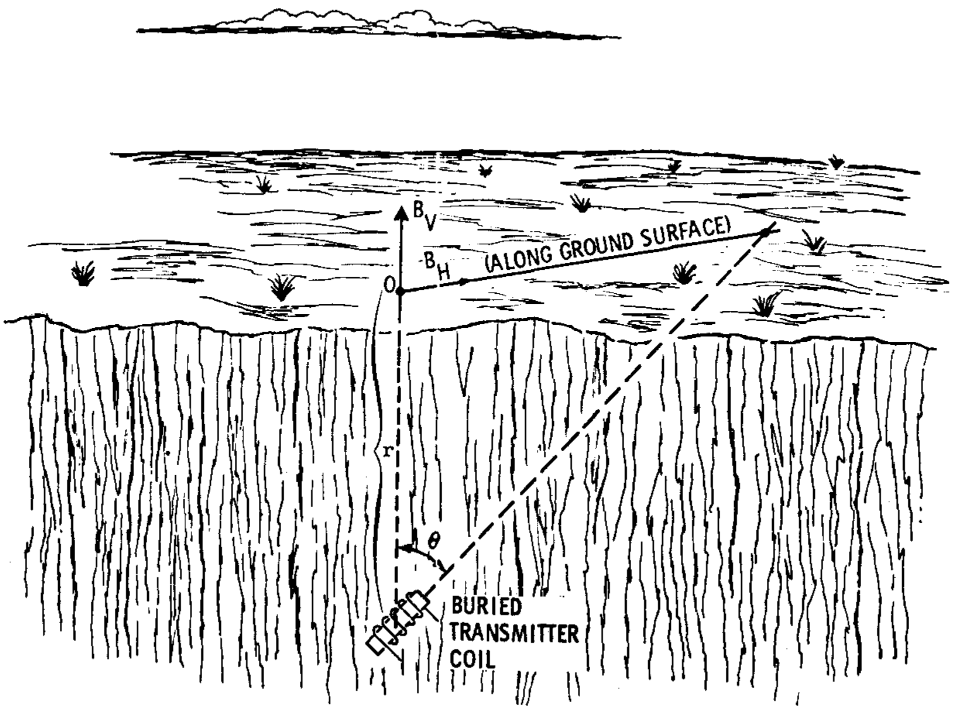


**FIGURE 1. Geometric Variables involved in Underground-to-Surface Telemetry Link**

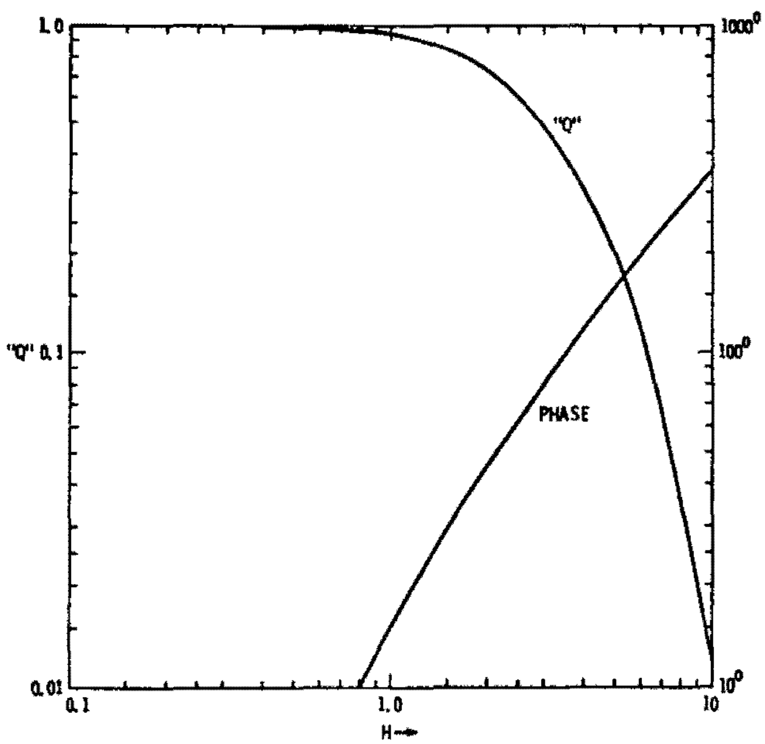


**FIGURE 2. "Q" - Q(0,H) versus Normalized Distance H**

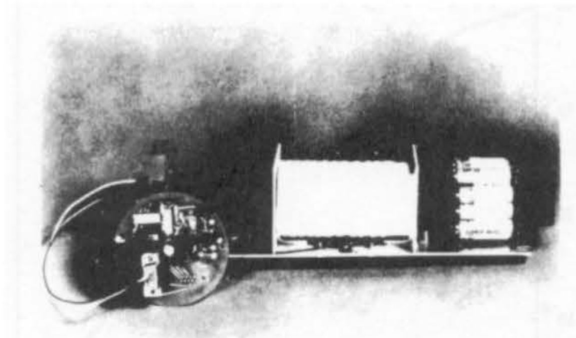

**FIGURE 3. Prototype Transmitter Package**

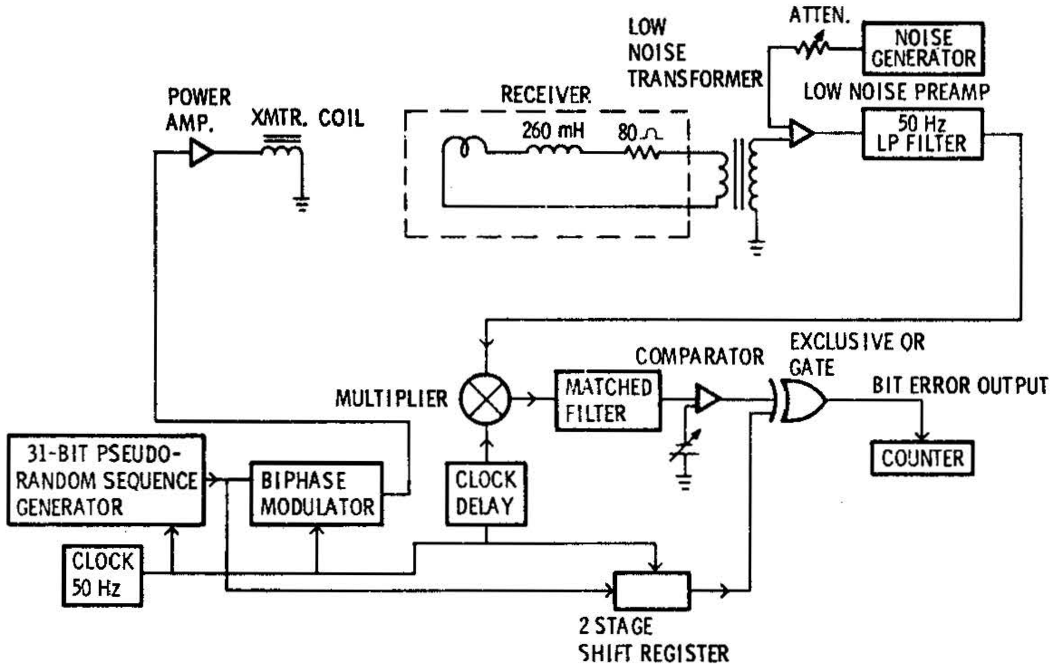


**FIGURE 4. Block Diagram of Simulated Telemetry System**

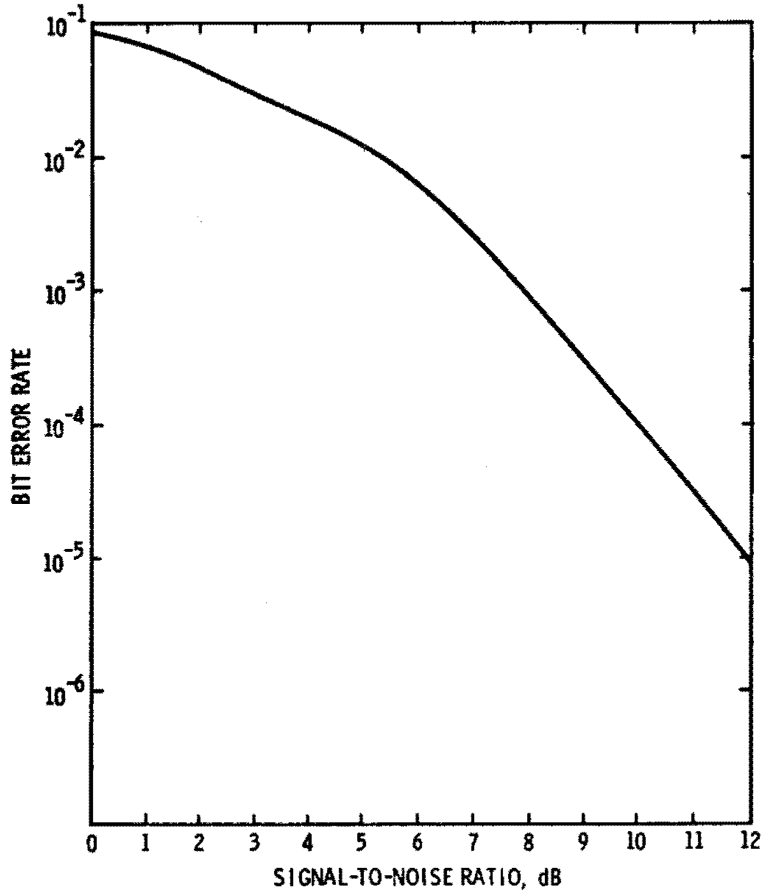


**FIGURE 5. Bit Error Rate versus Signal-to-Noise Ratio for Simulated Telemetry System**

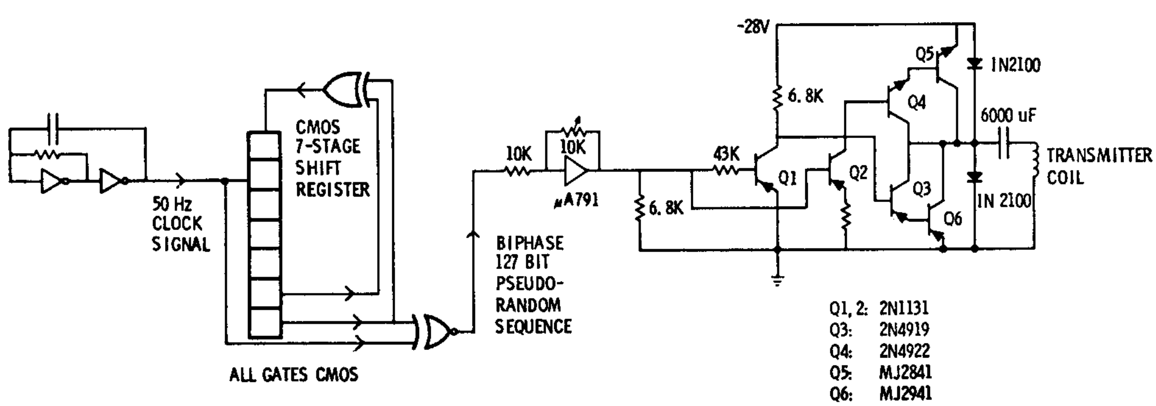


**FIGURE 6. Transmitter Driver Schematic**