POLARIZATION-DIVERSITY TELEMETRY RECEIVERS[1]

R. P. McCANN and R. D. JONES
Electro-Optics Division
Sandia Corporation
Albuquerque, New Mexico

Summary Studies at the Langley Research Center of the National Aeronautics and Space Administration have shown that certain physical properties of extraterrestrial surfaces can be determined by analysis of impact-acceleration, time-history signatures obtained by instrumented projectiles (penetrometers). This paper considers the theory and design of a polarization-diversity receiver developed to receive and combine FM/FM penetrometer telemetry data. The signals are radiated by a set of orthogonal magnetic dipoles fed in time quadrature to obtain an omnidirectional radiation pattern similar to the pattern from a conventional turnstile. A special polarization-diversity receiving system is required to reduce the effects of fading of the RF carrier resulting from random changes in the orientation of the radiating antenna system. Various combining techniques are evaluated. Finally, a maximal-ratio, postdetection, dual-channel receiver with dual conversion and subcarrier discrimination developed specifically for the application is described.

Introduction Information regarding the physical properties of lunar or planetary landing sites is required to support manned landing programs. Studies at the Langley Research Center of the National Aeronautics and Space Administration have shown that physical properties of an alien surface such as penetrability, surface hardness and load bearing strength can be determined by the use of impact-measuring instrumented projectiles (penetrometers). In the NASA technique, penetrometers, each containing an acceleration sensor, subcarrier oscillator, FM telemetry system, antenna and battery power supply, are directed toward the surface at selected velocities. On impact, acceleration data are transmitted to a space probe or orbiting vehicle where the impact-acceleration time-history signatures are analyzed to obtain comparisons between the physical properties of terrestrial surfaces and the alien surfaces under investigation.

A spherical penetrometer with an omnidirectional antenna was one scheme considered by NASA. In this arrangement elaborate deployment techniques are not necessary; transmission is maintained during impact regardless of penetrometer orientation. The antenna system consisting of orthogonal. magnetic dipoles fed in time quadrature for full

---

[1] This work was supported by the United States Atomic Energy Commission.

spherical coverage was designed by Wheeler Laboratories Inc.1 The orthogonal geometrywas used to eliminate radiation nulls along the dipole axes. The radiation pattern is similar to that from a conventional turnstile antenna.

A single receiving antenna with arbitrary polarization would inevitably be cross-polarized to the radiated signal at some point in space. In order to improve the reliability and to make more efficient use of the RF signal incident on a receiving system at any point in space, a diversity receiver with two orthogonally polarized antennas is required. This report describes some factors influencing the design of the polarization-diversity receiver developed to combine the two signals. Reliability, power consumption and physical size (volume and weight) were prime factors effecting the system design. The actual design used is not necessarily optimum. The system signal-to-noise ratio could be improved by the addition of a third channel. However, improvement in performance would not be warranted because of the increased power and size required.

Basic Assumptions It is assumed that the amplitude of the received RF carrier emitted by the penetrometer will fluctuate because of random changes in the orientation of the radiating antenna system. (Figure 1) This fading phenomenon is similar to the familiar random fading resulting from time-varying changes in the character of the transmission media which effect conventional communication links. It follows, then, that standard diversity combining techniques used for reducing the effects of fading can be applied to improve either the signal-to-noise ratio or the reliability of the penetrometer telemetry system.

Three types of diversity combining systems were considered for use with the penetrometer system: selection-diversity, equal-gain diversity and maximal-ratio diversity. A comprehensive evaluation of the three techniques has been given by Brennan.[2] Brief descriptions of the three techniques is sufficient for present purposes. Rectangular rather than Rayleigh fading is assumed. (See Appendix)

In a selection-diversity system the single channel with the better signal-to-noise ratio is selected and other channels are rejected. Switching transients associated with channel selection could degrade the transmission and complete loss of data would result if channel switchover was concurrent with data transmission. A second major disadvantage associated with this technique is that although two receivers are required, the signal from only one receiver is used regardless of the quality of the discarded signal. In view of these limitations, it was decided to adopt one of the linear signal-combining techniques; no further reference will be made to selection-diversity systems.

In a maximal-ratio combining system, the signal in each channel is weighed and amplified in proportion to the signal-to-noise power ratio associated with that channel. That is, the gain of each channel is proportional to the rms signal and inversely proportional to the noise in that channel. The weighted signals are then linearly combined. On the other hand, the equal-gain system simply sums both signals directly without weighting; both channels have exactly the same gain. Although an equal-gain system is easier to implement than a maximal-ratio system, the equal gain technique has the distinct disadvantage that no provision is made to cut-off a very noisy channel. Although post-detection combining is not suitable for equal-gain systems, either pre-detection or post-detection can be used with maximal-ratio combiners and a very noisy channel is automatically discarded. Accordingly, it was decided to use maximal-ratio combining for the penetrometer receiver system.

The output of a maximal-ratio diversity system (See Figure 2) is given by the linear combination

$$f(t) = \sum_{j=1}^{M} a_j \left[s_j(t) + n_j(t) \right]$$

where s_j and n_j are the signal and noise components, respectively, in the jth channel. If the coefficient aj is proportional to the rms signal and inversely proportional to the mean square noise in that channel it can be shown[2] that the maximum power realizable in a maximal-ratio system is equal to the sum of the individual power ratios. It is assumed that (1) the noise in each channel is independent of the signal and additive, (2) the signals are locally coherent, and (3) the noise components are locally incoherent and have zero means. In the present application local coherence of the signals means that if

$$s_j(t) = x_j m(t)$$

where the x_j are positive real numbers that change in time because of penetrometer spIn, the characteristic times associated with penetrometer motion are very long compared to the instantaneous variations of m(t). if it is further assumed that the local mean square noises, $\overline{n_j^2}$, vary so slowly that they may be considered constant and, for present purposes, unity, then the local signal-to-noise power ratio for a maximal-ratio, dual-diversity system subject to rectangular fading is given by

$$(S/N) = \left(\overline{m^2} / 2\overline{n_1^2} \right) + \left(\overline{m^2} / 2\overline{n_2^2} \right) = \overline{m^2} \quad .$$

That is, in the case of a dual diversity receiver using maximal-ratio combining and assuming rectangular fading <u>no</u> improvement can be realized over the signal-to-noise ratio for an ideal single channel receiver defined as one not subject to fading. However, the possibility of failure resulting from cross polarization of a single dipole and the electric field vector is virtually eliminated.

Calculation of the power ratio for an equal-gain diversity combining system on the basis of assumptions W-W above follows directly from application of the axioms that the average power of a sum of uncorrelated signals is equal to the sum of the individual average powers while the rms value of a sum of coherent signals is equal to the sum of the individual rms values. Again assuming a two-channel system subject to rectangular fading and considering $\overline{n_j^2}$ as constant and equal to unity the signal-to-noise ratio for equal-gain combining is given by

$$(S/N) = 1/2\left(4\sqrt{\overline{m^2}/\pi}\right)^2 = 8\,\overline{m^2}/\pi^2 .$$

That is, the average power ratio for a two channel equal-gain system is down roughly 1db from the average power ratio for a two-channel maximal-ratio system. In the extreme case (one antenna and the electric field vector cross polarized) the power ratio for an equal-gain system is 3 db down from a maximal-ratio system.

On the basis of these arguments it appeared that, except for the disadvantages imposed by increased complexity and power requirements, the maximal-ratio combining system was preferable to the other systems.

Receiver Design A preliminary communications analysis leading to the receiver design criteria is summarized in Table 1. The analysis is straightforward except that the signal loss resulting from partial impaction of the radiating antenna system is estimated to be 12 db. Taking into account the transmitter output power (20 dbm) and radiation efficiency as well as estimated transmission path, impaction and polarization losses a receiver noise figure of 10 db is required to ensure a minimum signal-tonoise ratio of 16 db. The maximum system bandwidth requirement has not been determined; tentatively, a 500 kc bandwidth has been selected for design purposes.

Figure 3 is a functional block diagram of the polarization diversity receiver. Post-detection instead of pre-detection combining is used to avoid the phase-control circuitry required to satisfy the local-coherence requirement. Adoption of post-detection combining allowed concurrent development of the RF and video combining portions of the circuitry. Referring now to Figure 3, the system contains two complete receiving channels with dual down conversion - from 416 Mc to 70 Mc and 70 Mc to 12 Mc. The first local oscillator is crystal controlled at 162 Mc and the output tripled to 486 Mc. The second local oscillator is crystal controlled at 82 Mc.

Low Q’s associated with conventional LC circuits exclude them from use at UHF. Most high Q circuits such as cavities or stub-tuned elements are prohibitively large. For the specific application described here, shorted strip transmission lines, folded to reduce the size, were used in both the RF pre-amplifier stages as well as the local oscillator tripler stage. A total volume of one cubic inch was required for the combined preamplifier., local oscillator, and mixer in the bread-board model. Gains to the first IF amplifiers or 20 to 25 db with 6 to 8 Mc bandwidths and 6 to 8 db noise figures were achieved in several models.

The 70 Mc and 12 Mc IF stages are conventional amplifier circuits mismatched to obtain stability. The circuitry is self limiting. Wide dynamic range is obtained by use of "back-to-back" diodes. The discriminator can be described as a bridge type followed by a cascade voltage-doubling AM detector.[3]

The diversity combining circuitry is patterned after techniques described by Kahn[4] and Mack[5]. After amplification, the output of the discriminator is fed to a variable gain amplifier controlled by an AGC voltage inversely proportional to the mean square noise. (See Figure 2) The baseband voltage is applied to one gate of a tetrode FLT; the integrated out-of-band noise is applied to the second gate. As the noise level rises in the baseband the gain of the tetrode is decreased and the output signal reduced. The high pass filter shown on Figure 3 is a passive, maximally-flat, Butterworth filter. The optimum AGC response time, obviously, is somehow related to the characteristic motions of the radiating antenna. At present the optimum response time is unknown; tentatively, the response time is set at 10 msec.

Outputs of the two receivers are summed in a common emitter combiner and fed to a sub-carrier discriminator consisting of a monostable multivibrator and an active, 3-pole, Butterworth, low-pass filter.

Figure 4 shows a breadboard model of the 416 Mc receiver. The receiver occupies a volume of roughly 27 cubic inches. Significant receiver specifications including performance data are summarized in Table 2.

Conclusion Although the tests of the breadboard receiver are incomplete, test data obtained by bench simulation of rectangular fading have demonstrated the feasibility of the design. It should be noted that a test of the complete penetrometer telemetry system has not been attempted. However, the object of the study reported here was to determine a reasonable set of design specifications for a prototype receiver. Power consumption, physical characteristics (volume and weight), stability and reliability, received particular emphasis.

No attempt was made to optimize the breadboard design. However., with minor modifications., the volume as well as power consumption of the present receiver could be reduced. Any extension of these studies should provide for investigation of pre-detection combining techniques which would probably provide a closer approximation to the theoretically realizable signal-to-noise ratio. The resulting system would be simpler than the system described here and it should be possible to achieve substantial reduction in power requirements.

Acknowledgment The authors wish to express their thanks to their associates, C. J. Reed and J. M. Merrill, for their assistance in fabricating and testing the circuits. The encouragement and helpful advice given by A. E. Bentz and R. P. Matthews is also appreciated. This work was supported by the National Aeronautics and Space Administration, Langley, under work order 14-12091.

References

1. Puttre, R. E., Study of Small Ormidirectional 250-Mc Antenna for Penetrometer-Final Report on Phase I, Wheeler Laboratories Report 1291, July 29, 1965.

2. Brennan, D. G., “Linear Diversity Combining Techniques”, Proc. IRE 47, pp 1075-1102, June 1959.

3. Reis, G. E. and Land, C. E., “An Improved FM Discriminator-Detector for Airborne Telemetry Receivers”, Sandia Corporation Reprint SCR-208, September 1960.

4. Kahn, L. R., “Ratio Squarer”, Proc. IRE 42, P 1704, November 1954.

5. Mack, C. L., “Diversity Reception in UHF Long-Range Communications”, Proc. IRE 43, pp 1281-1289, October 1955.

Appendix - Rectangular Fading First, consider a simple detection system which consists of two receivers whose antennas are dipoles at right angle to each other and in the plane of an electromagnetic wave of electric-field strength E. The input signal voltage to one receiver is proportional to E sin θ, where θ is the angle between the dipole and the electric-field vector of magnitude E; the signal voltage at the other receiver is proportional to E cos θ. Therefore, the signal power at the two receivers is S $\sin^2\theta$ and $S\cos^2\theta$, where S, which is proportional to E^2, is the signal power that would be received by a receiver whose dipole antenna was aligned with the electric field.

No information is available to make any particular value of 0 more likely than any other. Therefore, it is appropriate to assume for one channel an infinite number of possible sourcee of the form

$$s = E \sin\theta = m(t)x,$$

with

$$\theta = f(x) = \sin^{-1} x$$

distributed uniformly throughout the range a to a + π/2. For a rectangular distribution the probability density function q (θ) is

$$q(\theta) = \begin{cases} 0, & \theta < 0 \text{ and } \theta > \pi/2 \\ 2/\pi, & 0 < \theta < \pi/2 \end{cases}$$

The probability density function for x is

$$p(x) = q(f(x))\ f'(x) = (2/\pi)(1-x^2)^{-1/2}, \quad 0 < x < 1 .$$

The local signal-to-noise power ratio for the jth channel can be obtained from the second moment of the distribution. For unity circuit resistance, we have

$$(S/N)_j = \left(E^2 \big/ \overline{n_j^2}\right) \int_0^1 x^2 (2/\pi)(1-x^2)^{-1/2}\, dx = E^2 \big/ 2\overline{n_j^2}$$

and the local amplitude ratio, obtained from the first moment of the distribution, is

$$s_j \big/ \sqrt{\overline{n_j^2}} = E\left(\overline{n_j^2}\right)^{-1/2} \int_0^1 x (2/\pi)(1-x^2)^{-1/2}\, dx = 2E/\pi \sqrt{\overline{n_j^2}} .$$

Table 1
TELEMETRY SYSTEM DESIGN CRITERIA

Radiated Power

Power output	+20 dbm
Coupling loss	-4 db
Antenna loss	-3 db
Effective power radiated	+13 db

Transmission Losses (400 Mc)

Transmission path loss (3000 ft.)	-86 db
Impaction loss	-12 db
Total signal loss in transmission	-98 db
Effective power radiated	+13 db
Effective power at receiver	-85 dbm

Receiver Characteristics

Polarization loss	-3 db
Receiver antenna gain	0 db
Receiver power input	-88 dbm
Noise power (1 Mc BW)	-114 dbm
Receiver noise figure	+10 db
(S/N)	+16 db

Table 2
RECEIVER SPECIFICATIONS

RF	
RF Input Frequency	416 Mc
Gain	20-25 db
Noise Figure	6-8 db
Bandwidth	10-12 Mc
First IF	
IF Frequency	70 Mc
Gain	35 db
Bandwidth	4-5 Mc
Second IF	
IF	12 Mc
Gain	55 db
Bandwidth	1 Mc
Discriminator	
Bandwidth	1 Mc
Output Level	1 v
Video Amplifier	
Bandwidth	500 kc
Sub-Carrier Discriminator	
Center Frequency	50 kc
Bandwidth	50 kc
Signal Frequency	5 kc
Output Level	0.25 v
Output Impedance	200 Ω
General	
Sensitivity	-100 dbm
Full Limiting	-95 dbm
Maximum Input	-20 dbm
Power Requirements	
Total Power	300 mw
Voltage	6 v
Current	50 ma

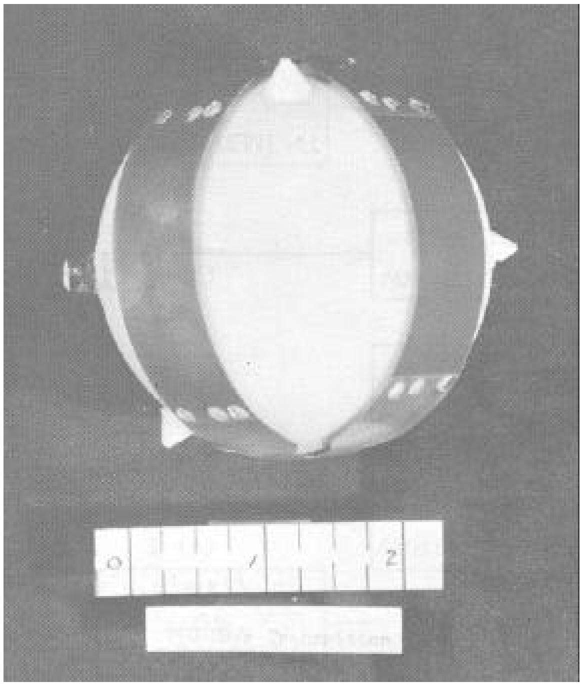

Fig. 1 - Unencapsulated Spherical Penetrometer (Note orthogonal loops)

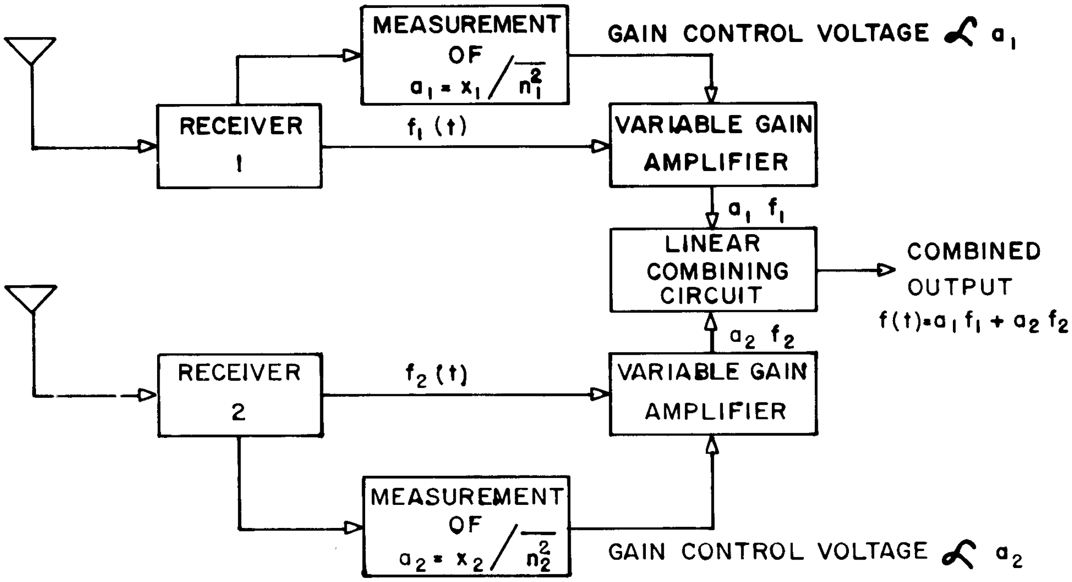

Fig. 2 - Maximal-ratio Diversity Combining System

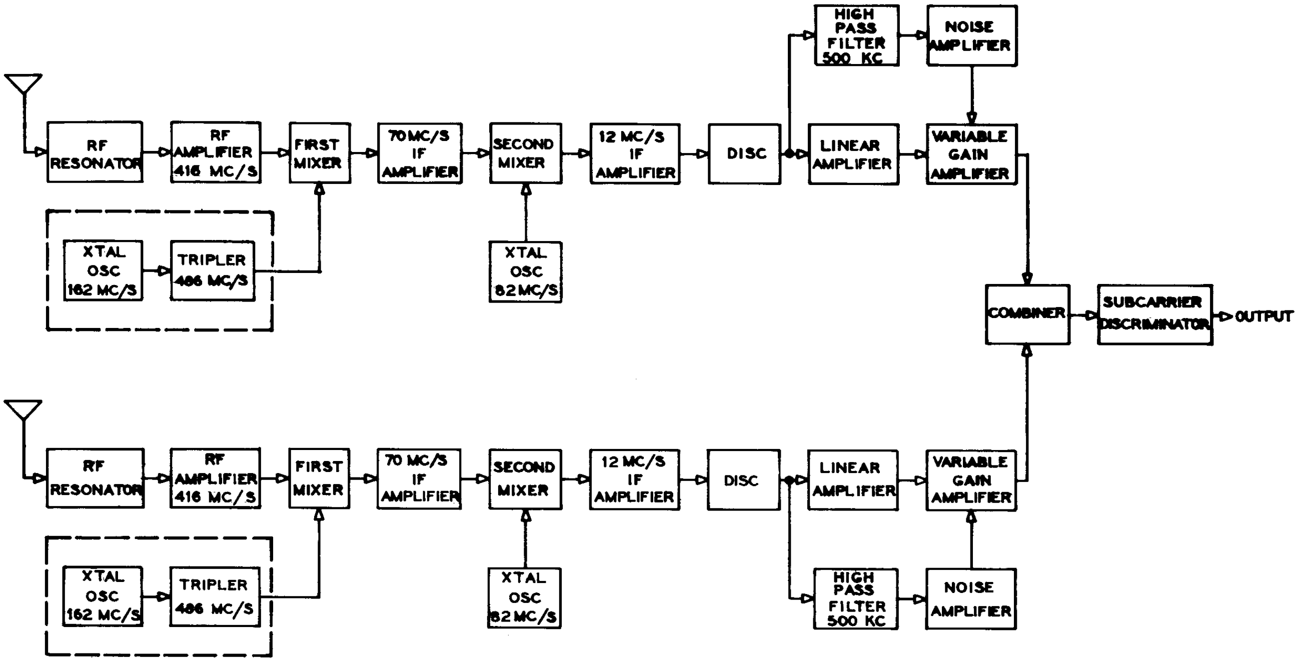

Fig. 3 - Receiver Block Diagram

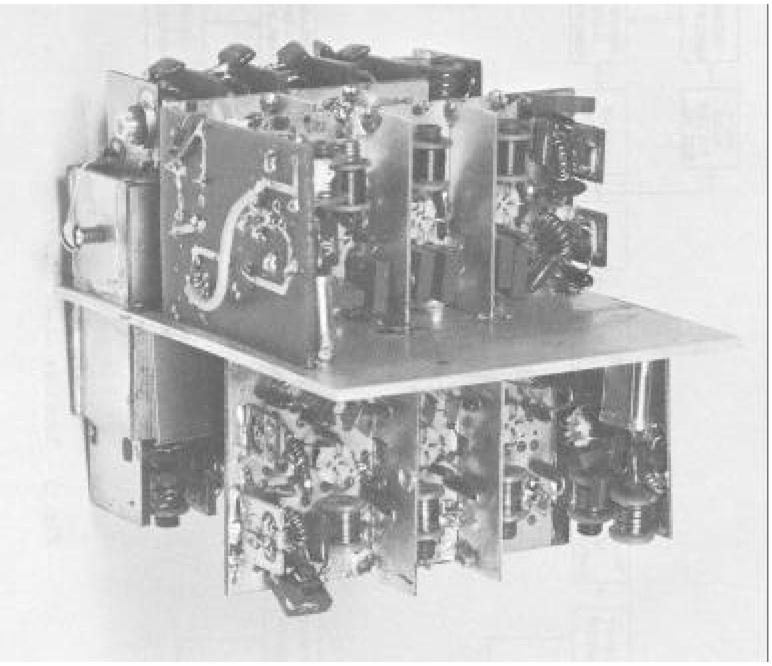

Fig. 4 - Receive Breadboard