ROCKY MOUNTAIN OILFIELD TESTING CENTER

SAM III PROJECT

Sandia National laboratories

Prepared for:

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ABSTRACT

The Rocky Mountain Oilfield Testing Center (RMOTC) conducted a demonstration of the Surface Area Modulation Downhole Telemetry System (SAM 111) at the Department of Energy's Naval Petroleum Reserve No. 3 (NPR-3), in partnership with Sandia National Laboratories (SNL). The project encompassed the testing of a real-time wireless telemetry system in a simulated Measurement-While-Drilling (MWD) environment. A Surface Area Modulation (SAM) technique demonstrated data transmission rates greater than present techniques, in a deployment mode which requires minimum deviation from standard oilfield practices.

Sandia National Laboratories has previously conducted two other field tests of the SAM technology: SAM 1 (11/6-10/95) and SAM 11 (9/2-20/96). The objective of the SAM I test was to investigate the capability of the equipment to transmit buffered downhole data to the surface at high data rates, by establishing a two-way real-time data link between the downhole package and the surface under a variety of oilfield conditions. The SAM 11 test was a continuation of the SAM I test. Final reports of these tests have not been provided by Sandia National Laboratories.

The SAM III test was conducted in well 46-1-SHX-3 (9/8-17/97). The equipment was deployed on 2.875" tubing in the open-hole-completion interval of the borehole. Various configurations of coated and uncoated tubing were tested at different depths in the well, using several different signal-return wells as grounds.

One phase of the test involved the immersion of only the tail section of the tool in the wellbore brine fluid. Communication with the tool was achieved at all baud rates from 110 to 19,200 baud using all of the three return wells. Subsequent testing phases confirmed that losses increased with depth, as expected.

The SAM technology uses the earth to complete the data-transmission circuit. Signal attenuation was highest using the uncoated tubing, because of electrical losses between the bare tubing and earth. Performance is limited by the signal power generated by SAM, the attenuation of the signal as it traveled back to the surface, and by the hardware used to encode and decode the data.

RMOTC's testing of the SAM technology does not lend itself well to technology transfer. Although the SAM III test was not considered a "proprietary" test, Sandia treated the data acquisition as such. Access to the realtime data was not permitted during testing, which made documentation and verification of the test impossible.

Sandia National Laboratories has finalized a report of the SAM III Project titled "Surface Area Modulation Downhole Telemetry System for Measurement While Drilling" (3/23/98). Sandia claims that the field test did demonstrate that the SAM technology has the potential to significantly improve the rates of data transmission.

ACKNOWLEDGEMENTS:

This report was prepared by the Rocky Mountain Oilfield Testing Center (RMOTC) based on field testing conducted at the Naval Petroleum Reserve No. 3 (NPR-3), located 35 miles north of Casper in Natrona County, Wyoming, in cooperation with the U.S. Department of Energy (DOE). Testing was funded jointly by Sandia National Laboratories and RMOTC.

RMOTC is operated by Fluor Daniel (NPOSR), Inc., the Management and Operating Contractor for the DOE's Naval Petroleum and Oil Shale Reserves in Colorado, Utah, and Wyoming. Project work was directed by Project Manager, Michael J. Taylor, and project support was provided by Engineering Technician, Brian Meidinger.

RMOTC's goal is to partner with the oil and gas industry to improve productivity, by field testing new petroleum technology, evaluating new equipment and techniques, disseminating information to industry, and conducting training. For more information, contact the Rocky Mountain Oilfield Testing Center, 907 North Poplar, Suite 100, Casper, Wyoming 82601; phone (888) 599-2200.

For information about the SAM III technology, contact Sanford Ballard, Project Manager, Sandia National Laboratories, P.O. Box 5800, MS-0750, Albuquerque, New Mexico 87185; phone (505) 844-6293; fax (505) 844-7354

Summary:
Surface Area Modulation Downhole Telemetry System for Measurement While Drilling

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Abstract

The need for a reliable, fast, wireless telemetry system in the drilling industry is great but the technical challenge to develop such a system is huge. A downhole wireless telemetry system based on Surface Area Modulation (SAM) has been tested. SAM telemetry modulates an electrical current flowing along the drillstring. The current modulation is monitored at the surface with an ammeter. Downhole data are encoded and transmitted to the surface as a pattern of current oscillations.

In a field test, the SAM system successfully transmitted downhole information from depths of 1,400 ft below the fluid level to the surface at a rate of 110 baud. One of the configurations tested improved the data transmission rate at a given depth by more than an order of magnitude, and increased the maximum depth from which successful data telemetry could be achieved by more than a factor of two.

Acknowledgements

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1. Introduction

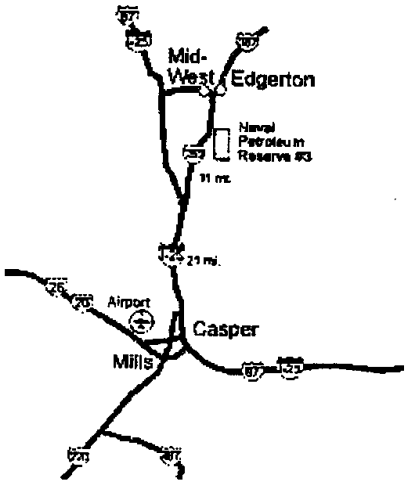
The drilling of boreholes into the subsurface is a huge industry in the world today. Boreholes are required for oil and gas exploration and production, geothermal resource exploitation, environmental applications, groundwater resource investigations and a host of other fields of endeavor. Drilling is a tremendously expensive operation, particularly for oil and gas and geothermal applications where holes are drilled to great depths and into challenging physical conditions. One way to reduce the cost of drilling such holes is to optimize the parameters of the drilling operation such as the weight on the drill bit, the drilling Fluid pressure and many other important parameters. In order to optimize these parameters it is necessary to monitor physical conditions at the drill bit in real time. Efforts to implement improvements in drilling operations have been hampered by the difficulty and expense of transferring data from downhole sensors back to the surface quickly and accurately.

In this report, a new technology for achieving wireless telemetry of downhole data up to the surface is described. In its simplest form, Surface Area Modulation (SAM) telemetry uses electrodes buried in the earth. It is envisioned that the electrodes would typically be either well casings or drillstrings. The amount of current that flows through the drillstring is modulated to encode downhole digital.

2. Test Site

Field testing of the SAM system was performed at the Rocky Mountain Oilfield Testing Center (RMOTC), located at the Naval Petroleum Reserve No. 3 (NPR-3) 35 miles north of Casper, Wyoming (Figure 2-1). The field site, Teapot Dome, is operated by Fluor Daniel, Inc. for the U.S. Department of Energy. Figure 2-2 illustrates the geologic column underlying the site. Because of the cost associated with testing the SAM system in an actual drilling environment, drilling was simulated by deploying SAM on 2.875-in. tubing hung in an open completion borehole. Well 46-1-X was the test well used during this field test at RMOTC. This well is located in Section 3 of Natrona County, Wyoming and was drilled to a depth of 2,250 ft in June of 1996. As this well had no significant oil show it has been dormant since completion. It was completed with 7-in. casing to a depth of 490 ft and left open hole from 490 ft to 2,250 ft (Figure 2-3). Three nearby wells, 45-SX, 45-SHX and 45-1-SHX, were also used.

Figure 2-1. Map showing location of NPR-3 relative to Casper, Wyoming.



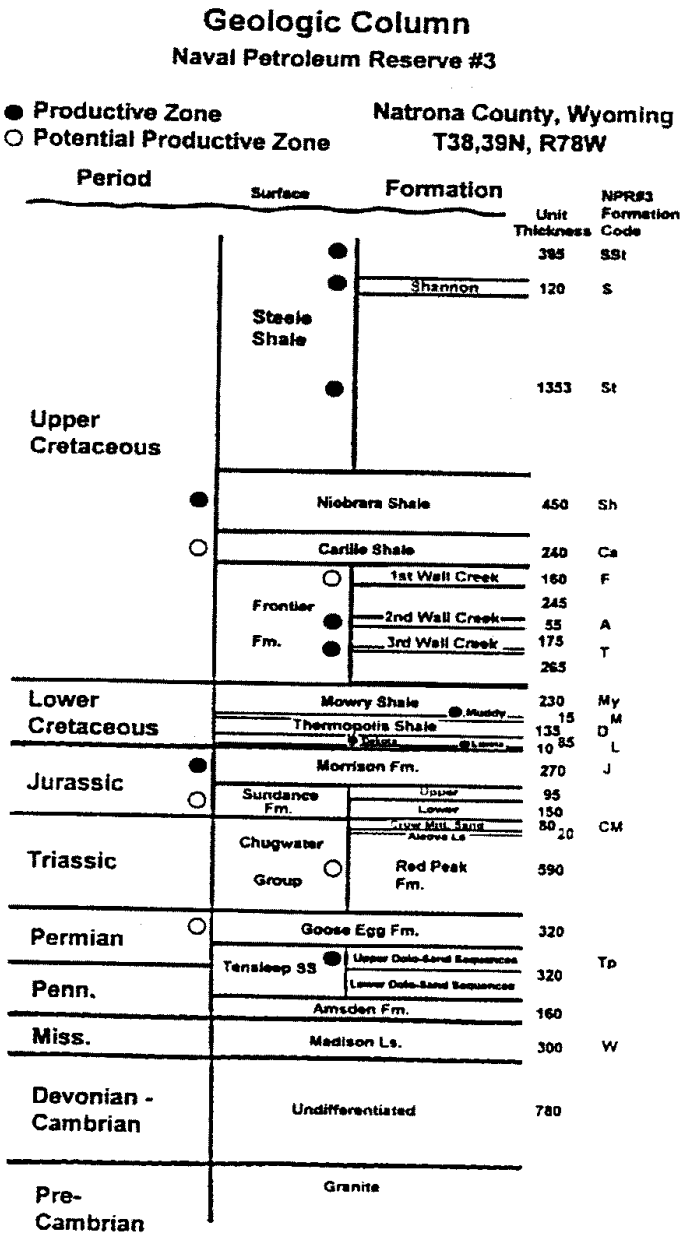
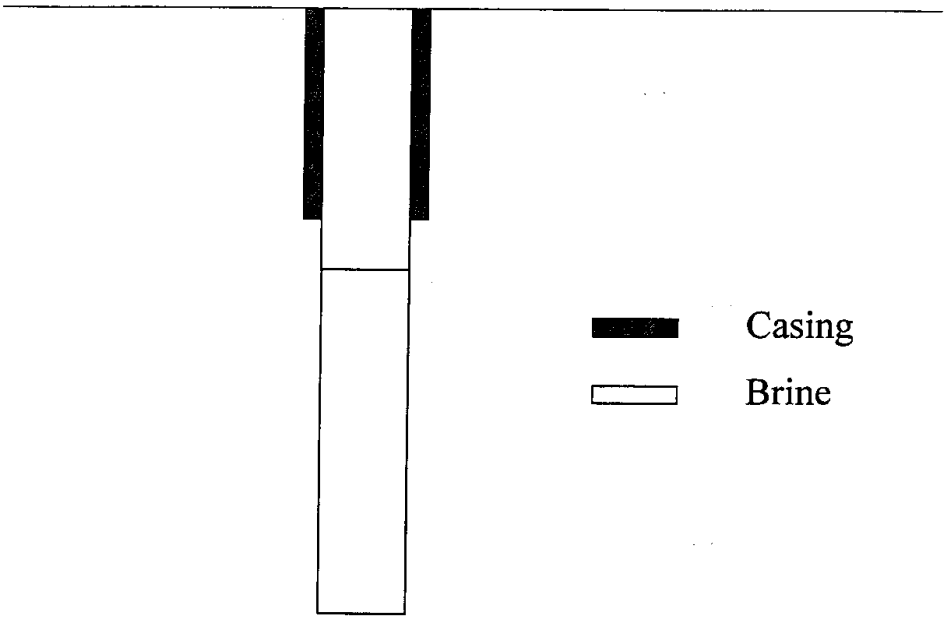

Geologic Column
Naval Petroleum Reserve #3
Productive Zone
Potential Productive Zone
Natrona County, Wyoming
T38,39N, R78W
Period
Surface
Formation
Unit Thickness
NPR#3 Formation Code
Upper Cretaceous
Steele Shale
Shannon
385
120
1353
SSt
S
St
Niobrara Shale
450
Sh
Cartile Shale
240
Ca
Frontier Fm.
1st Wall Creek
2nd Wall Creek
3rd Wall Creek
160
245
55
175
265
F
A
T
Lower Cretaceous
Mowry Shale
Muddy
Thermopolis Shale
Dakota
Lakota
230
15
133
85
10
My
M
D
L
Jurassic
Morrison Fm.
Sundance Fm.
Upper
Lower
270
95
150
80
20
J
CM
Triassic
Chugwater Group
Alcova Ls
Red Peak Fm.
590
Permian
Goose Egg Fm.
320
Penn.
Tensleep SS
Upper Dolo-Sand Sequences
Lower Dolo-Sand Sequences
320
Tp
Amsden Fm.
160
Miss.
Madison Ls.
300
W
Devonian - Cambrian
Undifferentiated
780
Pre-Cambrian
Granite

Figure 2-2.

Stratigraphic column at the field site.

Figure 2-3.



Test well.

3. Test Configuration

The motivation for developing SAM has been to provide a high data-rate system for Measurement While Drilling (MWD). Even though, from the beginning, the goal of the SAM project was MWD, the first two field tests used SAM configured for producing wells. A producing configuration well was chosen for initial tests so that the hardware could be debugged and tested under conditions where there was a high probability of success.

It is difficult to transfer electrical data along a drillstring because according to conventional wisdom (DeGauque and Grundzinski, 1987; Wait and Hill, 1979; Still, 1979) for an electric wave moving along a lengthy, perfectly conducting electrode buried in the ground, the propagation constant becomes equal to that of the ground. As such, skin-depth plays a major role in attenuating the signal transmitting along the drillstring. An oscillating current moving along the drillstring according to conventional wisdom will be attenuated according to

$$I(z) \rightarrow I_o e^{-z/\delta} \quad , \tag{3-1}$$

where I_O is the amplitude of current oscillation at $z = 0$, $I(z)$ is the amplitude of current oscillation at distance z along the drillstring, and δ is the skin-depth in the earth:

$$\delta = \frac{1}{\sqrt{\pi f \mu / \rho_e}} \quad , \tag{3-2}$$

where f is the frequency, μ is magnetic permeability (assumed to be $4\pi \times 10^{-7}$ Ω-Sec/m), and ρ_e is the resistivity of the earth. Figure 3-1 shows a plot of skin-depth (in feet) vs. frequency for 10 Ω-m earth. Figure 3-2 shows a plot of attenuation using Equations 3-1 and 3-2. The figure shows that there is an increase in attenuation from 16 orders of magnitude to 52 orders of magnitude ($10^{-16} \rightarrow 10^{-52}$) for a 20,000 ft deep well as the frequency increases from 100 Hz to 1000 Hz. Thus, an increase in frequency of one order of magnitude causes a decrease in signal strength of thirty-six orders of magnitude. A similar sensitivity to resistivity exists. Equation 3-1 has been tested by experiment (Xia and Chen, 1993; Maekawa et al., 1992; Lee and Smith, 1975; Chen and Jin, 1991).

Pretest analysis (finite-difference approximations to Laplace's equation specific to SAM) indicated that the potential for SAM telemetry to exceed that expected based on conventional wisdom depends upon the configuration deployed. Hence, two different configurations were tested.

The test well (46-1-X) was filled with 0.7 Ω-m brine up to a depth of 540 ft (initial fluid level). For convenience, 2 7/8-inch tubing was used instead of drill pipe. The SAM module (two joints or 63 ft long) was inserted into the tubing string five joints above the bottom.

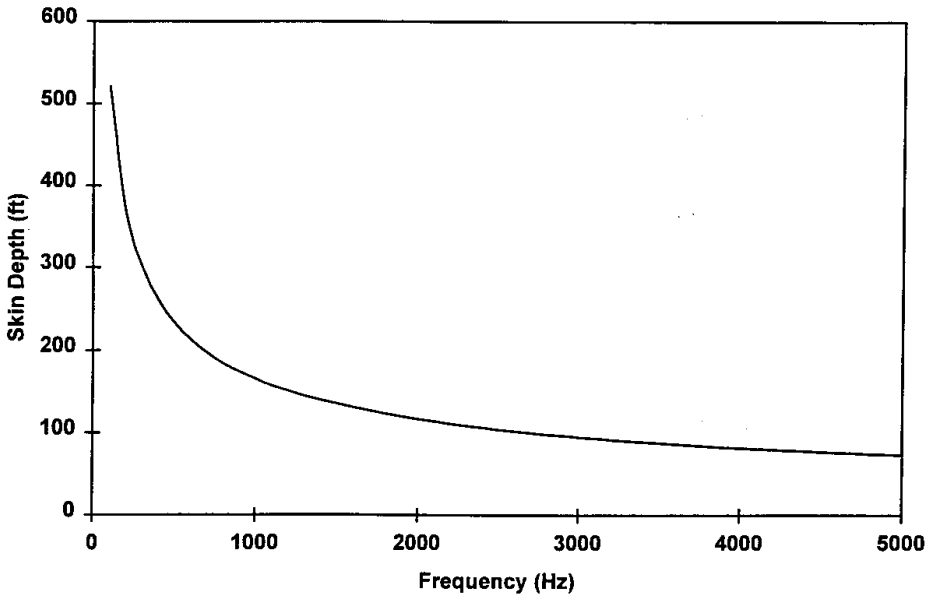


Figure 3-1. Skin-depth (in feet) for 10 Ω-m earth as a function of frequency.

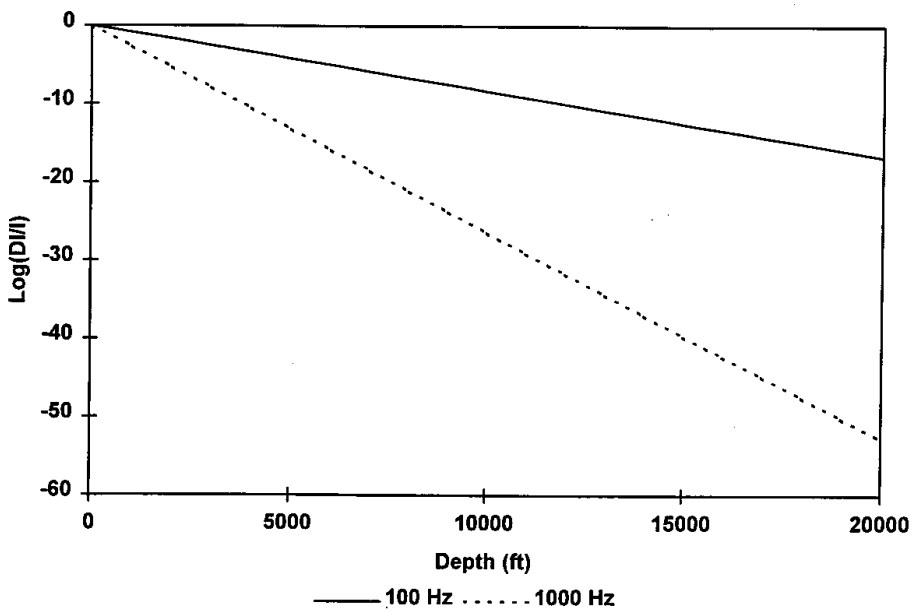


Figure 3-2. Conventional-wisdom attenuation of signal traveling along a buried electrode.

4. Surface Data Acquisition System

Current measurements were made using a Tektronix model A6302 current probe and model AM503 current probe amplifier. The current probe measured current flowing through the cable connected to the test well tubing. Predeployment tests verified the system could detect I piamp signal when 10 amps of DC current were applied. The output of the current probe amplifier is a voltage signal proportional to the current detected by the current probe. A digital spectrum analyzer, Stanford Research Systems SR780, and digital oscilloscope, Hewlett Packard 54645A, were used to record the output of the current probe amplifier. For receiving serial data transmission, the output of the current probe amplifier was conditioned and monitored by the RS232 transceiver. The output of the transceiver was decoded by a computer.

5. Data

The downhole SAM package was designed to send up two basic types of information, a serial data stream of ASCII characters and continuous frequency sweeps. The package was preprogrammed at the surface to automatically send up the serial data stream of diagnostic information at I 10 baud, then to pause for a few seconds, and then to send up the frequency sweep. It would repeat this sequence every few minutes. When the package was not transmitting, it could receive a command from the surface to change the baud rate at which the serial data stream was to be transmitted to the surface. If the package did not successfully receive a command from the surface within a specified period of time (10 minutes), it would automatically revert to transmitting at I 10 baud. This was programmed into the board so that if communication down to the board failed, the board would reset itself to a state where it was most likely that communication could be reestablished. Note that in order to instruct the package to switch from its current baud rate to some other baud rate, the instruction from the surface down to the SAM package to change baud rates, which had to be sent down at -the current baud rate, had to be successfully decoded by the SAM package. This was a significant limitation because it was not possible to optimize the downhole reception parameters. Since it was possible to optimize the surface decoding electronics, there were times when it was felt that it would have been possible to receive higher baud rate transmissions at the surface but it was not possible to instruct the SAM package to switch to the higher baud rate.

5.1 Serial Data

The downhole SAM package measured several types of diagnostic information and the temperature of the downhole SAM package. The diagnostic data were digitized, encoded as a binary ASCII string and transmitted uphole. A simple decoding scheme in the surface electronics package interpreted low current readings as "0" and high current reading as "I". The stream of binary data were interpreted at the surface as ASCII characters and displayed on a computer screen. SAM was capable of communicating at several baud rates ranging from I 10 up to 38,400.

Figure 5-1 illustrates some of the data acquired. CHI is the current measured at the surface during the transmission of a few bits of information at 600 baud. CH2 in Figure 5-2 is the output of the RS232 decoding circuit.

Figure 5-2 illustrates the maximum baud rate at which serial data transmissions from the downhole package were successfully received and decoded by the surface data acquisition system, as a function of the depth of the of SAM below the fluid. Data acquired with SAM deployed on both configurations are reported. The results indicate that configuration #2 performed more than an order of magnitude better than configuration #1 in terms of transmission speed and a factor of two better in terms of maximum depth.

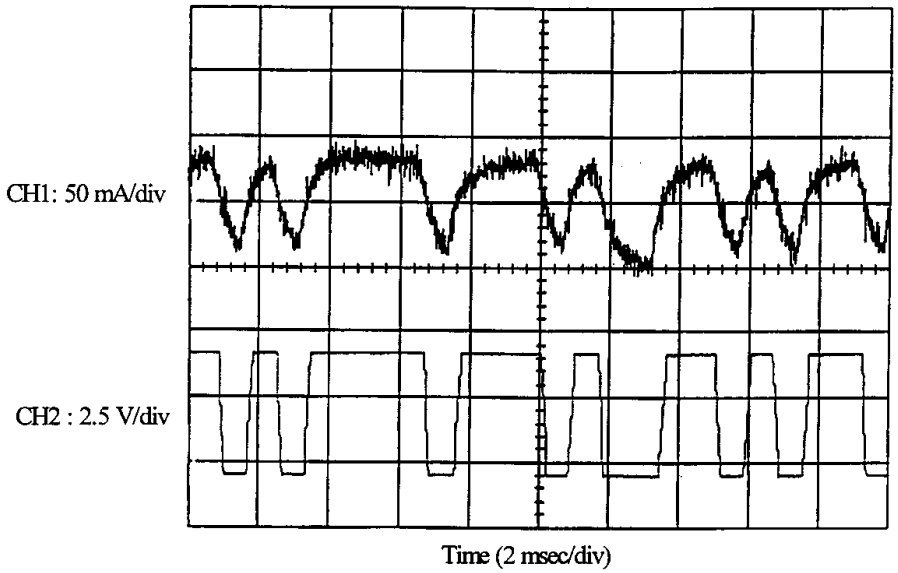


Figure 5-1. Oscilloscope traces of surface current measurements during transmission of a few bits of ASCII data.

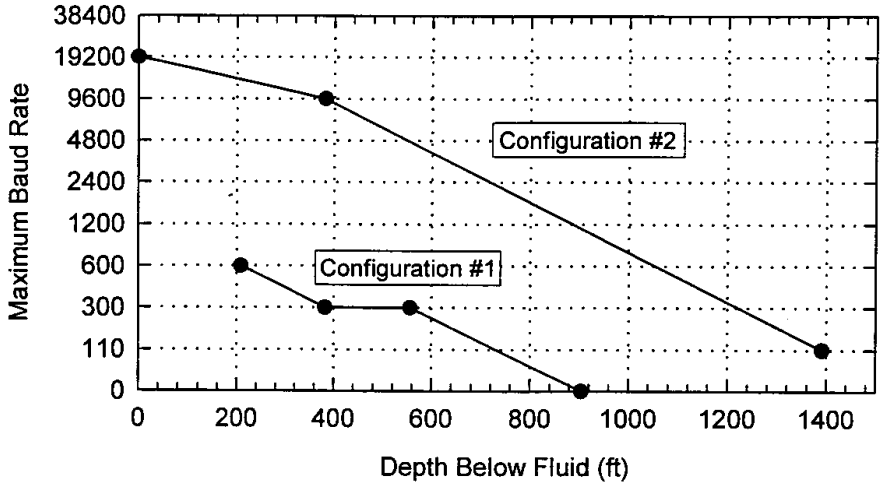


Figure 5-2. Maximum baud rates achieved on configuration #1 and configuration #2 as a function of depth.

5.2 Frequency Sweep Mode

In frequency sweep mode, the SAM transmitted a square wave pattern. SAM started out transmitting at a frequency of 45 kHz, and the frequency decreased linearly down to I kHz over a 30-second time interval. At the surface, the signal was acquired by a spectrum analyzer which measured the amplitude of the received signal as a function of frequency.

To acquire spectral data it was necessary to recognize when to turn the spectrum analyzer on and off. When the signals were strong, distinguishing between ASCII data, sweeps, and quiet periods was not hard, but when the signals were weak, the time window the spectrum analyzer should record was difficult to identify. This problem made it impossible to determine if there was cultural noise that varied throughout the test-clearly "60 cycle" noise existed but was not characterized.

5.3 Interpretation of Test Results

If kilo-baud serial data had been successfully transmitted from 20,000 ft, there would be no need to analyze the signals; interpretation of the test as a success would be self-evident. Current EM MWD systems transmit data at I to 10 bits per second up to 10,000 ft; thus some interpretation is required to say if the results shown on Figure 5-2 are an improvement over current technology. Because the test well was much shallower than wells for which MVvD is justified, it is necessary to extrapolate the results to depth. To do that, it is important to distinguish between the limitations on data transmission imposed by the hardware used for the test versus limitations on data transmission back to the surface through the drillstring. This point can be made by comparing the oscilloscope traces when the depth of tubing between the fluid level and the top of the SAM was 904 ft (nominal depth). Figure 5-3 shows such a trace during a quiet period (SAM was transmitting neither ASCII diagnostic data nor a sweep). This sweep establishes the noise level and indicates low frequency cultural noise that may be filterable. Figure 5-4 shows a trace when SAM was transmitting 110-baud ASCII diagnostic data. The figure clearly shows signal above the noise. Figure 5-2 indicates that at this depth the maximum baud rate was 0. Results at this depth were recorded as 0 because the signal could not be decoded. A better demodulation system may have been able to decode the signal shown in Figure 5-4.

Analyses of the potential of SAM to transmit data from depth independent of current hardware limitations has been done using three approaches: empirical, signal processing, and numerical solutions to Maxwell's equations. These three different approaches have been used as complementary. The empirical analyses have the advantage of being relative easy to understand, and transparent as to the assumptions being made. The signal processing approach has the advantage of flexibility, adapting to the data rather than force-fitting the data to a model, and is able to consider more complexities than the empirical analysis. The numerical solutions to Maxwell's equations have the advantage of being based on first principals but are difficult and require more assumptions. They also allow one to consider design changes, such as, changing the properties of the insulation. To the degree that these very independent approaches lead to the same conclusions, one can be fairly confident the extrapolation to depth is correct.

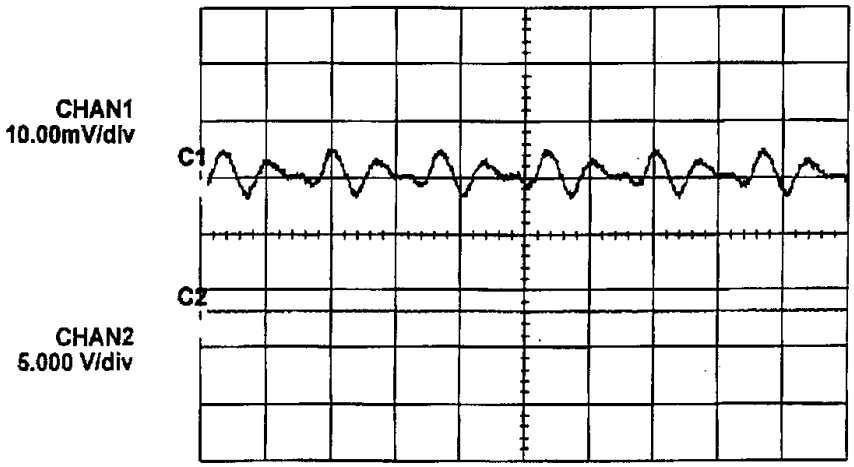


Figure 5-3. Noise with 904 ft of tubing.

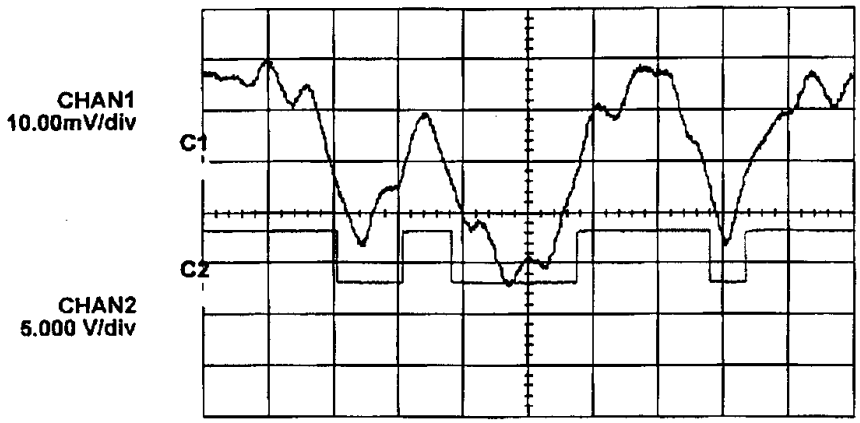


Figure 5-4. ASCII diagnostic data with 904 ft of tubing.

Figure 5-5 summarizes the extrapolation of these analyses to depth in terms of the frequency the signal drops below the noise as a function of depth. The performance of configuration #1 appears to be no better than current EM MWD systems. On the other hand, configuration #2 provides significant improvement in bandwidth and depth.

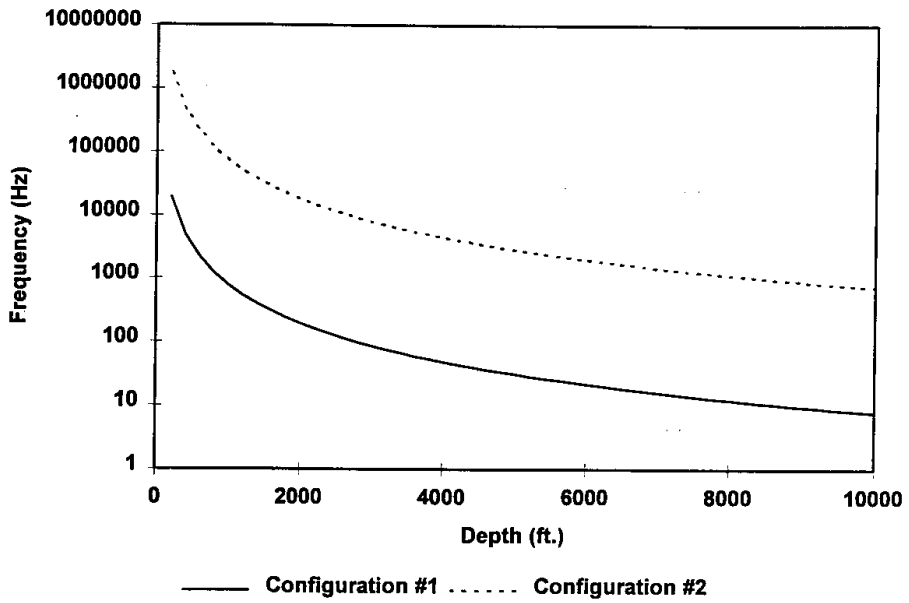


Figure 5-5: Comparison of frequency signal drops below noise as a function of depth for configurations #1 and #2.

6. Summary and Conclusions

The need for a reliable, fast, wireless telemetry system in the drilling industry is great, but the technical challenge to develop such a system is huge. The SAM system was field tested for MWD well applications. During the test, data were successfully transmitted at 300 baud from depths of 550 ft below the fluid level using configuration #1, and from depths of 1400 ft below the fluid level at a rate of I 10 baud using configuration #2. These performances were limited by the signal power generated by SAM, the attenuation of the signal as it traveled back to the surface, and by the hardware used to encode and decode the data. For example, signals were recorded from 900 fi below the fluid level with configuration # 1, but could not be decoded. The rise time of these signals suggest that with proper modulation /demodulation, I 10 baud data may have been transmitted from 900 below the fluid level with configuration #1.

Clearly the test did not achieve the "dream" of kilobaud data from 20,000 ft. Pretest predictions were that for configuration #I data transmission would drop to below I 10 baud before the bottom of the -2,000 ft test well, and it did. It was also predicted that configuration #2 would provide considerable benefit, and it did. In terms of actual measured performance, configuration #2 improved the data transmission rate at a given depth by an order of magnitude and increased the depth to which telemetry was successful by more than a factor of two.

Because the test well was only -2,000 ft deep, extrapolation is required to predict what telemetry rates might be achievable at depths at which MWD becomes economic. Analysis of the data was done using three different approaches which arrived at essentially the same conclusions, lending credibility to their extrapolations. Extrapolation of the configuration #1 results suggest that data rates of I to 10 bits per second should be possible at 10,000 ft depth, the same rates achievable by conventional EM systems. It would appear that the difference between conventional EM systems and configuration #1 SAM is primarily a function of the signal power at the SAM package.

Configuration #2 was found to provide, at a fixed depth, 100 times the bandwidth or, at a fixed bandwidth, 10 times the depth before signal drops below noise. Compared to configuration #1, configuration #2 provides the maximum signal power at the Sam package. Whereas extrapolations of configuration #1 to depth gave the same bit rates as conventional EM systems, configuration #2 was demonstrated to have significantly better performance.

Considerations beyond the scope of this test and analysis are changes in performance due to changes in geology, cultural noise, and input power. The test well penetrated shaly sand formations with 10 ohm-m resistivity, which, while not a worst case geology, was not favorable to data transmission. Although the test well was surrounded by producing wells, and some of the time the engines of the workover rig on the well were on, no variations in cultural noise were measured, and thus no conclusion should be made as to whether the tests were noise-favorable or -unfavorable. In theory, the signal can be increased by increasing the power supply output, provided the power supply does not contribute to the noise; however, such considerations are beyond the scope of this work.

The field test was not successful in demonstrating configuration #1 SAM telemetry as an improvement over current MWD EM telemetry, but it did demonstrate that configuration #2 has the potential to significantly improve the rates of data transmission.

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