VERY HIGH-SPEED DRILL STRING COMMUNICATIONS NETWORK

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ABSTRACT

Testing of recent upgrades to the drill pipe telemetry system in a 1000-ft vertical well has shown that the new system can achieve at least 1,000 ft passive transmission distance with sufficient bandwidth to accommodate a digital transmission rate of 2 Mbit/sec. Digitized data from a module at the bottom of the well has been successfully transmitted through the transmission line to the top of the well for a period of approximately one month. Manufacture of 30 prototype range 2 drill pipes has demonstrated greater simplicity of manufacturing and greater consistency of electrical characteristics from part to part, as compared to the first production run previously reported. Further work is needed to improve the high pressure capability of the system and to improve the robustness of the system in a high-vibration environment.

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BACKGROUND

The present work relates to the development of a high data rate communications system for the down-hole drilling environment. Applications for the communications system include asset characterization and optimization, wellbore stability monitoring, and real time assessment and control of the drilling process.

At the end of 1st quarter 2002, the author reported to the Department of Energy that improvements to the design of the high-speed data transmission line had been prototyped, showing substantial improvement in the gain and bandwidth of the system. In addition, manufacturing simplifications improved part-to-part consistency in electrical characteristics. Further work has since been undertaken to test the robustness and range of the new design in full-scale drill pipe. The following is a description of this work.

EXPERIMENTAL

Robustness testing of second revision pipes. Tool joint makeup robustness was verified through 100 make/break cycles on a single joint pair. Best-O-Life Premium Blend copper thread dope was applied to the tool joint per manufacturer's recommendation. The joint was made up by hand to the hand tight condition and was tightened to the recommended maximum torque of 56.6 kft-lbf, using a Scorpion® brand make-up unit. The joint was then broken out to the hand tight condition and retorqued without further application of grease or inspection. This procedure was repeated until 5 make/break cycles were achieved; the joint was then fully broken out, visually inspected, then regreased and torqued for 5 more cycles. Signal transmission through the mating tool joints was continuously monitored during the make-up/break-out cycles using a Hewlett-Packard model 3577A network analyzer. The above procedure was repeated until 100 torque cycles were achieved. The tool joints were then cleaned and inspected for damage.

Prototype full-scale pipes were tested in a 100 ft deep cased well under rotation, vibration and flowing conditions. Four pipes were tested at a time, each torqued together with 20 kft-lbf using a Scorpion® brand make-up tool. This torque value was selected to provide worst-case fluid access to the secondary shoulder region of the tool joint. Vibrational loads of up to 500 g magnitude (20 grms) were created by rotating a four pipe assembly with a rollercone bit on a steel plate at the bottom of the well. Weight on bit and rpm were varied to obtain the desired vibrational loads. Vibrations were monitored at the top drive (saver sub region) and down hole, using piezoelectric type accelerometers. Bottom-hole vibration information was gathered by a vibration module and was sent via the transmission line at 1 Mbit/sec rates. In addition, quantifiable digital bit patterns were successfully sent through the test string at rates of 500 kbit/sec, 1 Mbit/sec, and 2 Mbit/sec. This test was run over a period of 5 days for a total operating time of 50 hours. Slightly saline water was used as the operating fluid in all well tests.

Testing of design improvements. Design improvements developed and reported in the previous reporting period were implemented in 30 joints of full length range 2 drill pipe (32 ft nominal lengths) and tested for transmission line quality. Building 30 joints constituted a second substantial production run for which ease of manufacture and part-to-part variability were evaluated. After assembly and prior to deployment in the test well, each pipe was screened for proper electrical characteristics (bandwidth, attenuation) using screw-on test subs of our own design and the network analyzer. Screw-on test subs consisted of a loose XT57 threadform (threads overcut to eliminate initial taper interference), a nominal 2 inch tong space, and data couplers of the same generation as those implemented in the drill pipe. These test subs were tightened to 200 ft-lbf using a 1000 ft-lbf torque wrench.

Pressure-rated test subs were then assembled onto each pipe and the pipe was filled with brackish water and pressurized to 3000 psi internal pressure for a minimum of 15 minutes. Pressure-rated test subs consisted of XT57 threadforms, a nominal 12 inch tong space, and data couplers of the same generation as those implemented in the drill pipe. Pressure-rated test subs were torqued to 20 kft-lbf to allow worst-case fluid access to the secondary shoulder region. Electrical characteristics were measured and recorded for each pipe before, during and after pressurization. As testing progressed through the production run, pipes were tested 2 and 3 at a time by tightening them together and to the pressure-rated test subs using 20 kft-lbf torque. In these latter tests, multiple pipe characteristics were recorded; individual pipe characteristics were not recorded unless the multiple pipe characteristics were seen to degrade during pressurization. Pipes not maintaining consistent electrical characteristics during the full test period were removed and reworked.

Following pressure tests, the vibration module used in previous testing was made up to a used 8-1/2 inch rollercone bit with 20,000 ft-lbf torque. The bit was fitted with one #10 and one #12 nozzle to allow generation of up to 1500 psi system pressure at flow rates of 350 gpm. The vibration module was programmed to provide a sine wave swept in frequency from 3.0 to 7.8 MHz. The 30 drill pipes were then added singly to the string and run in a 1000 ft vertical cased test well, each pipe torqued to the string with a minimum manufacturer's recommended torque of 45,000 kft-lbf. Bestolife™ Copper Supreme Special Blend thread dope was used on all joints. At the top of the string, a rotary signal sub comprising a further set of data couplers similar to those used in each pipe was made up to the drill string with 12-20 kft-lbf; lower torque values were used to expedite tripping (rig torque limit without using the Scorpion® is 20 kft-lbf). The function of this sub is to relay the data signal from the rotating drill string to the stationary world. The received signal was analyzed with a Tektronix TDS 224 digital oscilloscope in fast Fourier transform (FFT) mode, displaying signal intensity in dBrms vs. frequency. The signal was measured both with and without rotation each time a pipe was added to the string.

Once 30 drill pipes were in the well, a steel plate on the bottom of the well was tagged with the bit, flow was established, and rotation was begun. The assembly was tested for 24 hours while rotating on a steel plate at 70 rpm. Fluid flow was 230 gallons per minute at a pressure of 1250 psi.

The drill rig was then moved to a cased 100-foot well, leaving twenty-nine pipes in the 1,000 foot well. A second, identical vibration sub was programmed to cycle between transmitting canned data and digitized 3-axis accelerometer data at three different data rates: 0.5, 1.0, and 2.0 million bits per second. The carrier frequency of the data transmitter was set to the center frequency observed in the 30-joint test. A string consisting of four pipes and the module and an 8-1/2 bit was assembled and run into the 100 ft well. Error rates at each data rate were tallied by comparing the transmitted data stream to its native format. Again, testing was accomplished with and without flow and rotation.

Longevity testing of electronic module and transmission line. Stability of the drill pipe communications system was monitored over a period of one month. During this period, the 29 pipe joints were left hanging off bottom in the 1000 ft well, and the electronic module was left to broadcast full-time (no power-down or other conservation sequence was employed). Frequency spectrum measurements were taken and digitized from TEK TDS 224 oscilloscope FFT images to quantify the transmission line.

RESULTS & DISCUSSION

Robustness testing of second revision pipes. Tool joint makeup/breakout testing revealed no measurable differences in drill pipe electrical characteristics while tightening the pipe joint, as compared to characteristics measured before torquing. Furthermore, pipe characteristics remained constant for the duration of the 100 torque cycles.

Three out of six pipes deployed in the 100 ft well for the combined vibrational and pressure test survived at least 30 hours of the testing. Three other pipes exhibited a substantial decrease in signal output after as few as 7 hours into the test. Each of the failed pipes was removed from the test and replaced with new pipe. Of the 3 surviving pipes, two survived the entire 50 hours of operational testing, and one pipe was placed in the well as a replacement for a failed pipe 20 hours into the test, and therefore only saw 30 hours of testing. Two possible sources of failure have been identified: competency of the connection between the coupler and the transmission cable and leakage of fluid into the transmission cable. Design improvements were implemented to provide a more repeatable connection with the transmission cable. The last pipe inserted in the test incorporated these changes with apparent success. However, leakage of fluid into the transmission cable was noted in each of the 3 failed parts. Further improvements to the sealing mechanism are required to eliminate the possibility of leakage. These improvements and further robustness testing are required.

Testing of design improvements. Figure 1 shows the dry electrical characteristics of several of the pipes manufactured in the 30 pipe production batch. As shown, the characteristics are very repeatable, which represents a substantial improvement over our first production run at the end of 2001. Though the speed of manufacture of the pipe has also substantially increased over the last production run, several processes still exist that are time consuming and require highly skilled personnel. Improvements and simplifications to these processes will be beneficial to the economic viability of the product. Furthermore, it should be noted that the scheme used presently for sealing the cable from fluid intrusion has exhibited leakage at pressures above 10,000 psi (and, as mentioned above, at lower pressures and high vibration). This seal scheme requires further development before the system is field ready.

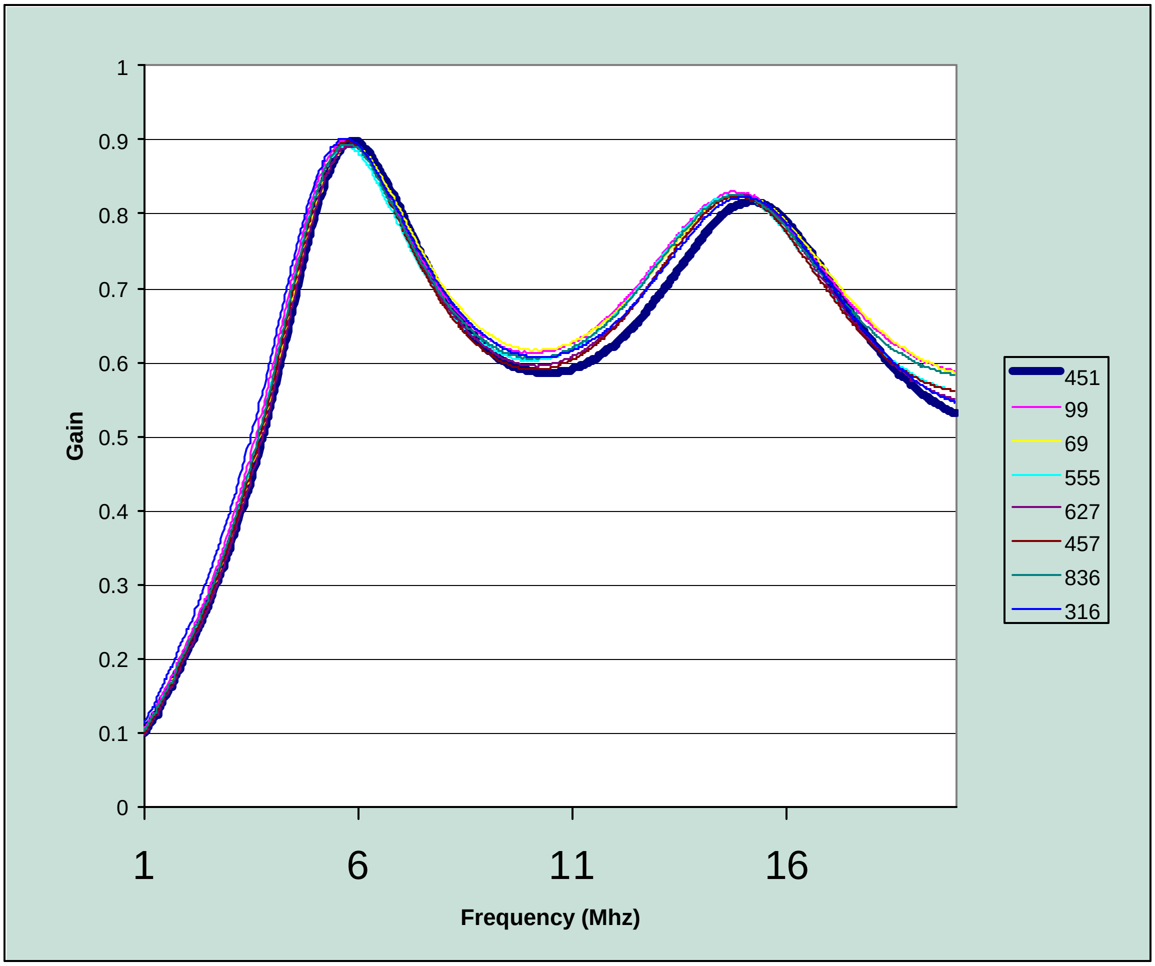

Figure 1. Frequency characteristics of new design prototype transmission line drill pipes

Passive transmission distance of 1000 ft was successfully demonstrated in full-length drill pipe, using the revisions to the transmission line mentioned previously. This demonstration took place in front of U.S. Department if Energy and industry guests in a 1000 ft (cased) test well in Provo, Utah. Quantitative measurements taken through all 30 drill pipes in the test string have shown a usable bandwidth of at least 2.5 MHz and a 0.23 Vpp peak magnitude. The usable bandwidth is sufficient to accommodate at least the targeted 2 Mbit/s data rate. Signal strength data taken during the trip in the hole is shown in Figure 2. The blue data points are in dBrms (left axis), the red data points are the corresponding peak-peak voltage (right axis). As shown, a very predictable relationship exists between number of joints in the well and signal attenuation. The dB data fit a straight line that projects to a signal of –40 dBrms (28 millivolts PP) at 60 joints (1920 ft, 0.36 mile). That is close to the minimum signal strength required by present electronics. Improvements to the electronics are possible that should eventually permit even greater spacing between modules. The raw signal strength presented includes the attenuation from the rotary joint and 150 ft of RG-8 coaxial cable. Data obtained from the December 2001 Catoosa test (reported previously) are plotted for comparison. As shown, the improvements to the transmission line since the Catoosa test are substantial.

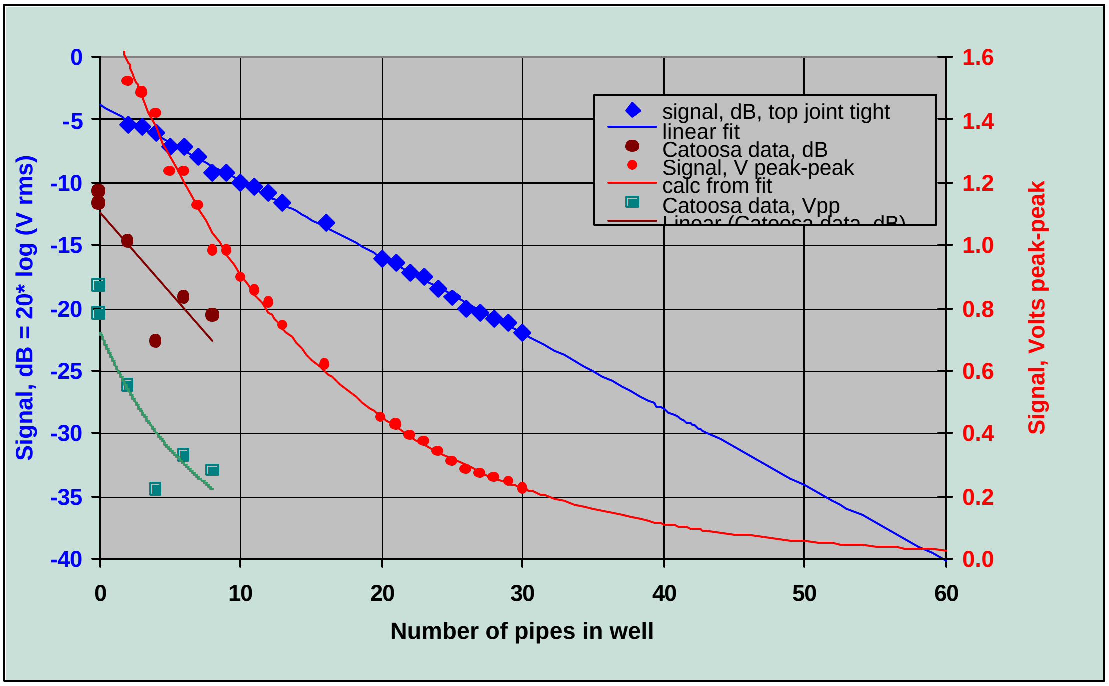

Figure 2. Transmission line strength as a function of number of pipes

It is noteworthy that the data shown in Figure 2 represents a non-rotating condition. Frequency spectra recorded during rotation (vibration) and flow through the drill pipe showed approximately 0.4 dB decrease in the signal strength of the 30-joint system as compared to signal characteristics in non-rotating/non-flowing conditions. Continued testing of the 30-joint system while rotating on a steel plate showed no measurable signal degradation during a 24 hour period.

Further investigation of the worthiness of a shorter transmission line (a four-pipe assembly) for digital data transmission demonstrated error-free transmission at two million bits per second while drilling on a steel plate under the same conditions as the 30-pipe test. Although this test and the above frequency-sweep test indicates that the gain and bandwidth of the transmission line should be more than adequate for error-free transmission of digital data at two million bps, a confirmatory test is planned by repeating the 30-joint test in digital mode.

Longevity testing of electronic module and transmission line. The electronic module was placed in service on May 16, 2002 and the 30th pipe was added May 18th. The 30-pipe measurement remained stable through May 30th, after which the rig was moved for servicing and further testing, taking 30th pipe with it. Figure 3 shows the frequency spectrum received at the top of the 29th pipe on days 14, 15, 19, 26, and 33 of the test in the 1,000-ft well. The raw data (blue) is in dBrms, left axis. The conversion to volts peak-peak (red) is on the right axis. This data was taken directly off the 29th pipe, without the rotary joint and long cable.

As shown in Figure 3, the signal is constant to within measurement error through at least day 26, demonstrating excellent long-term stability of the system under immersion to 1,000 ft. The pressure at the bottom of the hole is about 450 psi. The signal decrease on day 33 (violet and yellow) is due to battery depletion; the batteries were completely depleted by day 40.

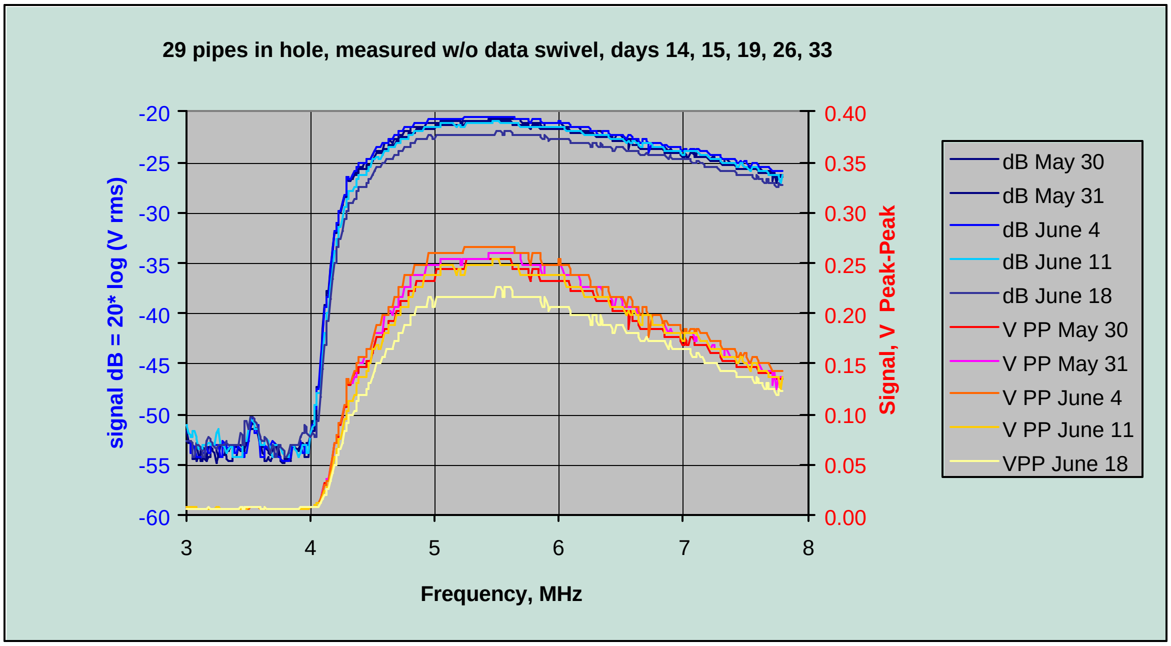

Figure 3. Transmission line strength as a function of time in well

CONCLUSIONS

Based on the above data and discussion, the following conclusions may be drawn:

1) The design changes incorporated in the present revision of the transmission line are effective in providing at least 1000 ft of passive transmission distance in range 2 drill pipe, at standpipe pressures up to 1250 psi and rotary speeds up to 70 rpm. Sufficient bandwidth and signal strength are provided by the new design to transmit at 2 Mbit/sec data rate. Longer transmission distances may be possible.

2) The transmission line and electronic transmission module display continuous transmission longevity of approximately a month under non-rotating, non-flowing conditions. Battery life limits the longevity. Further testing under rotating conditions is required.

3) The present design requires further work to improve the robustness of the sealed connections under high vibration levels and pressures greater than 10,000 psi.

REFERENCES

None.