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High Data Rate MWD Mud Pulse Telemetry – From Mysteries to Discovery

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Abstract

Our new approach to MWD mud pulse telemetry offers significant increases over conventional data rates. Using waveguide acoustics, we show that common drilling communications channels support carrier frequencies exceeding several hundred Hertz. Such signals are prone to attenuation over large drill pipe distances. Low power, self-spinning "turbosirens" are designed, providing high torque and rotation rate performance at all flow rates without electric or hydraulic motor drives. The sirens rotate, drawing only on the kinetic energy of the mud, like flapping flags oscillating in wind. Our turbosirens are minimally affected by LCM jamming. Turbine and siren rotor components ride freely along longitudinal trenches built into rotating shafts. Both magically float into the oncoming mud as it slows down, thus, widening all gap spaces and freeing any trapped debris even as both travel opposite to the mud flow. In addition, "turbosirens in series" signal superposition, drawing on constructive wave interference, offers strong pressure signals at high frequencies without mechanical complexity. Rapid modulations are possible, also without motor drive, relying on rapidly acting electro-magneto rheological brakes powered by turbosirens. To take advantage of hardware capabilities, "Intelligent *i* FSK" telemetry, or Frequency Shift Keying creates clean signals without the ambiguous wave reflections found with PSK and randomized time shifts. Frequency pairs are not selected arbitrarily, but chosen from "neighboring pressure peaks and valleys" in frequency space as determined from bottomhole assembly waveguide Fourier analysis. Finally, surface signal processing and reflection removal are facilitated with time delay and differential equation algorithms. For deep wells where multiple drill pipe reflections are unlikely, analytical solutions for both are obtained assuming single reflections which do not involve windowing challenges and complicated digital filter design. Software and hardware developments patented, published and validated over the years, are integrated, refined and readied for controlled field tests.

Keywords

Carrier frequency; frequency shift keying; measurement while drilling; mud pulse telemetry; negative pulser; positive pulser; turbosiren

1. Introduction: Background, Mysteries and Reconciliation

We will review the development of Measurement While Drilling mud pulse technology over the past four decades, in particular, the reasons for its continuing lack of progress and importantly, physical insights acquired over the past decade offering a credible path toward high data rate MWD telemetry. Reviews are subjective and biased toward a writer's experience and personal perspectives. Thus, it is important to understand this author's background so comments can be taken in context.

1.1 Author Background

In 1981, the author joined Schlumberger as MWD Telemetry Manager, chartered to increase siren data rates from 3 bits/sec (or, "bps") to 12. This was supposedly straightforward, doable by changing carrier frequencies from 12 Hz to 48. This would not be the case, with any type of pulser, for reasons explained later. In the intervening decades, the author would continue his efforts with multiple organizations. This work, with Schlumberger, NL Industries, Halliburton, Gyrodata Schlumberger, GE Oil & Gas, BakerHughes, CNPC and Sinopec, was often separated by years, dependent on funding, industry interest and simply luck. During this time, companies would disappear or merge, personnel would leave the industry or retire, with any accumulated knowledge relegated to passages in forgotten papers never to be shared. This author, however, persevered throughout his journey, and finally, new methods and an integrated perspective on MWD technology have emerged that will define improved approaches to hardware, telemetry and signal processing design.

The author's early background includes a Ph.D. from the Massachusetts Institute of Technology (MIT) and a M.Sc. from the California Institute of Technology (Caltech), with majors and minors in physics, applied math, aerospace engineering and electromagnetics. His Doctoral Thesis, "Physics of Slowly Varying Wavetrains in Continuum Systems," sought to unify disparate ideas in wave propagation, waveguide physics, group velocity, energy propagation, and the like. This background should, at least theoretically, prepare him to effectively combine modern communications concepts with downhole acoustics physics and hardware design, but this would not be the case. When individuals make radical changes, for example, transitioning from urban to rural environments, or in his case, high speed aerodynamics to petroleum engineering, fundamental learned principles can lie dormant until that final “Ah ha” moment. This, in fact, has been the case, but all unresolved pieces of the puzzle have now fallen in place. We will discuss both anecdotal stories and true-to-life incidents chronologically.

1.2 Conventional MWD Pulser Types and Principles

In the 1980s literature, and continuing to the present, mud pulsers appear in three categories, negative pulsers, positive pulsers (or “poppet” valves), and mud sirens (or “rotary shear valves”), as shown in Figure 1. Here, cross-hatched or shaded areas represent the drill collars that contain these signal sources. A negative pulser creates disturbance pressure signals by *slowly* “opening and closing a door” in the collar. When the door opens, drill pipe pressures drop as shown, and when it closes, pressures return to prior hydrostatic levels. Negative pulsers have not proven popular, because resulting fluid jets and high pressures can damage formations.

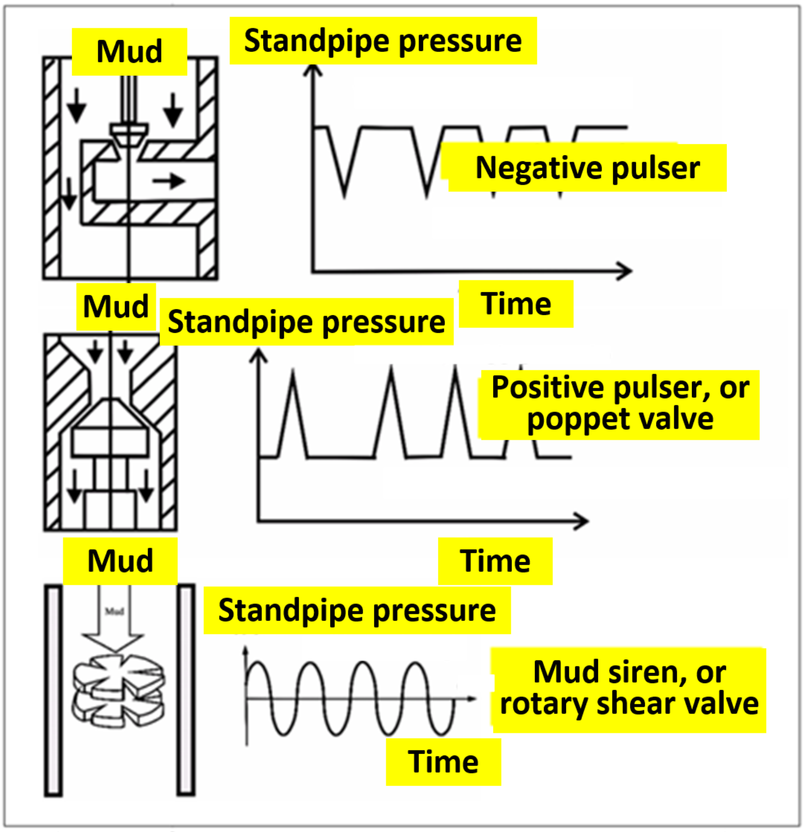


Figure 1 Three mud pulse pressure source designs.

Positive pulsers, on the other hand, are very popular. They are easily fabricated, with the number of worldwide manufacturers in the dozens and rapidly increasing. In *Measurement While Drilling*, they are described as “Frankenstein tools” because numerous designs have evolved dangerously and erratically in “Mom and Pop” shops. As depicted in Figure 1, higher positive pressure signals are created when an upgoing plunger or piston *slowly* moves against a narrowing passage toward a small orifice, thus increasing drill pipe pressure, as indicated. When the piston or poppet valve is retracted, pressures return to hydrostatic levels. It is clear that directly confronting and stopping oncoming mud flow requires large mechanical power and energy expenditures, so that data rates will be severely limited.

Finally, “mud sirens” and “rotary shear valves” are depicted in Figure 1. “Mud sirens,” for example, those operated by Schlumberger, rotate continuously in one direction, slowing down as required to introduce phase changes. They create classic “water hammer” pressure signals when oncoming mud impacts rotor-stator combinations in closed positions. The term “rotary shear valve” implies fundamental differences in operating principles, but the inherent physical laws used are little different. Like sirens, rotors move transversely relative to the oncoming mud. As before, audible signals are only created upon complete rotor-stator closure. They do not “quickly slice” through the mud as the word “shear” implies, but actually “bang” into it just as sirens do, although now in alternate rotating and counter-rotating directions. However, these actions are neither energy nor time efficient. For every change in direction required, a deceleration to zero velocity is needed, followed by an acceleration from zero that must be made. This process needlessly consumes energy, time and slows bit rate. A mud siren that is able to efficiently reduce phase shift times will easily produce higher data rates than a comparable rotary shear valve. Rotary shear methods, introduced to provide siren competitive alternatives, were originally designed to avoid patent infringement issues.

In our research, we will focus on mud siren and “turbosiren” designs that rotate only in one direction. Again, rotors move relative to stationary stators, and then, transversely against the mud flow. Periodic pressures in time are created with constant rate rotations, and for this reason, siren processes are synonymous with “continuous wave telemetry.” Negative and positive pulsers may execute one or two mechanical closures per second, at best, given the “brute force” nature inherent in direct confrontations with high momentum mud. In contrast, sirens are “see through,” that is, half-opened and half-closed for the duration of a time cycle. Thus, they permit 50% of the oncoming flow to move through temporarily aligned “port” (or “empty”) spaces. As such, they consume much less energy, at the same time supporting higher “open and close” operations per second, taking care not to invoke “bits per second” terminology for now. While these rates are faster, the strengths associated with siren disturbance pressures are much lower than those of positive pulsers due to incomplete closure, falling rapidly as gap distances between rotors and stators increase or as erosion takes hold. This reduces effective bit rates because created signals cannot travel over large drill pipe distances. The simple 1980s introductions above shown in Figure 1 (without our detailed explanations) have not changed over four decades. Prominent oil and gas trade journals, not to mention experienced petroleum engineers and designers, continue to offer such over-simplified descriptions. They are only partially correct and at best misleading, and have resulted in stalled progress in an important engineering endeavor and in continuing low data rate expectations.

1.3 Confusion over “Hydraulic” versus “Acoustic” Signaling

For slow pulser motions, or “hydraulic events,” the overview above just *might* suffice. In the petroleum literature, Bernoulli’s equation “$P + \frac{1}{2}\rho U^2 = \text{constant}$” (strictly applicable to inviscid flows) and Hagen-Poiseuille’s law “$\Delta P = 8\mu LQ/(\pi R^4)$” for viscous Newtonian pipe flow only, are indiscriminately used to describe pressures as they react to changes in speed, which in turn result from orifice area changes at moving pulsers. Incorrect usage of these formulas proliferates in numerous company publications. Throughout MWD history, in fact, drilling researchers have rarely described mud pulse events in “acoustic” terms. This semantic barrier has not allowed MWD to benefit from the wealth of scientific information available from a maturing technology. Many MWD applications were and are simply “hydraulic,” as in civil engineering. However, as the technology increased in popularity in the 1980s, relevant but confusing questions arose while the knowledge base grew slowly but surely.

To avoid reader confusion, we will define “hydraulic” and “acoustic” in laymen’s as well as mathematical terms. Imagine Person A communicating with Person B over a given distance. This is possible using “smoke signals,” initiated by native tribes long ago in American history, which are clearly limited in range. On the other hand, A and B can be connected by a long tube through which either physically slowly blows fluid to the other, intermittently blocked by a slowly closing valve to convey information. This “hydraulic” approach involves actual movements of large bodies of fluid, and its efficiency depends on separation distance, frictional loss and fluid density. On the other hand, it is not necessary to move the entire body of fluid. A and B can simply “speak” to each other, through words, grunts and groans, or “0 and 1” clicks of a rapidly acting valve. This is “acoustic,” or “sound” transfer.

Sound travels quickly through a medium at “sound speed,” usually denoted by “c,” about 5,000 ft/sec in water, 3,000 ft/sec in heavy mud, and 1,000 ft/sec in air in acoustic wind tunnels. Like waves propagating along stretched jump ropes, disturbances move throughout the entire length unimpeded, while portions of the rope only move temporarily and locally while the disturbance is passing through it. Thus, acoustic methods are more efficient. Hydraulic motions are governed by the incompressible flow equations, say the constant density Navier-Stokes model for Newtonian fluids – these generally require computational finite difference or finite element methods for analysis, which are plagued by truncation errors and grid dependencies. Acoustic equations solve simpler classical wave equations, for example, “$\partial^2 P/\partial t^2 - c^2 \partial^2 P/\partial x^2 = 0$.” Reflections and impedance changes at drill string area changes, and effects like constructive and destructive wave interference, can be rapidly and efficiently studied in acoustic wind tunnels, although attenuation effects must be pursued by more labor intensive but practically doable empirical means.

Some historical anecdotes are worth mentioning. Halliburton engineers, for example, had noted that changes in measured standpipe pressure were often accompanied by “sonics,” strange pressure occurrences referring to undefined events associated with sound propagation. Rig personnel would also notice how desurgers would severely distort upcoming MWD pressures on numerous occasions. In contrast, Schlumberger engineers claimed the opposite, to the extent that field kits included spare desurger bladders just in case one was damaged. Such differences in conclusions could only be resolved by introducing acoustic wave descriptions now becoming more apparent and common as mechanical efficiencies increased.

The 1990s acoustic model proposed by this author was consistent with both observations. Halliburton’s positive pulsers created high amplitude, slowly acting, low-frequency waves, allowing them to interact strongly with elastic bladders. On reflection from the desurger, signals would severely distort; from physics, elastic boundary conditions assumed at pipe ends are known to convert square waves into stretched exponentials. By contrast, Schlumberger’s oscillations were much more rapid, at the same time much lower in signal strength. These would not act long enough for bladders to distort signals effectively. This model resolved differences offered in two conflicting but credible observations, pointing to the significance of frequency and amplitude in understanding surface acoustic wave telemetry.

Interestingly, the author's new model would resolve additional issues. In the foregoing scenario, Halliburton engineers found that broken desurgers, that is, those which were not operable, actually benefited signal detection (of course, the positive benefits of desurger operation would be lost, but MWD detection really *did* improve). The reason is again provided by acoustics. Without an active desurger, upcoming signals would continue directly toward the mud pump pistons, where they would reflect and propagate downward. It is known that incident waves traveling toward solid reflectors would reflect with unchanged pressure sign (or polarity). Since data rates are slow, the waves are long and reflected pressure waves with identical polarity would effectively double local amplitudes. This renders signals more detectable at standpipe transducers, doubling the measured signal to noise ratio. This advantage, of course, disappears as frequencies increase and wavelengths shorten. Years later, at the company's Fort Worth test well, this author would monitor pressure transducers placed in close proximity to pump pistons, verifying first hand that signals in fact doubled. This contradicts conventional wisdom where such locations are to be avoided, even today, because "they are inherently noisy."

If *broken* desurgers benefited Halliburton, why would they hurt Schlumberger? With sirens, upcoming waves would continue directly toward the pistons and reflect downwards. However, since mud sound speeds and surface travel lengths are not controlled or recorded, waves will reflect with uncertain phase or time shifts that introduce random cancellations. A functioning desurger would absorb all upcoming signals so they would not reflect. MWD signals measured at the standpipe, we emphasize, would represent only upgoing transmissions from downhole. Of course, strong downgoing pump pulsations are still present, which must be removed with bandpass filters or other "delay" means.

Finally, one service company would field test a new MWD tool with unexpected frustration. Transmissions from downhole, measured at the standpipe, produced no perceptible signal. The tool was retrieved, carefully examined, and re-tested again and again as no mechanical defects were apparent. However, an acoustic explanation would resolve the issues. A plane wave in a long conduit, it is known, reflects at open ends with reversed pressure polarity. In this case, a quick "walk around" rigsite examination showed that the mud pump used was not the usual "positive displacement piston" variety, but a centrifugal pump which reflected MWD signals as an acoustic open end. This implied reversed pressure polarity, leading to significant cancellations. The lesson was obvious: never operate centrifugal pumps unless transducer methods with directional sensing capabilities (discussed later) are used.

1.4 More Acoustic Signal Subtleties

We have introduced slow "hydraulic" movements, as well as more rapid "acoustic" wave motions. Mud flows through slowly closing orifices are "hydraulic," satisfying convenient Bernoulli or Hagen-Poiseuille relationships that may be inapplicable. Mud interactions with rapidly closing valves, on the other hand, created so-called "acoustic" or "water hammer" effects. These are well known in pipeline engineering and refinery operations and amenable to acoustic description. Sound waves in long conduits impinging at moving solid ends, for example, follow "$P = \rho Uc$," where P, ρ, U and c denotes pressure, mass density, local velocity and sound speed, with $P \sim U$ taking a linear and not quadratic dependence. Why is this important? While drilling, tools operate deeper and deeper, and MWD signals reside longer in the attenuative environment than at shallow depths.

Stronger starting signals are needed, a requirement easily fulfilled by increasing mud velocity linearly. We emphasize that hydraulic and acoustic modes do coexist in the downhole environment. The former creates the signal, while the latter provides the transmission medium. However, they act independently, just as sound propagates effortlessly through wind, noting that attenuation and turbulence effects are secondary. This is evident on any windy day – speech is not impeded, although added noise and speed variations may require additional effort to distinguish words properly.

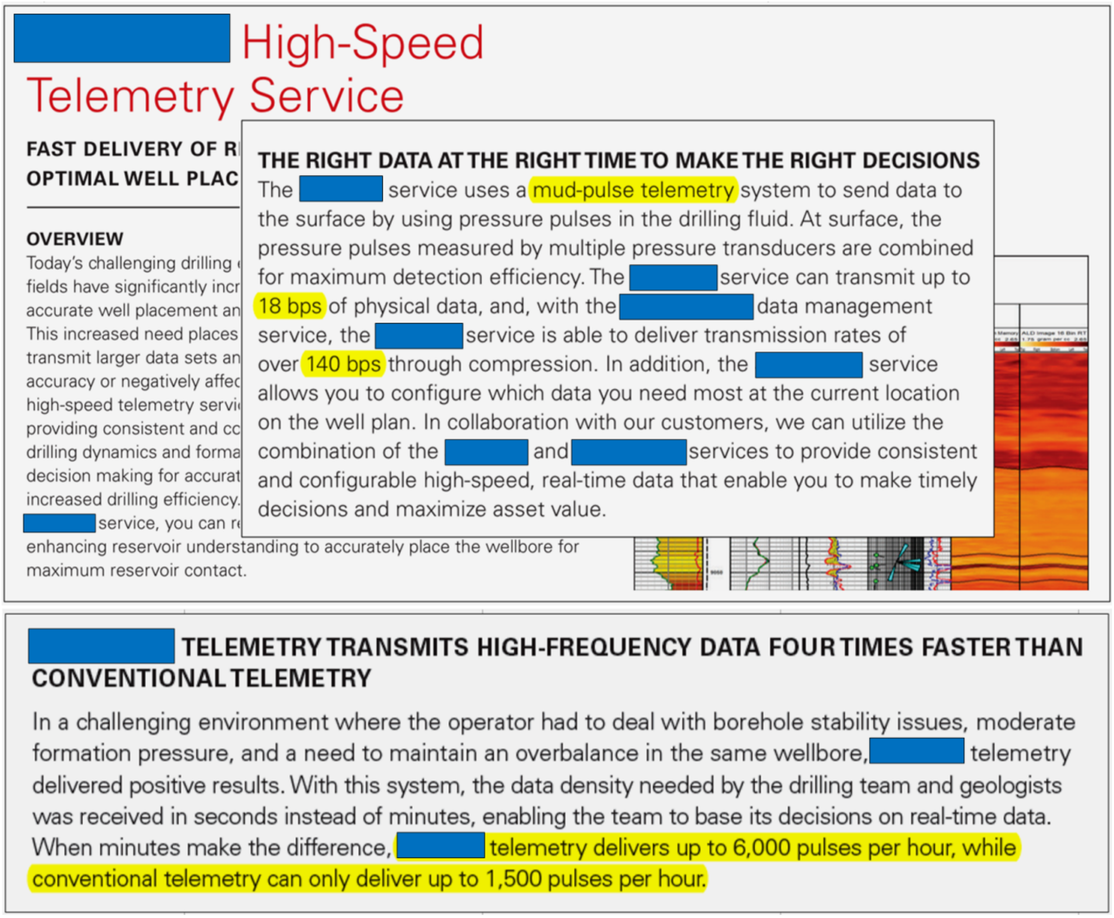
1.5 Ambiguities in Bit Rate Reporting

Comparison of different commercial MWD systems can be difficult. The literature, particularly advertising brochures, proliferates with dubious claims to high data rate performance. However, the assumptions behind “bits per second” numbers are rarely defined. Many illustrate their methods with ideal sinusoidal waveforms, with one conservative estimate requiring two full cycles for one “unit” of information, while others ambitiously claim four units per single cycle despite the fact that real waves are hardly sinusoidal as will be shown later. Because “bit rates,” in this sense, are ambiguous, we will avoid bps labels, preferring instead to focus on actual mechanical rpm cycles that can be measured. In summary, data rate depends on encoding techniques, also rarely discussed. However, in publications where encoding *is* discussed, little information is offered regarding surface reflection removal. In fact, the author knows of several companies that leave reflections intact with decoding issues unresolved. In at least one company, both Engineering Director and Chief Software Architect left reflections intact, because “resources are presently limited.” And so, incorrect information is often embedded in results, contributing to logging ambiguities and questionable operational decisions, whereas the present author would preferably have discarded the improperly processed data streams entirely. As for sinusoidal assumptions, oscilloscope traces offered later in this paper show real waveforms are sharp, peaky and often unpredictable. This arises from local geometric effects and harmonic generation associated with fluid nonlinearities. Thus predicted high performances are not likely to materialize. Additional ambiguities relating to mud type, attenuation properties and depth again are rarely discussed in case studies, and undisclosed details on data compression, contribute to further confusion. Whether or not high data rates really prevail throughout a particular drilling process is never known. Successful trials obtained in the laboratory are often not repeatable over large multi-mile drill pipe distances. At least two organizations, to this author’s knowledge, operate rotary valves at shallow depths while reverting to stronger but slower positive pulsers at deeper locations.

Another uncertainty in data rate testing arises from downhole wave reflections. Consider a positive pulser or a siren *closing* against downward flowing mud. A positive disturbance pressure (relative to hydrostatic levels) or compression wave is created that propagates uphole. Simultaneously, a negative pressure wave forms at the opposite side of the source as fluid pulls away and propagates toward the drill bit. If the bit is acoustically open – and narrow bit nozzles *do* behave in this manner – the wave will reflect with opposite pressure polarity as previously described. In other words, downgoing expansion waves reflect as compression waves. This adds to the upgoing compression wave created initially, resulting in a doubling in amplitude. Similar considerations apply to sources *opening* toward the mud, creating upgoing expansion and downgoing compression waves, that likewise result in pressure doubling. In one disturbing advertisement, the company's bottomhole assembly was shown suspended off-bottom. This suggested that tests were conducted with an open end, resulting in optimistic but misleading signal doubling that cannot be realized in practice. While drilling in hard rock, the reflected pressures would be exactly opposite to those above, instead leading to cancelations. Thus, even "controlled tests" may not have controlled everything properly, so optimistic predictions must often be considered with caution.

Again, we have found numerous instances where companies completely ignore the effects of surface reflections simply because they are unable to remove them. Success in signal extraction is measured only by the ability of software to operate without crashing. This author, on the other hand, believes that only those instances where reflections have been completely and properly removed should be counted in bit rate reporting. This more conservative measure provides a more accurate assessment of "true bits per second." It also highlights the need to physically increase signal amplitudes at the source and to improve accuracy in telemetry and signal processing. While test wells with known rock layer properties are routinely used, say in resistivity and acoustic logging tool calibration, similar "acoustic calibration facilities" monitoring the ability of MWD signal processing methods to properly monitor and remove reflections and desurger distortions should also be standard. Acoustics expertise should be a requirement of the job.

In closing this section, we have duplicated in Figure 2 an industry advertisement for a company's latest high speed telemetry service, claiming data rates as high as 140 bps. In the second publication shown beneath it, its tool delivers "up to 6,000 pulses per hour," which translates to 6,000 pulses per 3,600 seconds, or a mere 1.7 pulses per second. How 140 bps, which is two orders of magnitude greater, is achieved is not explained. On the other hand, APS Technologies, in its published specifications for its rotary valve, simply writes ">1 bps," a more credible disclosure given our arguments above. For all the reasons cited above, we will refrain from quoting our results using customary "bits per second" or "bps," in favor of mechanical "pulses per second" or "pps," whose relationship to rpm is more clear and less ambiguous. Clever encoding represents an important next step in our MWD development. We will not discuss encoding methods in this paper, an integral element of our "intelligent *i*FSK" platform under development. For now, we only emphasize the need to physically increase signal strength at the source, required to improve telemetry, encoding and signal processing methods, to truly deliver high data rates without ambiguity. These objectives, forming the thrust of this paper, are addressed by a new physics-based telemetry scheme accompanied by newly developed self-spinning, self-cleaning, "sirens in series" approaches to hardware design and direction-based surface signal processing.



[redacted] High-Speed Telemetry Service

FAST DELIVERY OF R
OPTIMAL WELL PLAC

OVERVIEW
Today's challenging drilling
fields have significantly incr
accurate well placement an
This increased need places
transmit larger data sets an
accuracy or negatively affec
high-speed telemetry servi
providing consistent and cc
drilling dynamics and forma
decision making for accurat
increased drilling efficiency.
[redacted] service, you can r
enhancing reservoir understanding to accurately place the wellbore for maximum reservoir contact.

THE RIGHT DATA AT THE RIGHT TIME TO MAKE THE RIGHT DECISIONS

The [redacted] service uses a mud-pulse telemetry system to send data to the surface by using pressure pulses in the drilling fluid. At surface, the pressure pulses measured by multiple pressure transducers are combined for maximum detection efficiency. The [redacted] service can transmit up to 18 bps of physical data, and, with the [redacted] data management service, the [redacted] service is able to deliver transmission rates of over 140 bps through compression. In addition, the [redacted] service allows you to configure which data you need most at the current location on the well plan. In collaboration with our customers, we can utilize the combination of the [redacted] and [redacted] services to provide consistent and configurable high-speed, real-time data that enable you to make timely decisions and maximize asset value.

[redacted] TELEMETRY TRANSMITS HIGH-FREQUENCY DATA FOUR TIMES FASTER THAN CONVENTIONAL TELEMETRY

In a challenging environment where the operator had to deal with borehole stability issues, moderate formation pressure, and a need to maintain an overbalance in the same wellbore, [redacted] telemetry delivered positive results. With this system, the data density needed by the drilling team and geologists was received in seconds instead of minutes, enabling the team to base its decisions on real-time data. When minutes make the difference, [redacted] telemetry delivers up to 6,000 pulses per hour, while conventional telemetry can only deliver up to 1,500 pulses per hour.

Figure 2 A typical industry mud pulse telemetry service advertisement.

2. Methods and Results: Motivating Acoustic Laboratory and Field Experiments

The incidents and lessons collected above, reflecting this author's understanding of MWD in the early 1990s, would motivate and redefine his research direction. While he introduced "short wind tunnel testing" (SWT) at Schlumberger, streamlining signal strength, torque, jamming and erosion testing by evaluating balsa wood and plastic models in wind, the need for greater sophistication became apparent as the acoustic nature behind MWD transmissions gained acceptance. The author would introduce "long wind tunnels" (LWT) for telemetry testing – not only for communications concept evaluation, but for physics-based studies of constructive and destructive wave interference effects which became apparent at larger length scales. Such wind tunnels, important to evaluating the telemetry concepts offered in this paper, deserve additional elaboration in view of their increasing importance.

2.1 Long Acoustic Wind Tunnel Innovations

The author introduced "short wind tunnel" (SWT) testing in the 1980s, powered by simple blowers acting through 6 ft long see-through plastic tubes. Inexpensive flow meters, pressure gauges, tachometers and force gauges supported signal, torque and rpm measurements, while neutrally buoyant helium soap bubble generation enabled flow visualization for erosion remediation. While powerful, SWTs were not feasible for studying acoustic events like wave propagation, constructive and destructive wave interference, array signal processing, and transducer placement. For such applications, "long wind tunnel" (LWT) testing was introduced and developed. Photographs for several SWT/LWT facilities developed at oil service companies are shown in Figure 3, Figure 4 and Figure 5, and further described in recent MWD books from Chin et al. [1] and Chin [2].

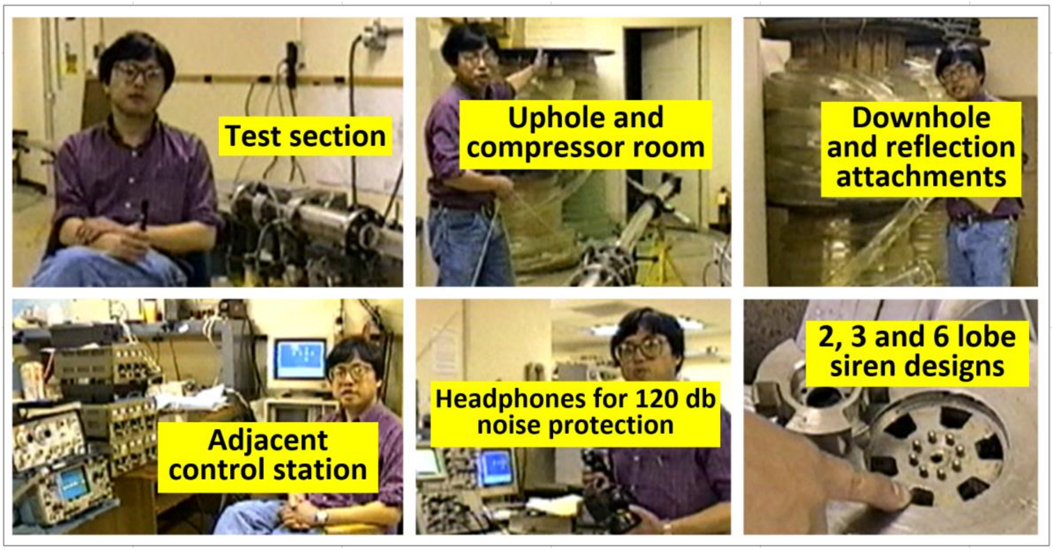


Figure 3 Earliest long acoustic wind tunnel (Halliburton, 1990s).

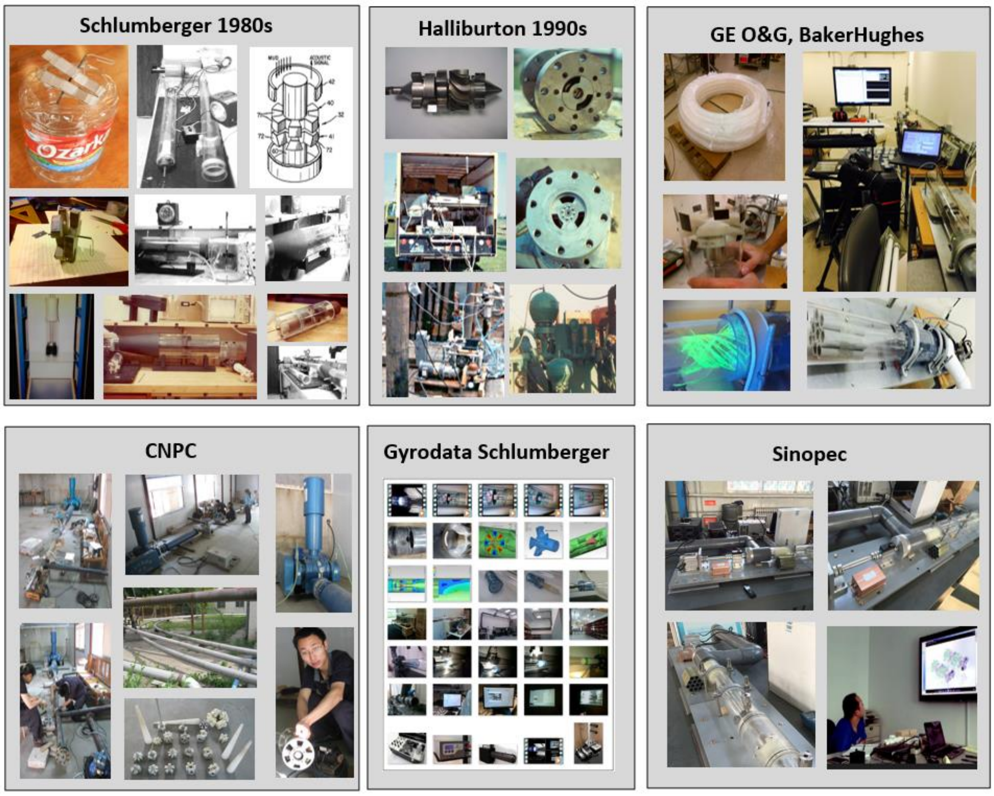


Figure 4 Short and long wind tunnel systems developed for major oil service companies. Early SWT discoveries under "Schlumberger 1980s," cardboard siren model led to "stable open" design from simple wind tunnel analysis.

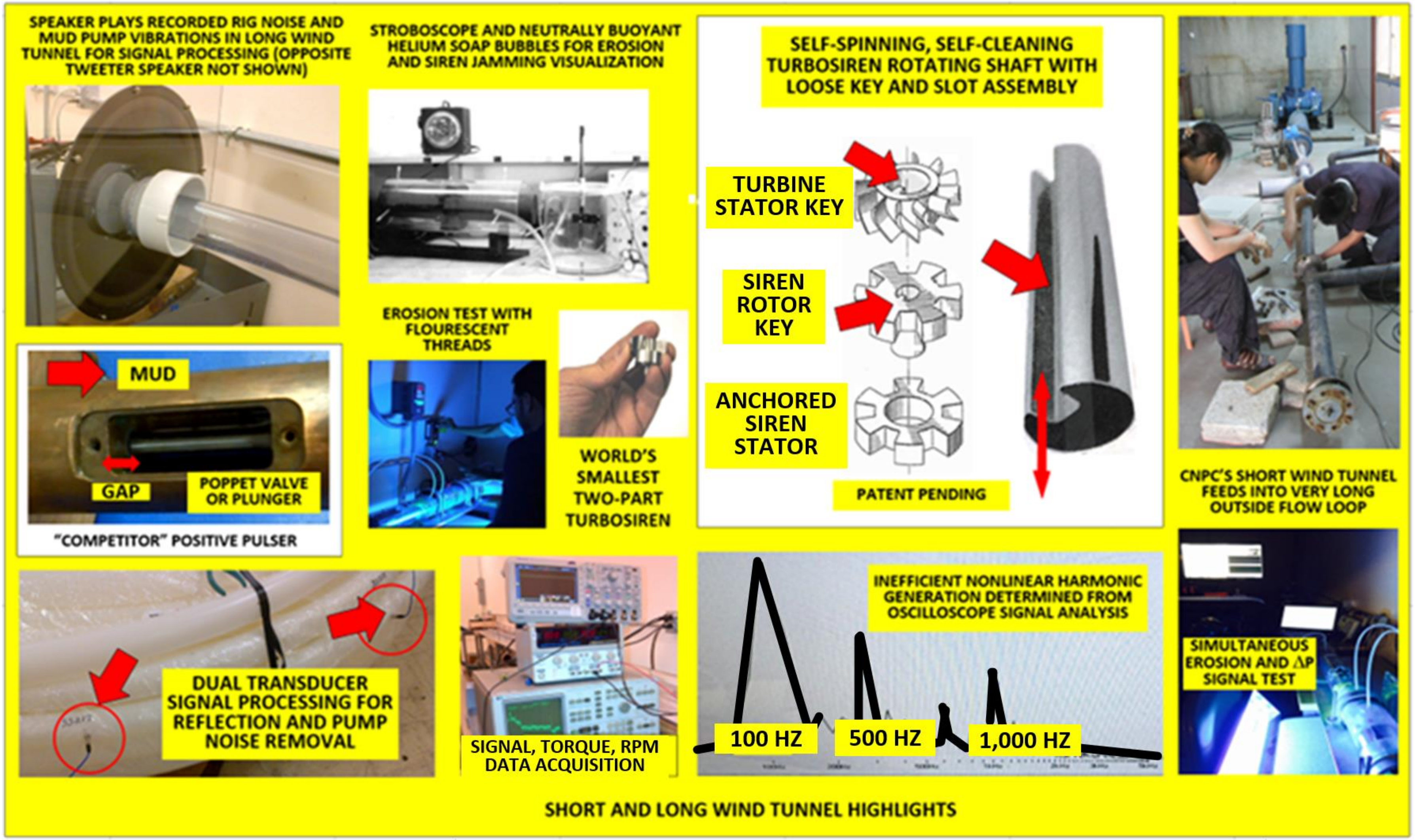


Figure 5 Short and long wind tunnel highlights.

Aside from cost, labor and material (e.g., the use of wood or plastic models) advantages, not to mention convenience, LWTs need not be as long as mud flow loops which often approach 10,000 ft. Mud sound speeds are typically 3,000-5,000 ft/sec, while those in air are 1,000 ft/sec. The wavelength for a 10 Hz signal in mud is 300-500 ft, while that in air is 100 ft, both lengths consistent with “long wave” phenomena as observed in practice. This 100 ft length greatly exceeds plastic tubing diameters of 0.25 ft as required in acoustic theory. Importantly, high data rate applications, say at 500 Hz, still imply a wavelength to diameter ratio of 1,000 ft/sec/500 Hz to 0.25 ft, or 8, which is more than enough for analytical models to apply. Plastic tubing, we emphasize, is inexpensive and readily accessible.

The earliest LWT, developed at Halliburton in the early 1990s, was modestly housed in cramped quarters as shown in Figure 3. Although more sophisticated and larger LWT facilities were later developed for Schlumberger Gyrodata, GE Oil & Gas, BakerHughes, CNPC and Sinopec, the simple LWT directly contributed to a dozen hardware and software patents important to our work. Detailed descriptions for all SWT and LWT facilities and applications appear in two MWD books, Chin et al. [1] and Chin [2], and in Stratamagnetic Software Company Brochure [3] and Software and MWD Technology Proposals [4]. The newer methods were instrumental to turbosiren, “sirens in series,” directional filter signal processing, and array transducer placement, all of which motivated and guided our research. Turbosiren videos and brochures are available on request or through cited download links. Collaborations with readers’ organizations are welcome.

2.2 Wind Tunnel Observations of PSK Interactions

At Halliburton’s LWT, studies of acoustic nearfields surrounding rotating mud sirens were performed. While local “hydraulic” efforts are complicated, involving rotating, separated, turbulent flows with viscous wakes, plane wave acoustic fields a foot away at opposite sides of sirens are coherent and amenable to simple description. As noted, acoustic effects act independently of hydraulic phenomena; the former propagate and affect large-scale telemetry while the latter affect local torque, drag, signal strength and erosion. Detailed pressure versus time traces, tediously recorded on rolls of strip charts, revealed what is now obvious. It was found that, as a rotor-stator pair closes to oncoming wind, a high pressure compression wave propagates into the wind while a low pressure expansion wave propagates away from the siren at its opposite side as fluid pulls away.

Relative to hydrostatic pressure levels, the disturbance pressures at either sides were antisymmetric, making physical sense. This would not be apparent in surface mud loops since downstream cavitation would release dissolved gas bubbles that severely attenuate signals at the siren underside. Just as interesting were verifiable reflection properties, noted in acoustics books – for instance, pressure sign reversals for incident waves reflecting at open ends and sign preservation at closed ends. Moreover, an upgoing pressure wave with two oscillatory parts separated by a quiet interval (representing Schlumberger’s “Phase Shift Keying” or PSK transfer) would “see” a reversed pressure pattern traveling downhole. This would then reflect at the “drill bit end” of the wind tunnel, only to join the upgoing wave created an instant earlier. In practice, reflection conditions further depend on unknown lithological parameters with additional phase-shifting. This leads to confusion, with the randomized chaos just described multiplied many times, as multiple PSK transfers are lost in numerous random phase shifts. This suggested that Frequency Shift Keying or FSK might prove more beneficial, a concept we would develop.

2.3 Short and Long Wind Tunnels, Strengths and Limitations

When this author introduced wind tunnel analysis in the 1980s for downhole research, the resounding reaction was "No! Air is Newtonian, but muds are non-Newtonian – Air is dry while water and mud are wet." However, simplistic rules can be incorrect. For example, large airplanes may be wind tunnel tested, with scaling laws and (large) Reynolds number corrections used to correct one-foot scale model results. Results for designs the size of a mosquito, unfortunately, are inapplicable because they operate at very low Reynolds numbers. For the same reason, mosquito-sized stealth planes require original research, and performance cannot be inferred from airplane data. And so it is, with short and wind tunnel tests. Useful tips are now offered.

(1) Turbine and siren rotor torque versus flow speed can be determined from SWT data by rescaling, using formulas based simply on speed, density and length. This is appropriate as transverse forces are inviscidly based. However, properties like thrust, important to determining bearing loads, cannot use SWT testing because streamwise effects are strongly affected by mud inertia and viscosity.

(2) Reflection propagation and cancellation, transducer array signal processing, constructive and destructive wave interference are important to direction-based filters and surface signal processing. LWT testing is ideal. Speakers can be placed at either end, or both ends, "woofers" for low frequency and "tweeters" for high. Air flow is not required since air is only used to *create* pressure pulses – again, air flow and sound propagation proceed independently and do not interact. If turbulent noise and sound pulses are required, they can be added to the audio recording and replayed.

(3) Mud sound attenuation data cannot be inferred from wind results. The LWT is useful only for "plane, or long wave" acoustic modeling. Mile-long mud loops are not required to study dissipation. Simply fill a long conduit constructed from multiple drill pipe sections with mud. One pipe end terminates with a metal plug, while the other, a slightly movable piston that is to be struck by a hammer. Attenuation and sound speed characteristics can be calculated from (a) total start to finish time, (b) conduit length, and (c) number of round trips. This data can be used to select the number of "sirens in series" needed to produce detectable high frequency signals at the surface.

(4) Sirens rotating at constant rate create frequencies that depend on rpm and lobe number that are readable from spectrum analyzers connected to flow conduits. However, additional lines appear on amplitude versus frequency plots, representing losses arising from nonlinear fluid-dynamic harmonic generation. These lines may not be relevant to mud, since high-order terms in air and mud physical math models usually differ. Primary harmonic results are always useful for amplitude signal generation efficiency. For example, low amplitudes will point to excessive gap flow leakage.

(5) True siren signal strength (or, "ΔP, upstream *minus* downstream differential pressure" versus flow rate) depends on flow rate, sound speed, rotation rate, and geometry. It is measured in short or long wind tunnels using "differential pressure" data, with one sensor upstream and the other downstream of the siren. Such measurements automatically remove reflections

and extraneous sound. Firecracker explosions at one end of the fixture will not be recorded since sound inputs at one transducer are immediately subtracted at the other. On the other hand, “single transducer” data will be contaminated by reflections and other noise, and if placed outside the flow conduit, will largely measure room acoustics. Importantly, while acoustic pressures at either side of “ideal sirens” are anti-symmetric, for example, those created by speakers, real rotating sirens are associated with large rotating wakes formed only at downstream locations. Thus, differential pressure measurements will not be perfect, unless the probes are widely separated and additional “flow straighteners” are used to remove viscous wake effects.

(6) Facilities constraints may not support long wind tunnel (LWT) construction. However, for “long waves” at “low frequencies,” *acoustic* losses at 90° bends are minimal and less than 1%. This does not apply to *viscous* losses in pipes actually transporting fluids. Thus, our “six segment wave guide” model unwraps pipe and annular sound transmissions for simpler yet rigorous analysis. At high frequencies exceeding 5,000 Hz where diffractions may be important, this approximation may be less valid. In Figure 4, observe how multiple 90^o bends appear along an LWT ceiling piping arrangement for the Schlumberger Gyrodata facility shown. Space constraints precluded milder bend angles, but nonetheless, reflections are not to be found for the range of typical frequencies tested.

2.4 Two Observations Impacting MWD Research

The 1990s provided opportunities for MWD acoustic model development. Our experiences seeded curiosity, motivating the search for additional clues from day-to-day activities. Two independent observations, occurring within a ten-year time frame, guided us along a fruitful path of discovery into the 2000s. These remained unpublished, even to this day, as their significance had not been grasped until recently. In the first, two decades ago, siren tests were performed at the two-mile mud flow loop at Louisiana State University in Figure 6. Tests showed how measured signals at a fixed location from the siren decayed continuously as frequencies increased from 0 to 24 Hz, at which point they were not observable. This was consistent with prevailing studies citing 24 Hz as the theoretical upper limit to mud pulse telemetry. Despite failing hydraulic equipment restricting initial signal strengths to a fraction of those in lower frequency tests, this author’s tests continued to a hardware failure point near 50 Hz. *Surprisingly, measured signals would double the amplitude of initial results.*

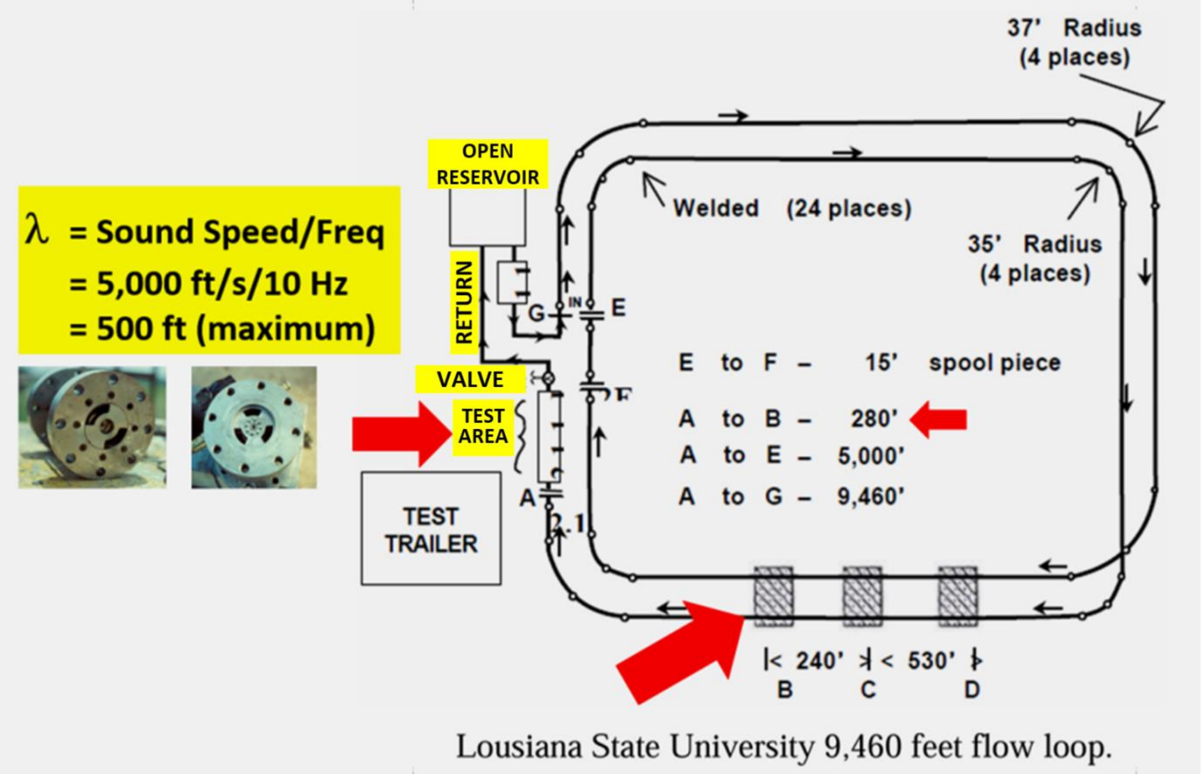
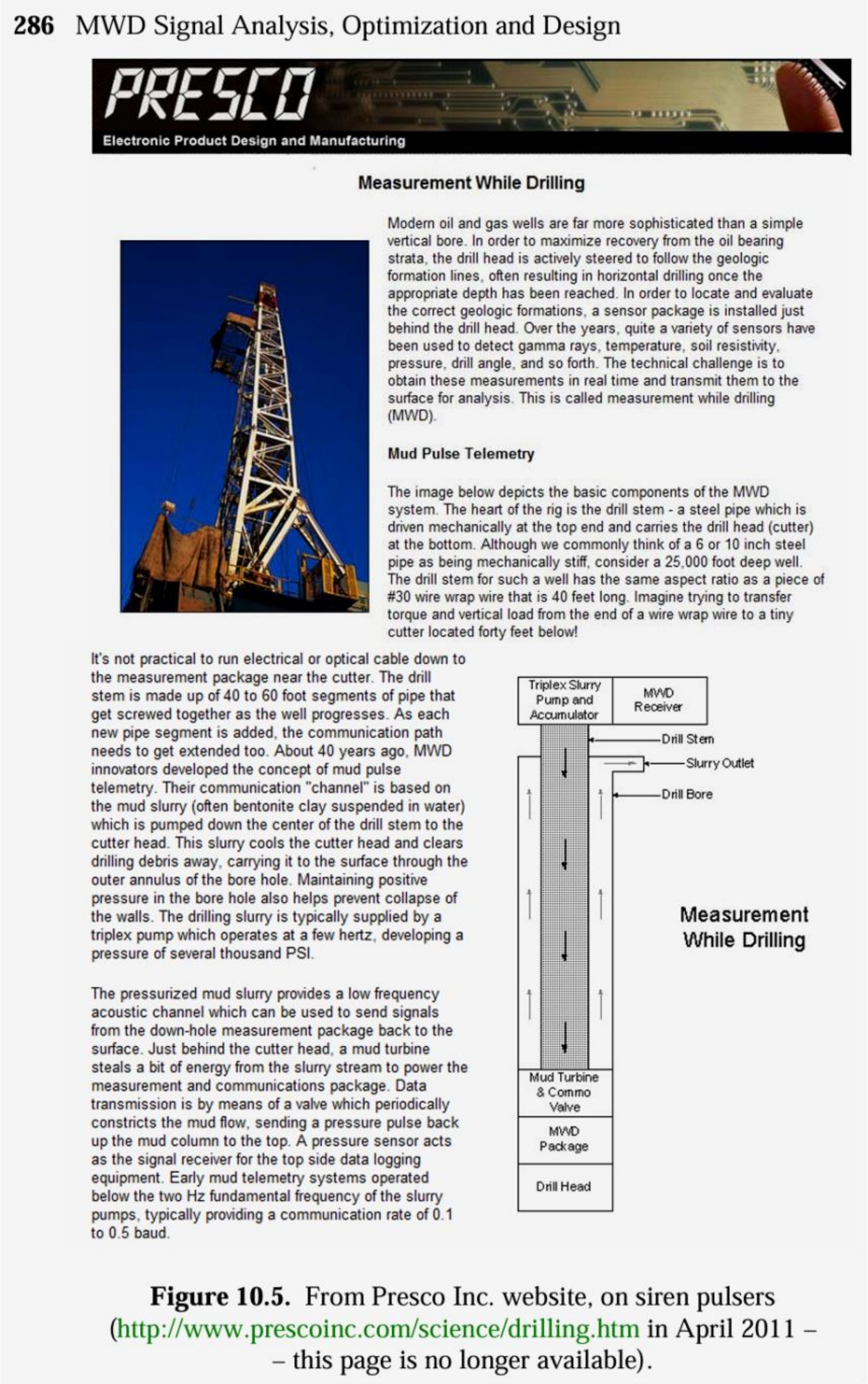


Figure 6 Louisiana State University 9,460 feet mud flow loop.

Only one explanation was possible. While "two mile" distances misleadingly suggest simple propagating events, such experiments, in fact, merely created different reverberant environments with varying echo patterns – for instance, as in a stretched jump rope hosting different vibratory waveforms. Decreases previously attributed to irreversible attenuation in simple systems actually described moving and evolving systems of nodes and antinodes in more complicated waveguides associated with frequency increases. Ten years later, field studies reported by Presco Inc., affiliated with Yale University and apparently funded by Schlumberger, described how certain drilling channels actually supported frequencies in the 100 Hz range. Problems blamed on damping and faulty equipment in reality arose from non-attenuating multiple wave reflections which obscured transducer measurements. The research group posted its findings online, duplicated in their entirety below in Figures 7(a), (b), but these were later apparently removed by the sponsoring entity. The independent 50 and 100 Hz observations above suggested that increased data rates should be possible. This motivated our continuing and successful search for better siren sources, and more intelligent and accommodating telemetry schemes. Next, we will describe telemetry, hardware and signal processing results which have come full circle in supporting a new technology. The time to integrate our efforts is now, with risks minimized, physical ideas better understood and our vision well defined. As of this writing, hardware prototypes for field tests are undergoing design evaluation.



Measurement While Drilling

Modern oil and gas wells are far more sophisticated than a simple vertical bore. In order to maximize recovery from the oil bearing strata, the drill head is actively steered to follow the geologic formation lines, often resulting in horizontal drilling once the appropriate depth has been reached. In order to locate and evaluate the correct geologic formations, a sensor package is installed just behind the drill head. Over the years, quite a variety of sensors have been used to detect gamma rays, temperature, soil resistivity, pressure, drill angle, and so forth. The technical challenge is to obtain these measurements in real time and transmit them to the surface for analysis. This is called measurement while drilling (MWD).

Mud Pulse Telemetry

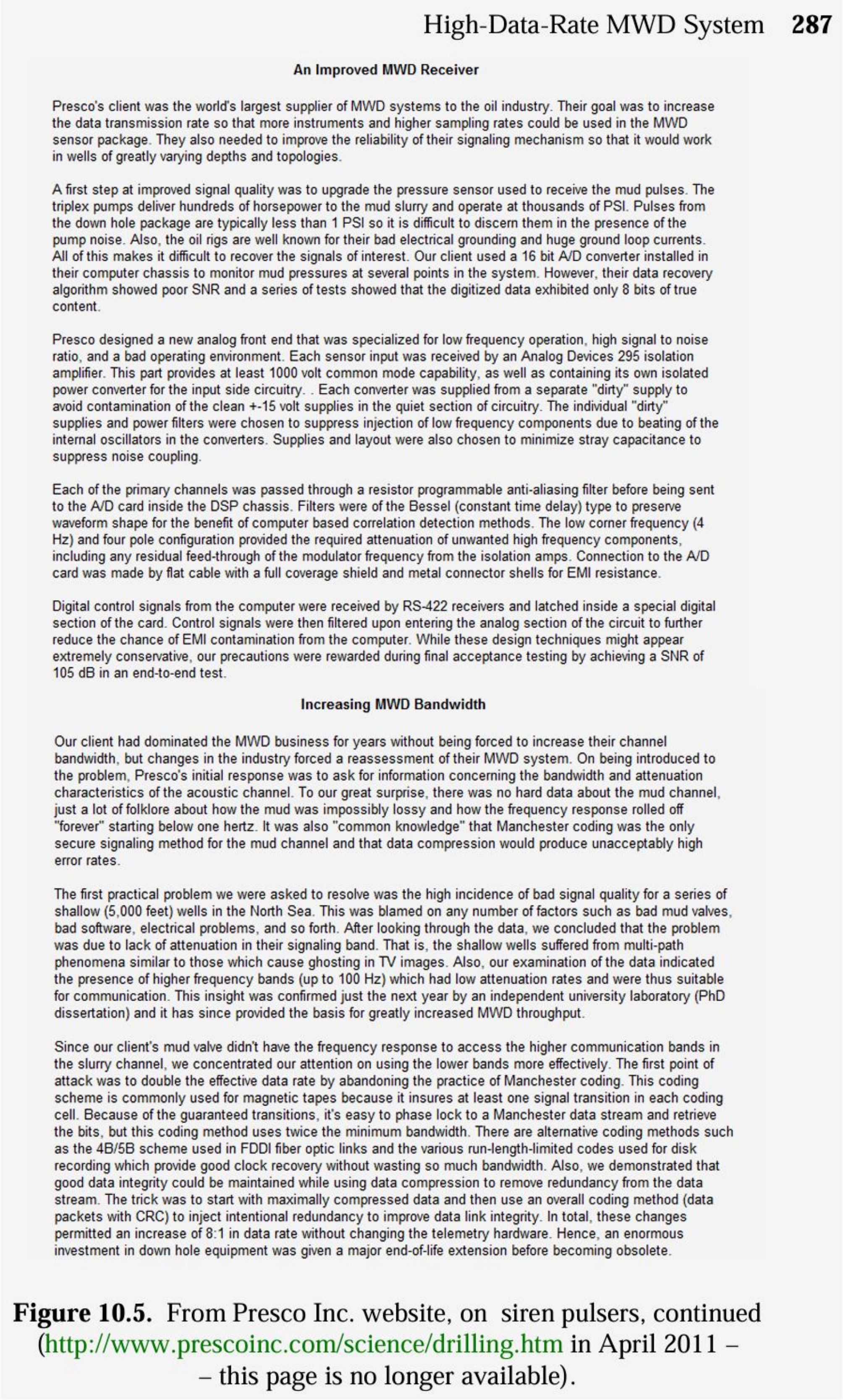
The image below depicts the basic components of the MWD system. The heart of the rig is the drill stem - a steel pipe which is driven mechanically at the top end and carries the drill head (cutter) at the bottom. Although we commonly think of a 6 or 10 inch steel pipe as being mechanically stiff, consider a 25,000 foot deep well. The drill stem for such a well has the same aspect ratio as a piece of #30 wire wrap wire that is 40 feet long. Imagine trying to transfer torque and vertical load from the end of a wire wrap wire to a tiny cutter located forty feet below!

It's not practical to run electrical or optical cable down to the measurement package near the cutter. The drill stem is made up of 40 to 60 foot segments of pipe that get screwed together as the well progresses. As each new pipe segment is added, the communication path needs to get extended too. About 40 years ago, MWD innovators developed the concept of mud pulse telemetry. Their communication "channel" is based on the mud slurry (often bentonite clay suspended in water) which is pumped down the center of the drill stem to the cutter head. This slurry cools the cutter head and clears drilling debris away, carrying it to the surface through the outer annulus of the bore hole. Maintaining positive pressure in the bore hole also helps prevent collapse of the walls. The drilling slurry is typically supplied by a triplex pump which operates at a few hertz, developing a pressure of several thousand PSI.

The pressurized mud slurry provides a low frequency acoustic channel which can be used to send signals from the down-hole measurement package back to the surface. Just behind the cutter head, a mud turbine steals a bit of energy from the slurry stream to power the measurement and communications package. Data transmission is by means of a valve which periodically constricts the mud flow, sending a pressure pulse back up the mud column to the top. A pressure sensor acts as the signal receiver for the top side data logging equipment. Early mud telemetry systems operated below the two Hz fundamental frequency of the slurry pumps, typically providing a communication rate of 0.1 to 0.5 baud.

Figure 10.5. From Presco Inc. website, on siren pulsers (http://www.prescoinc.com/science/drilling.htm in April 2011 – – this page is no longer available).

(a)



High-Data-Rate MWD System **287**

An Improved MWD Receiver

Presco's client was the world's largest supplier of MWD systems to the oil industry. Their goal was to increase the data transmission rate so that more instruments and higher sampling rates could be used in the MWD sensor package. They also needed to improve the reliability of their signaling mechanism so that it would work in wells of greatly varying depths and topologies.

A first step at improved signal quality was to upgrade the pressure sensor used to receive the mud pulses. The triplex pumps deliver hundreds of horsepower to the mud slurry and operate at thousands of PSI. Pulses from the down hole package are typically less than 1 PSI so it is difficult to discern them in the presence of the pump noise. Also, the oil rigs are well known for their bad electrical grounding and huge ground loop currents. All of this makes it difficult to recover the signals of interest. Our client used a 16 bit A/D converter installed in their computer chassis to monitor mud pressures at several points in the system. However, their data recovery algorithm showed poor SNR and a series of tests showed that the digitized data exhibited only 8 bits of true content.

Presco designed a new analog front end that was specialized for low frequency operation, high signal to noise ratio, and a bad operating environment. Each sensor input was received by an Analog Devices 295 isolation amplifier. This part provides at least 1000 volt common mode capability, as well as containing its own isolated power converter for the input side circuitry. . Each converter was supplied from a separate "dirty" supply to avoid contamination of the clean +-15 volt supplies in the quiet section of circuitry. The individual "dirty" supplies and power filters were chosen to suppress injection of low frequency components due to beating of the internal oscillators in the converters. Supplies and layout were also chosen to minimize stray capacitance to suppress noise coupling.

Each of the primary channels was passed through a resistor programmable anti-aliasing filter before being sent to the A/D card inside the DSP chassis. Filters were of the Bessel (constant time delay) type to preserve waveform shape for the benefit of computer based correlation detection methods. The low corner frequency (4 Hz) and four pole configuration provided the required attenuation of unwanted high frequency components, including any residual feed-through of the modulator frequency from the isolation amps. Connection to the A/D card was made by flat cable with a full coverage shield and metal connector shells for EMI resistance.

Digital control signals from the computer were received by RS-422 receivers and latched inside a special digital section of the card. Control signals were then filtered upon entering the analog section of the circuit to further reduce the chance of EMI contamination from the computer. While these design techniques might appear extremely conservative, our precautions were rewarded during final acceptance testing by achieving a SNR of 105 dB in an end-to-end test.

Increasing MWD Bandwidth

Our client had dominated the MWD business for years without being forced to increase their channel bandwidth, but changes in the industry forced a reassessment of their MWD system. On being introduced to the problem, Presco's initial response was to ask for information concerning the bandwidth and attenuation characteristics of the acoustic channel. To our great surprise, there was no hard data about the mud channel, just a lot of folklore about how the mud was impossibly lossy and how the frequency response rolled off "forever" starting below one hertz. It was also "common knowledge" that Manchester coding was the only secure signaling method for the mud channel and that data compression would produce unacceptably high error rates.

The first practical problem we were asked to resolve was the high incidence of bad signal quality for a series of shallow (5,000 feet) wells in the North Sea. This was blamed on any number of factors such as bad mud valves, bad software, electrical problems, and so forth. After looking through the data, we concluded that the problem was due to lack of attenuation in their signaling band. That is, the shallow wells suffered from multi-path phenomena similar to those which cause ghosting in TV images. Also, our examination of the data indicated the presence of higher frequency bands (up to 100 Hz) which had low attenuation rates and were thus suitable for communication. This insight was confirmed just the next year by an independent university laboratory (PhD dissertation) and it has since provided the basis for greatly increased MWD throughput.

Since our client's mud valve didn't have the frequency response to access the higher communication bands in the slurry channel, we concentrated our attention on using the lower bands more effectively. The first point of attack was to double the effective data rate by abandoning the practice of Manchester coding. This coding scheme is commonly used for magnetic tapes because it insures at least one signal transition in each coding cell. Because of the guaranteed transitions, it's easy to phase lock to a Manchester data stream and retrieve the bits, but this coding method uses twice the minimum bandwidth. There are alternative coding methods such as the 4B/5B scheme used in FDDI fiber optic links and the various run-length-limited codes used for disk recording which provide good clock recovery without wasting so much bandwidth. Also, we demonstrated that good data integrity could be maintained while using data compression to remove redundancy from the data stream. The trick was to start with maximally compressed data and then use an overall coding method (data packets with CRC) to inject intentional redundancy to improve data link integrity. In total, these changes permitted an increase of 8:1 in data rate without changing the telemetry hardware. Hence, an enormous investment in down hole equipment was given a major end-of-life extension before becoming obsolete.

Figure 10.5. From Presco Inc. website, on siren pulsers, continued (http://www.prescoinc.com/science/drilling.htm in April 2011 – – this page is no longer available).

(b)

Figure 7 (a, b) Presco MWD online research report, from Chin [2].

3. Discussion: Quantitative Wave Mechanics and Intelligent *i*FSK Telemetry

Acoustic models vary from propagating waves in long tubes solved one-dimensionally with transient models, to standing wave patterns created by periodic excitation, modeled by multi-dimensional differential equations with assorted boundary conditions. In petroleum engineering, modeling of MWD transmissions is often simplified by ignoring bottomhole assembly effects (BHA), since BHA length is greatly exceeded by a much longer drill pipe. Simple piston excitations are then used to create upgoing disturbances which, however, act independently of events at the opposite side of the piston. This model, surprisingly, is presently used at two leading oil service companies.

Thus, mud pump pulsations and MWD signals are never found in the annulus despite strong empirical evidence attesting to their existence. In fact, pipe signals detectable in the annulus are commonly used for undissolved formation gas detection, a practice supporting the fact that waves on both sides of the hypothetical piston do interact. This interaction occurs because long waves are known to propagate through bit nozzles, just as compression and expansion waves created at opposite sides of sirens are known to interact through rotor-stator gaps to produce upon re-reflections within the collar.

Outside of simple MWD models, standing wave patterns in other areas of physics are modeled using partial differential equations where time is Fourier transformed out and replaced by a term proportional to frequency. The literature is rich with examples, ranging from water waves to drumhead vibration patterns that strongly depend on boundary geometry, frequency and excitation location as shown in Figure 8. In our research, we address the more complicated problem in Figure 9, here shown in more common terms to avoid reader biases that may arise from preconceived petroleum ideas. The general volume contains one or more oscillating sources that may range from pulsating monopoles to vibrating dipoles (or "trampolines") placed at different locations. When the red plugs shown remain in place, periodic wave patterns are obtained that depend fluid, elastic or electromagnetic details. When the plugs are removed, however, these patterns are adjusted by waves escaping through the conduits shown. On the scale assumed, what occurs at the far ends of these conduits will not affect the local wave patterns created. Because these conduits are extremely long, waves within them are modeled using "radiation conditions" assuming that outgoing waves never return, simplifying the study of wave interactions.

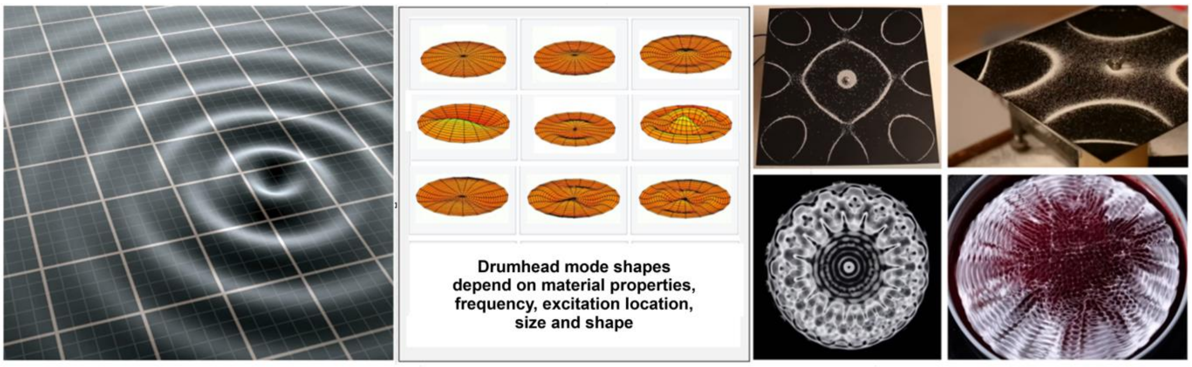


Figure 8 Surface water waves, vibration patterns on a drumhead, loose sand accumulations on oscillating membranes.

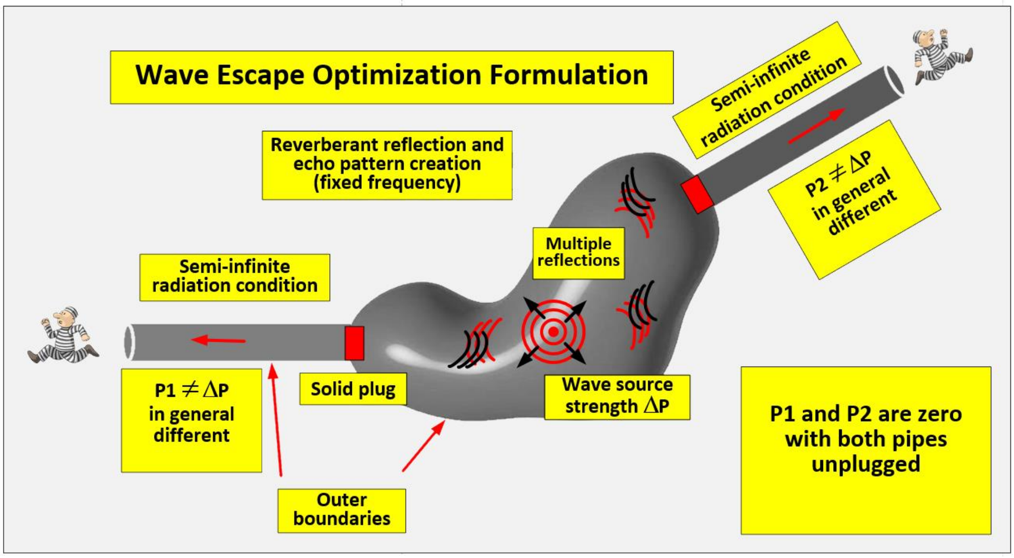


Figure 9 General propagation and standing wave problem formulation.

3.1 Wave Guide Modeling in MWD Telemetry

The problem formulated is useful in multiple applications. The large volume might represent a water body in which an explosive is detonated so that damaging effects transfer into connecting tributaries. Or, the volume might contain a resonating gas that discharges strong "acoustic bullets" at police targets. How are these discharges minimized or maximized? Our general model is consistent with one reasonable expectation – *for all frequencies, waves always emerge and propagate into connecting narrow conduits*. Now we specialize this model to MWD applications where the general volume morphs into a typical BHA. While positive pulsers operating at a 1-2 Hertz range may be consistent with simple piston excitations, higher frequency problems will result in situations where nontrivial internal interactions are the rule. Consider a mud with a 100 Hz source, where the wavelength $\lambda \approx 3{,}000$ ft/s/100 Hz ≈ 30 ft, or about half of a 50 ft collar. This suggests that downhole interactions arising from impedance changes may strongly affect waves that ultimately escape into the drill pipe and borehole annulus. If so, one naturally asks how to maximize the signal propagating up the pipe while minimizing that in the annulus. By introducing the problem using Figure 9, we have set the stage for reader curiosity. *Something will happen, but what*? And why have MWD companies, despite decades of experience with sirens and rotary valves, not posed this question and solved the problem with widely available math tools, taking advantage of modeling methods long available? Finally, how can we use newly obtained knowledge to develop truly high data rate MWD telemetry? In particular, what types of hardware, telemetry and signal processing schemes are required?

3.2 Application to MWD Bottom Hole Assemblies

Anticipating that the geometry of the MWD bottomhole assembly (BHA) may be important to signal generation, to avoid "throwing the baby out with the bath water," we support all physical parameters in case they are relevant. If they are not, as will be seen in examples below 5 Hz, their irrelevance will demonstrated in calculations. Thus, we consider the "six segment waveguide model" in Figure 10, comprising of semi-infinite conduits (the upgoing drill pipe and upper borehole annulus surrounding the pipe), the collar hosting the siren or poppet valve, a collar section with a logging tool or mud motor, a bit box and the lower annulus surrounding the collar. A single frequency “dipole source” located at a given position is assumed. Dipoles include poppet valves (or positive pulsers) and sirens with special dynamical features. In particular, when the source closes against flowing mud, an upgoing compression wave is created together with an equally strong downgoing expansion wave. When it opens, the opposite occurs as observed experimentally. Negative “monopole” pulsers are not considered in this paper. The software menu for Figure 10 appears in Figure 11.

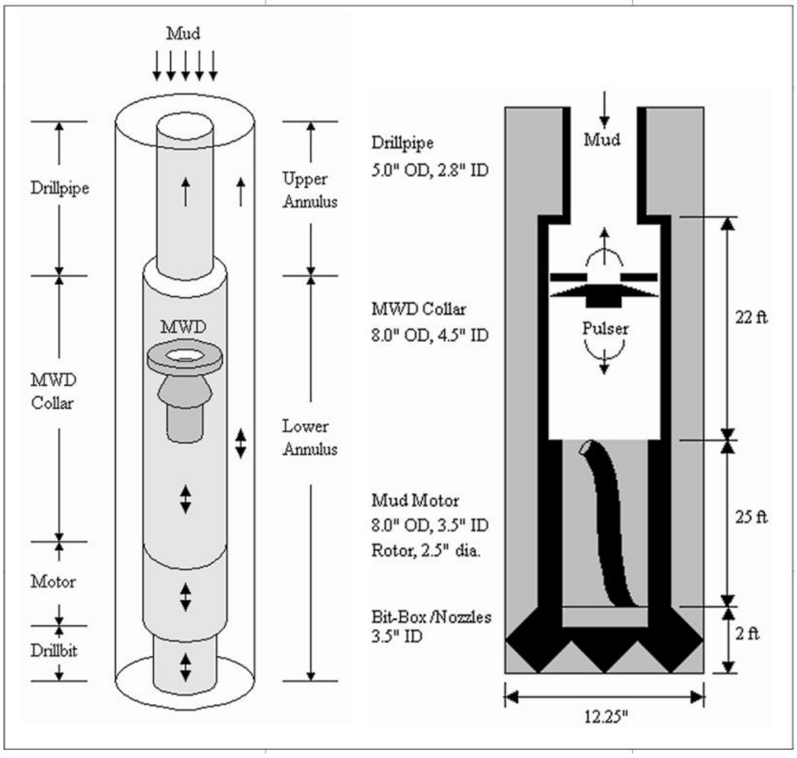
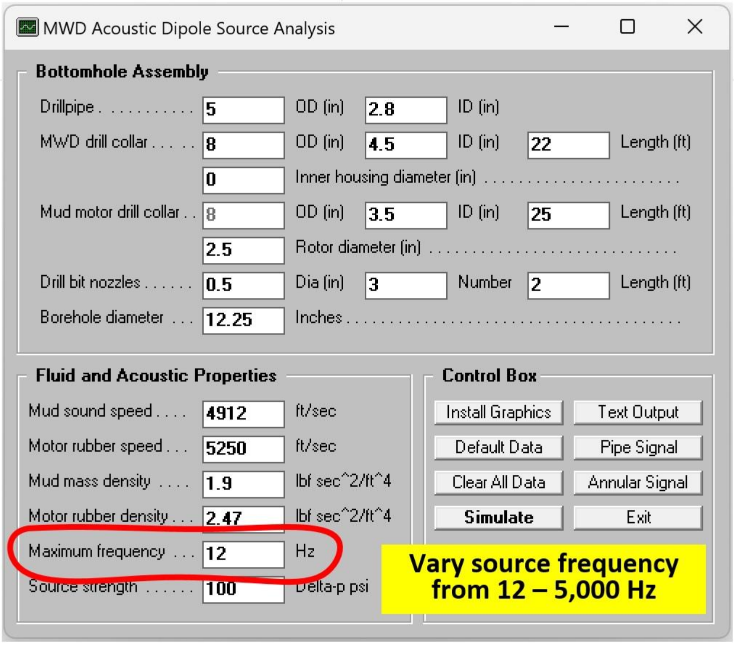


Figure 10 BHA acoustic model, a limit of Figure 9 – for math formulation, exact analytical solution and computational details, refer to Chin et al. [1] and Chin [2].



Bottomhole Assembly

Drillpipe . . . . 5 OD (in) 2.8 ID (in)
MWD drill collar . . . . . 8 OD (in) 4.5 ID (in) 22 Length (ft)
0 Inner housing diameter (in) . . . .
Mud motor drill collar . . 8 OD (in) 3.5 ID (in) 25 Length (ft)
2.5 Rotor diameter (in) . . . .
Drill bit nozzles . . . . . . 0.5 Dia (in) 3 Number 2 Length (ft)
Borehole diameter . . . 12.25 Inches . . . .

Fluid and Acoustic Properties

Mud sound speed . . . . 4912 ft/sec
Motor rubber speed . . . 5250 ft/sec
Mud mass density . . . . 1.9 lbf sec^2/ft^4
Motor rubber density . . . 2.47 lbf sec^2/ft^4
Maximum frequency . . . 12 Hz
Source strength . . . . . . 100 Delta-p psi

Control Box

Vary source frequency from 12 – 5,000 Hz

Figure 11 Software menu and calculation assumptions.

This model has been validated in LWT air studies where cavitation does not exist. This smoothness is impossible in surface mud loops because downstream cavitation (not present far downhole) destroys the pressure pattern sought. Because the disturbance acoustic pressure field P field (measured relative to hydrostatic levels) is antisymmetric with respect to source position, a resulting "delta P" or ΔP strength for that location is found, noting that ΔP depends *only* on valve geometry, closure speed, mud velocity and sound speed. Pressures elsewhere are described by a P(x,t) where a single "x" is consistent with our long wave approximation. At any point, the P(x,t) field will contain our ΔP, but for wave analysis, only the ratio P/ΔP at the drill pipe entrance is important for signal creation efficiency. We note that MWD transmissions are modeled with LWT acoustics alone without need to understand how ΔP is formed. The value of ΔP itself is separately measured in mud flow loop tests or inferred from rescaled SWT results. It is clear, with some imagination, how Figure 10 easily "morphs" into Figure 9 and vice-versa.

The complete math formulation and analytical solution to the problem are motivated as follows. In acoustics modeling, many dependent variables can be used, for instance, "Eulerian velocity potentials ϕ(x,t)," "Lagrangian fluid displacements u(x,t), or pressure itself." In fact, more exist; any space or time derivative of either, to any order, satisfies the wave equation. However, boundary conditions dictate the ultimate choice. Ours was first motivated by transverse string vibrations, with $\rho U_{tt} - TU_{xx} = f(x,t)$, where ρ is lineal mass density, T is tension, U(x,t) is transverse displacement and f denotes applied force. When f is a point load, as for guitars and violins, the string "sees" a local slope discontinuity as is obvious visually. That is, $\partial U/\partial x|_{x0+} - \partial U/\partial x|_{x0-} = -f(t,x_0)/k$ where $k^2 = \omega^2/(T/\rho)$, x_0 is the contact point ("+" and "-" denote either sides of the contact), and ω is the circular frequency. $U(x_0,t)$ itself is continuous because the string is unbroken. At all other points, U(x,t) and ∂U/∂x are both continuous. This formulation is given in differential equations books, where Laplace transforms and Dirac delta function solutions are offered.

Second, we importantly observed that string and Lagrangian displacement fluid models are identical, with $\rho U_{tt} - TU_{xx} = f(x,t)$ as compared to $\rho u_{tt} - Bu_{xx} = \Delta P$. We have U replaced by u, f by ΔP and T by B, where B is the fluid bulk modulus and ρ is full mass density. In acoustics, discontinuities in the "slope u_x" appear at the source because the pressure $P = - B\partial u/\partial x$ is discontinuous, although u itself is continuous. This is analogous to the behavior of $\partial U/\partial x$ and U at the contact point for vibrating strings. For areal changes at drill pipe and collar locations, and material differences at turbodrill and drill bit locations, impedance changes will arise that are constrained by "continuity in volume velocity and pressure" in longitudinal fluid displacement formulations. Our overall formulation for u(x,t) is similar to that for U(x,t), although slightly more complicated with multiple impedance effects introduced as needed. A resulting linear system of ten complex algebraic equations is solved, which includes all necessary impedance matching conditions. Computations on Windows i7 machines typically require 5-10 seconds for each of the pictorial frames in the next section. Our exact analytical formulas are preferred over finite difference or finite element solutions which are inaccurate at discontinuous pressure sources. Automatic plotted color solutions display $P_{drillpipe}/\Delta P$ and $P_{upper\ annulus}/\Delta P$ on vertical axes as functions of Source Position (ft) and Frequency (Hz) on two horizontal axes. Details appear in Chin et al. [1] and Chin [2], while physical implications are emphasized below. These references did not pursue calculations in the high frequency ranges considered in this paper.

3.3 Physical Implications for One MWD Bottom Hole Assembly

Calculations were carried out for the physical dimensions in Figure 10 up to a maximum of 5,000 Hz. The software menu is shown in Figure 11. Calculated results are interesting and, while anticipated in general terms, are surprising from engineering and drilling perspectives. Conclusions are labelled in Figure 12, where all parameters are fixed with only maximum frequency varying from run to run. Our results apply *only* to the BHA shown.

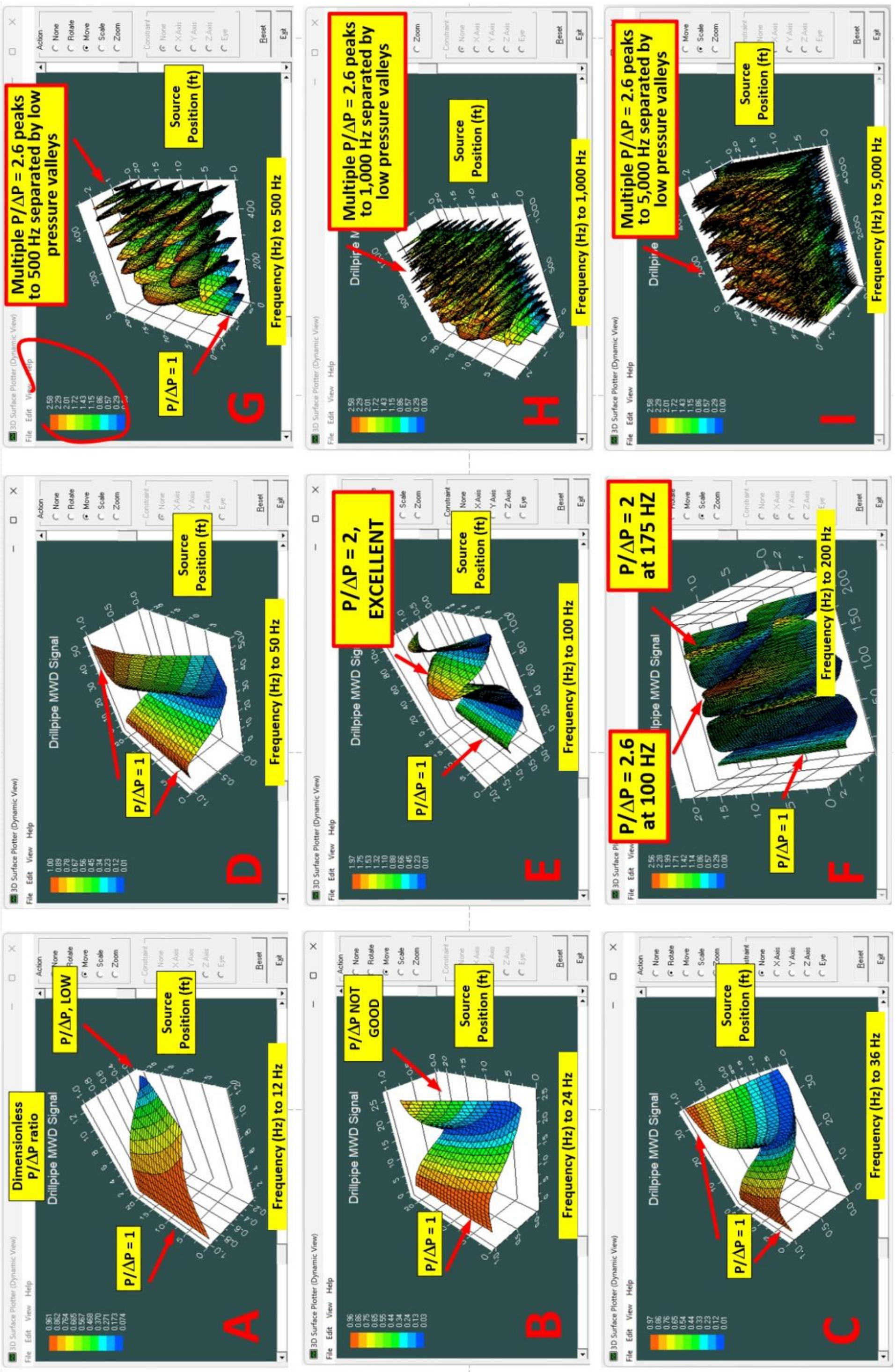


Figure 12 Drill pipe pressure signal plot. Maximum frequency in parentheses, in A(12 Hz), B(24 Hz), C(36 Hz), D(50 Hz), E(100 Hz), F(200 Hz), G(500 Hz), H(1,000 Hz) and I(5,000 Hz), expanded in Figures 13 (a, b, c), 13 (d, e, f) and 13 (g, h, i).

The nine "Drillpipe MWD Signal" frames in Figure 12 are automatically output by software with three-dimensional color capabilities. Included are "Upper Annulus Signal" plots not shown nor discussed here. The maximum source frequency range extends to 5,000 Hz, which may appear unrealistic in view of present sirens now operating at maximum 12 or 24 Hz values. We emphasize that, even at 5,000 Hz in water base muds, the wavelength λ ≈ 5,000 ft/sec/5,000 Hz ≈ 1 ft still exceeds characteristic pipe diameters of 0.5 ft and are therefore relevant acoustic-wise. Because these results are seen as relevant, they offer strong arguments for developing self-spinning, low energy turbosirens, and "sirens in series" prototypes, described here and in U.S. Patent 5,583,827 or Chin [5].

Before presenting results, we introduce one reference calculation important to interpretation. Consider an ideal infinite drill pipe with a poppet valve or siren at its center. For any given differential pressure ΔP, it is clear from symmetry that signal strengths of + ½ΔP and -½ΔP must propagate away from the source at each side. For this example, the signal efficiency ratio is P/ΔP = ½. Now suppose that one semi-infinite side is instead terminated by an open end. From acoustic theory, propagating long waves will reflect at the termination with a change in sign, and proceed to propagate through the source that created it. Thus, the net propagating signal strength is ½ΔP + ½ΔP or ΔP, so that the signal efficiency ratio here is ΔP/ΔP or 1. For our BHA calculations, the bottom drill bit end is never fully opened, but long waves *will* effectively "see" and open end. Thus, a value near, but not equal to one, is expected (our calculations, in fact, produce 0.96 – 0.97). We now comment on computed results.

- Run A applies to Schlumberger sirens operating at 12 Hz carrier frequencies. At all siren locations, for frequencies extending to about 5 Hz, drill pipe signal strengths are optimal with P/ΔP ≈ 1. At higher frequencies, this ratio falls rapidly as source position approaches the drill pipe. Here, destructive wave interference destroys any benefit a good hardware design (with small rotor-stator gap) may have conferred.
- Run B, again for Schlumberger sirens, extends the above calculations to 24 Hz. While strength versus position properties differ from Run A, net produced signals are nonetheless low. This inhibits high data rate operation, especially given more rapid attenuations at the higher frequencies.
- Run C applies to sirens recently developed by China Oilfield Services Limited (COSL), which operate to 36 Hz (see Wang et al. [6] for detailed hardware and test descriptions). *Despite higher frequencies than those in Runs A and B, the upgoing signals at the top of the collar are just as strong as those near at extremely low frequencies.* Of course, high 36 Hz frequencies mean higher attenuation in the drill pipe, but this can be separately addressed using "sirens in series" wave superposition discussed later in hardware development. Similar comments apply to Run D for 50 Hz maximums.
- Runs E-I are optimistic and very surprising. The periodic math formulation underlying our exact analytical solution implies the existence of P/ΔP ratios that vary periodically with respect to position and frequency. Calculated results suggest much greater optimism. Not only do these merely exist. At 100 Hz and greater, to include frequencies near 5,000 Hz – excitation ranges long regarded by the petroleum industry as unfruitful, predicted constructive interference effects demonstrate the existence of P/ΔP values as high as 2.6, or more than 200% of the usual "optimum" found near zero Hertz. These arise from multiple reflections and possible resonance. Again, once the signal enters the drill pipe, it will be affected by irreversible attenuation. However, as before, this can be remedied by "sirens in series" hardware solutions.

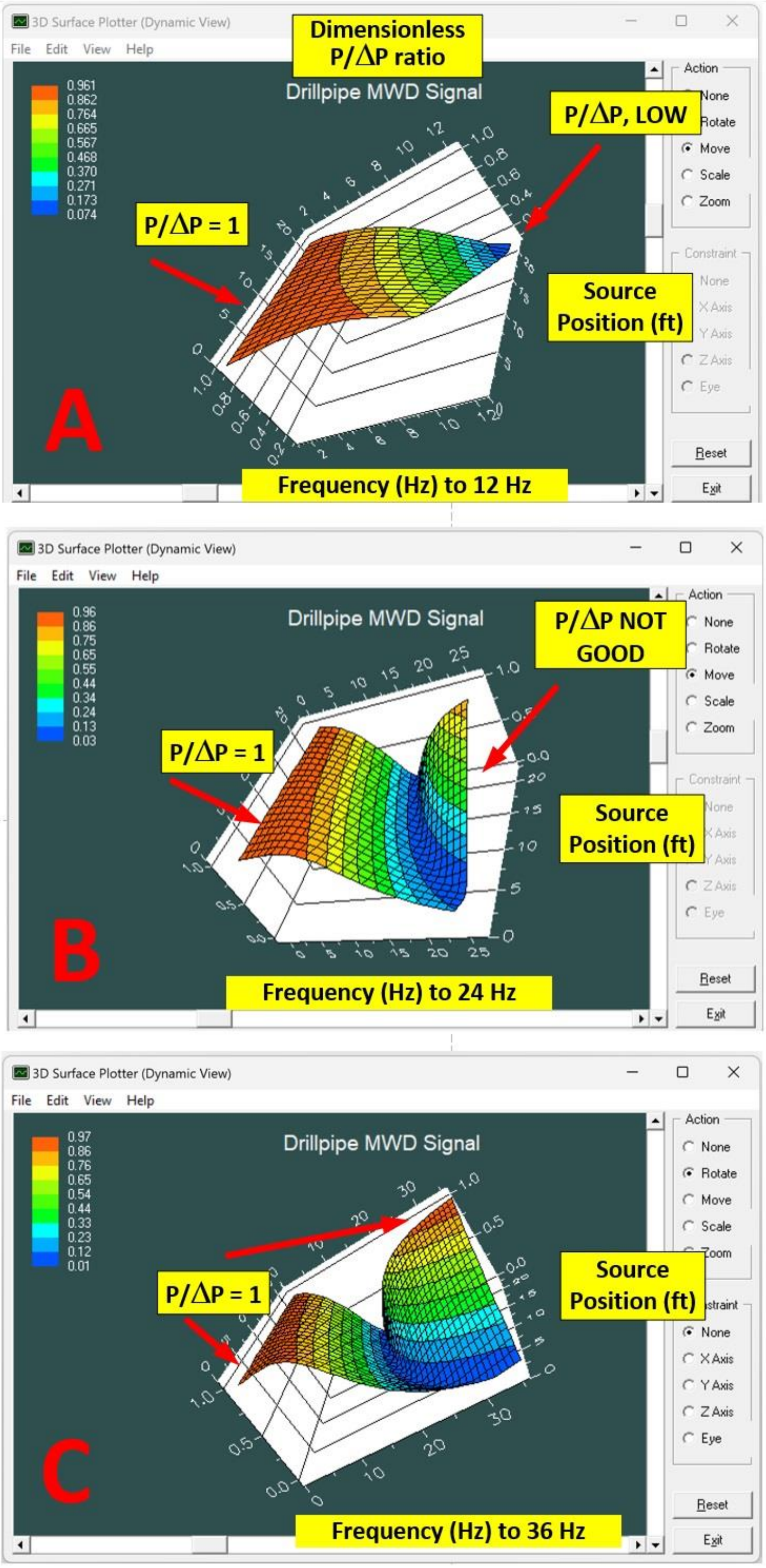


Figure 13 (a, b, c) Drill pipe pressure signal plot. Frequencies 12, 24 (Schlumberger), 36 Hz (COSL). Near 0 Hz, P/ΔP = 1 (red) is optimal, for all source positions. Beyond 5 Hz, P/ΔP decreases significantly, with slight recovery (orange) at top of collar for 24 Hz. Strong recovery (red) with P/ΔP = 1 appears at 36 Hz near top of drill collar.

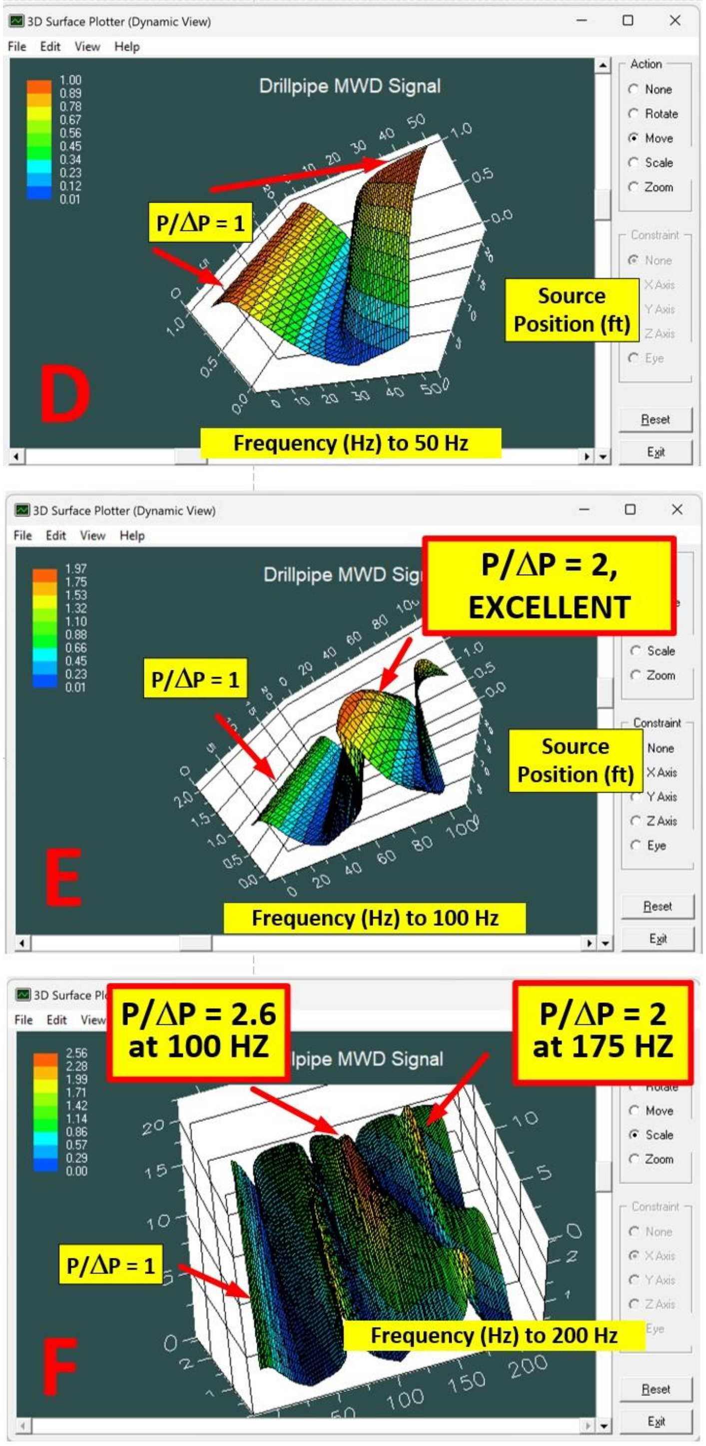


Figure 13 (d, e, f) Drill pipe pressure signal plot. Top, 50 Hz and 36 Hz results are similar (P/ΔP = 1 is red for sketches “C” and “D”). Middle, P/ΔP surprisingly increases to 2 near 70 Hz for wide range of source positions (here P/ΔP = 2 is red, while P/ΔP = 1 is now green). This results from constructive wave interference, improving on “hardware only” ΔP. As 100 Hz is approached, P/ΔP falls, although some signal recovery is found near 100 Hz. Bottom, large P/ΔP ratios of 2.6 and 2 detected at 100 and 175 Hz, again due to constructive interference.

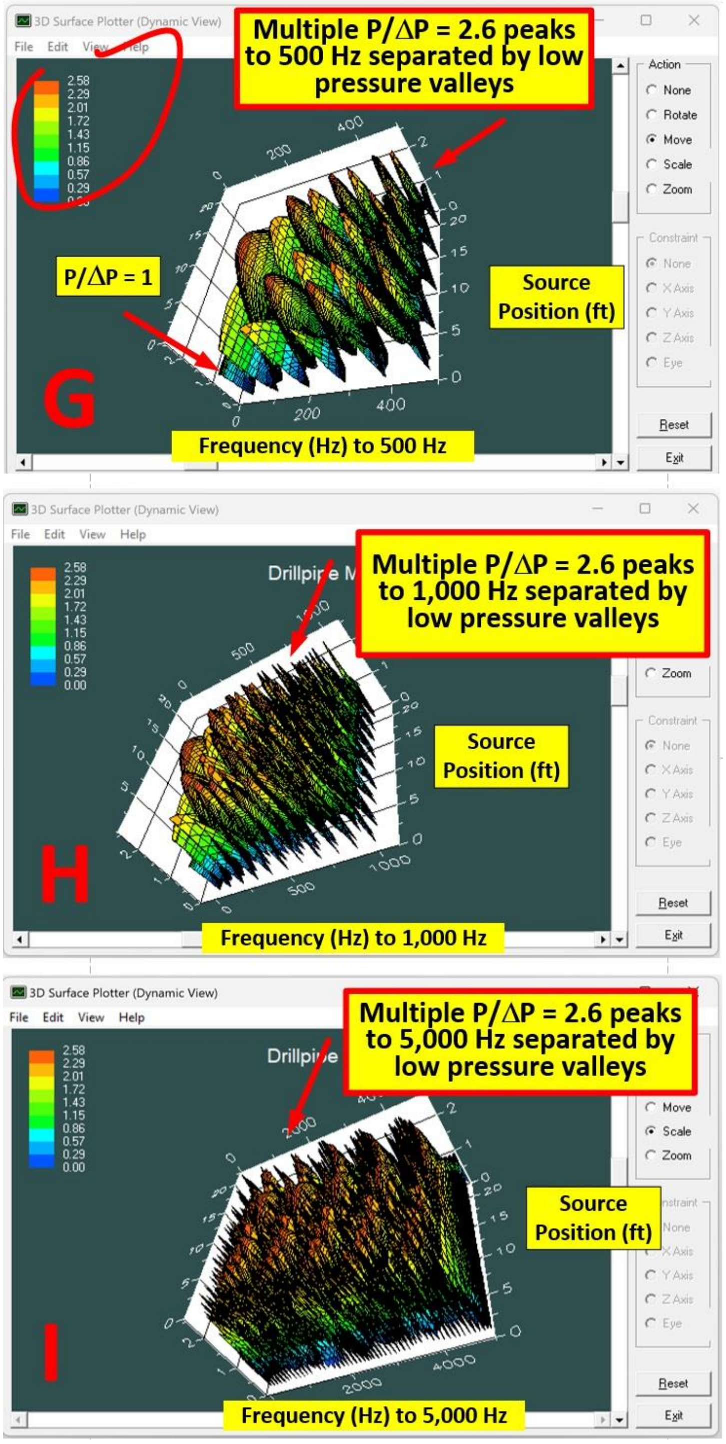


Figure 13 (g, h, i) Drill pipe pressure signal plot. Results surprisingly show strong P/ΔP = 2.6 periodic peaks for wide ranges of source position and frequency. Any pair of adjacent "peak and valley" frequencies can be used for "Intelligent *i*FSK" modulation. Calculations apply to BHA signal generation. Attenuation in long drill pipe is addressed separately by using "sirens in series, high signal, low power" hardware solutions.

We have shown how telemetry at frequencies well beyond those presently used are doable for high data rate mud pulse telemetry. Calculated results confirm speculation and predictions independently offered by this author in his LSU experiments and by Presco Incorporated in its assessment of Schlumberger data, as discussed earlier. Of course, while constructive wave interference can offer much higher signals that propagate up the drill pipe initially, these will attenuate due to viscous mud dissipation under single-siren scenarios. Importantly, a practical solution exists using “sirens in series” methods developed by the author, that is “self-spinning turbosirens” that rotate without motors, drawing only on the kinetic energy of the flowing mud. To overcome high damping at high frequencies, such signal superpositions select appropriate numbers of sources by adding or activating dormant sirens. This low power process creates high strength signals at very high carrier frequencies economically. Scarce turbine and battery power is importantly reserved for rapid modulation purposes, which in turn require rapidly acting braking (say, based on electro or magneto-rheological brake technology), and complementary “brakes in series” to reduce wear and anticipated abrasion.

In closing, one might ask, “What hasn’t the MWD industry, despite its half-century of experience, employed such obvious concepts?” The problem rests with siren and rotary valve designs, all of which require electric or hydraulic motor drives. Since downhole power is limited, it is difficult to rotate rapidly and modulate at the same time. This limits rotating sirens to low frequencies, presently 36 Hz at best, but even if fast rotations were possible, weak signals created without “sirens in series” technology cannot be detected uphole. Thus wave based physics is as important in hardware design as it is in BHA constructive interference. In a sense, a blind man will “see” only as far as his stick allows, and mud pulse telemetry has unfortunately fallen to a similar fate. However, this can be overcome by combining sound physics-based telemetry schemes, and optimized hardware designs and signal processing techniques.

3.4 Optimism for Frequency Shift Keying Methods

As noted under Section 2.2, “Wind tunnel observations of PSK interactions,” Phase Shift Keying introduces confusion to transient wave patterns because random phase shifts (arising from constantly changing lithology information) create pressure snapshots that vary from instant to instant. Thus, the use of constructive wave interference for signal strength augmentation is impossible. An alternative to PSK is FSK in which a physical system alternates from one steady-state solution to another. When linear physical systems are excited by a single frequency, as opposed to random PSK “hammering,” transient results are more orderly regardless of BHA geometric complexities. In other words, sudden area changes at pipe and collar intersections, or rapid material changes at turbodrill and bit box interfaces, are just as likely to produce smooth visually clear solutions as problems where FSK signals are produced in simple pipes.

An example is shown in the oscilloscope traces of Figure 14, measured in a long wind tunnel with multiple area changes connecting different sections of flexible to plastic tubing. Simple and rapid changes in frequency are clearly seen which can be distinguished visually. The time interruptions associated with PSK are absent – this clarity arises because “frequency is simply frequency” and nothing more. Moreover, transitions from one frequency to another are “clean” and rapid, even though the air used is highly compressible. In a liquid, the transitions would be even cleaner. And finally, the peaks shown arise from hardware differences (e.g., the geometry in rotor and stator port spaces) as well as nonlinear harmonic generation in fluids. Whatever the reason, viscous attenuation along the long drill pipe *will* remove or smear these peaks, leaving near-sinusoidal waveforms that are more amenable to signal processing. At the surface, different acoustic environments are found, but again the periodic nature of our signals will make direction based filtering more doable. New directional processing methods, both delay and differential equation based, discussed later will augment frequency methods.

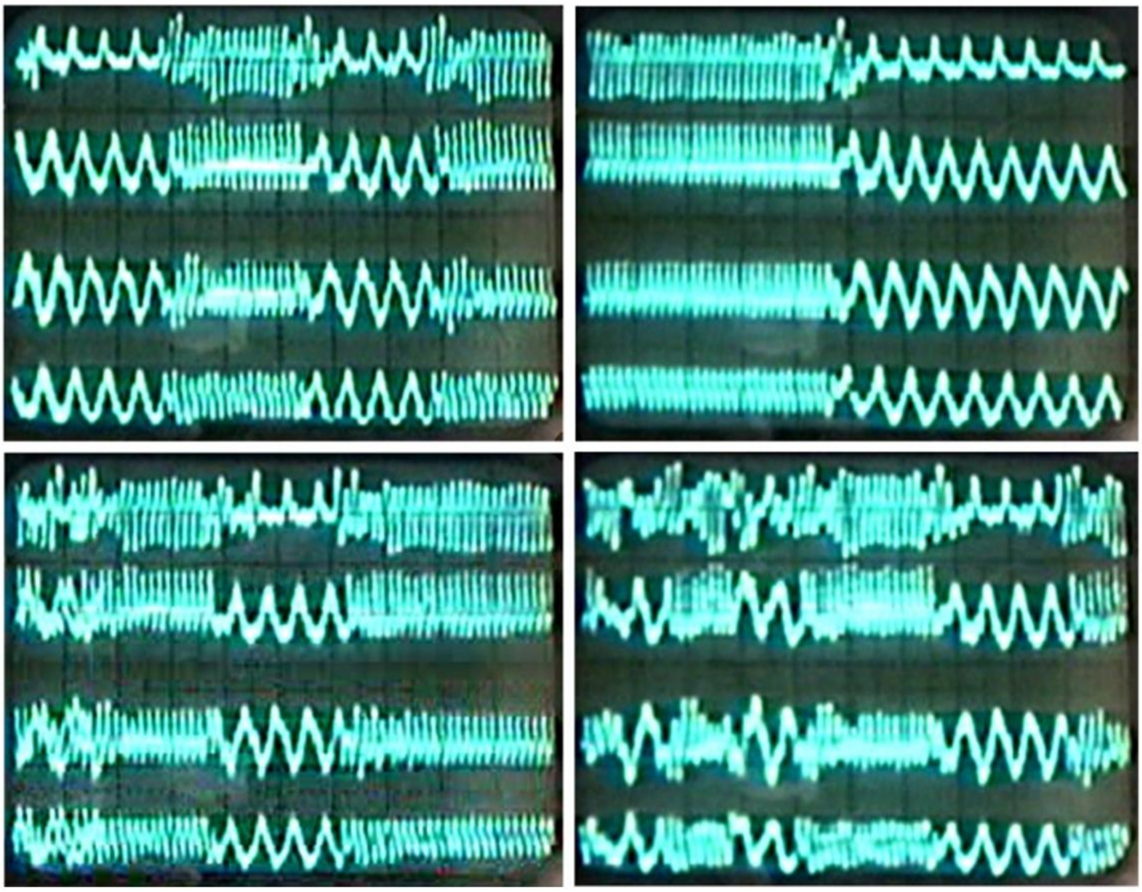


Figure 14 Oscilloscope traces at a specific location in long acoustic wind tunnel.

3.5 Physics-Based Approach to "Intelligent iFSK" Telemetry

Given our understanding of PSK versus FSK transients and the prominent distribution of acoustic pressure peaks and valleys in frequency space, as shown in Figures 13 (a-i), we suggest a novel method to execute frequency shifts. We emphasize that our three-dimensional plots of P/ΔP versus Source Position and Frequency apply strictly to FSK applications, and are particularly useful in frequency selection, but are not meaningful for PSK analysis. In communications theory, two frequencies are selected in dual level schemes, often arbitrarily. For example, in radio and television, frequencies may be assigned per government spectrum allocation requirements. For Schlumberger's siren, one might select 12 Hz and 24 Hz, simply because the tool already operates at these frequencies, or perhaps 12 Hz and 18 Hz, or 6 Hz and 12 Hz.

Since our calculations suggest that stronger P/ΔP signals will be found at frequencies much greater than 100 Hz, with values up to 2.6 instead of the present 0.96, we suggest the use of high frequency pairs, especially those defined by one pressure peak and its adjacent valley. For discussion purposes, suppose one pair consists of 100 Hz and 120 Hz frequencies. An obvious representation for "1, 0, 1, 1, 0" might be 100 – 120 – 100 – 100 – 120 in frequency space, a pattern not unlike the waveforms in Figure 14. Frequency changes are effected by changing rotation rate, noting that frequencies depend on rpm and the number of lobes and ports in the siren used. Rotations must always be unidirectional, in order to save time; reversals are never permitted nor considered. Note that our sirens *never* cease rotation – they are *always* moving, so that inefficient work against strong inertial forces is never required. The large frequency numbers we have assumed in illustrating "Intelligent *i*FSK" modulation assume that sirens are available offering high carrier frequencies at very high amplitudes while requiring only minimal power. In practice, candidate frequency pairs are identified using results like Figure 12 or from surface measurements. Again, one frequency may represent a local pressure peak, while the other a local pressure valley. The required hardware is introduced in the next section. Our distributions of peaks and valleys, and hence the shapes assumed by upgoing pressure versus time traces depend *only* on bottomhole conditions. These traces will propagate up the drill pipe and attenuate somewhat until they arrive at the surface. There, other phenomena come into play, including MWD wave reflections at desurger bladders and pump pistons, unpredictable downgoing mud pump noise, and so on, requiring special but doable directional filters considered later in this paper.

4. Discussion: Hardware Advances in Mud Siren Design

We first provide a chronological description of siren design milestones so our contributions can be viewed in context. Design details generally are not shown in generic sketches like that in Figure 1, nor even discussed in published journals. In fact, few research papers recognize the convoluted path we have taken to introduce the subtle contours and flow components needed to optimize signal strength while reducing power expenditure. When this author joined Schlumberger in the 1980s, the siren rotor was placed above the stator, so that mud impinges on the rotor, and then flows through its port spaces, creating "water hammer" signals as rotor and stator move relative to each other. This would be a poor mechanical decision with severe operational consequences, as will be explained.

Siren lobe number affects on signal amplitude. Early researches were directed toward the lobe number, or the preferred number of circumferential solid lobes needed to increase data rate. Obviously, the greater the number, the higher the "pulses per second" for a fixed rpm rotation rate. It turned out that high numbers greater than five produced small signals due to excessive flow leakage past gaps and tip clearances. As many as fifteen circumferential lobes have been tested. For this reason, sirens and rotary valves presently used by MWD vendors are fabricated with four "lobes," separated by intervening "ports," or port spaces. We have found that two or three are preferable from signal strength perspectives, but few electric or hydraulic motors are able to overcome their higher resistive torques. The "turbosiren" introduced below does not suffer from such deficiencies.

4.1 Debris Jamming and Removal

A more pressing 1980s problem related to jamming in the narrow rotor-stator gap spaces needed to create strong signals, resulting in severe operational problems. For example, these included damaged tools, high drill pipe pressures that jeopardized rig safety, and pressures that damaged formations. Tool removal required expensive, time-consuming "fishing" operations, which on disassembly would always reveal excessive debris. Thus, it was natural to assume that jamming arose from debris accumulation. To solve the problem, engineers introduced helical springs, pressure relief valves, and other obvious "fixes" to no avail. The final "solution" used metal rotors biased open by permanent magnets, which were susceptible to vibration and heat (as many magnets as solid lobes were needed). Since these disrupted electromagnetic measurements, non-magnetic drill collars were required for shielding. The unacceptable end cost exceeded $200,000 per tool in 1980s dollars.

However, debris presence was more a by-product than the cause. Wind tunnel (SWT) testing at Schlumberger, introduced by this author, initially focused on this problem. It turned out that “rotor upstream” designs naturally tended to close and jam, even in clean debris-free air flows; later, the entire process was visualized using both neutrally buoyant helium soap bubbles and glass beads introduced into the flow. Over a hundred balsa wood models were constructed and wind tunnel tested over two weeks. The end result in U.S. Patent 4,785,300 by Chin and Trevino [7] moved the rotor behind the stator to a “rotor downstream” position. When rotor sides were tapered outward, with underlapping at gap interfaces added, the siren proved as “stable open” as the older design was “stable closed.” This simple solution solved company’s jamming problem while introducing a new and powerful test method.

4.2 Turbosiren Design and Low Power Expenditures

The “rotor downstream” design, adopted by several MWD companies, is not ideal. While jam-free operations are welcome, signal strengths are not sufficient for deep downhole telemetry. At Halliburton in the 1990s, this author continued his “short wind tunnel” (SWT) efforts, useful in signal analysis, stable open evaluation, torque characterization and erosion modeling, and would extend this work to “long wind tunnel” (LWT) simulations as described in Section 2. These efforts opened up multiple avenues for productive MWD telemetry research.

Our efforts first addressed limitations of the Schlumberger invention. An improved SWT provided excellent opportunities to make mistakes rapidly and inexpensively, and importantly, to learn lessons which were necessarily lab based. Toward this end, we reverted to earlier “rotor upstream” designs without tapers and underlaps, and kept rotor-stator gap separations (dangerously) small to enhance signal strength. However, the author would introduce a fixed turbine stator upstream of the siren combination, as in Figure 15. Thus, our so-called “turbosiren,” with multiple connected units along the same shaft forming additive “sirens in series” configurations. The invention is described in U.S. Patents 5,586,083 and 5,740,126 due to Chin and Ritter [8, 9]. Sample designs, displayed below, have been built and tested by this author, with detailed signal, torque and rotation rate results published in Measurement While Drilling Signal Analysis, Optimization and Design, 2nd Edition, by Chin [2], a recent book offered by John Wiley & Sons. These first detailed experimental results, we emphasize, *not* funded by Halliburton, were obtained some twenty years after the initial patent dates. We now summarize the benefits offered by turbosiren technology.

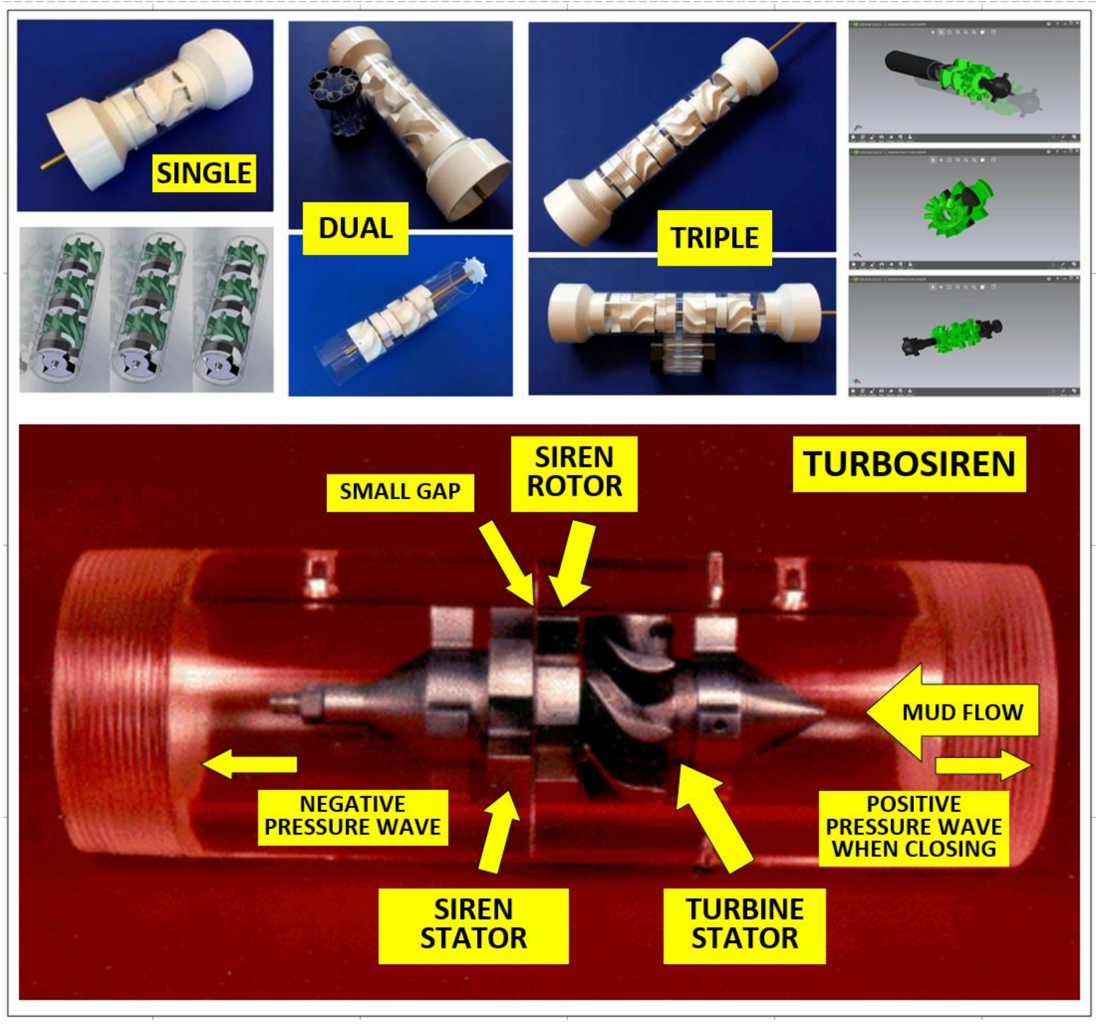


Figure 15 Self-spinning, low power turbosiren, later used in dual and triple "sirens in series."

Our rationale behind turbosiren design was obvious. High camber, closely spaced turbine blades would efficiently induce flow deflections that produce high torque rotors capable of rapid rotations even in low velocity muds. Our rotations (and carrier frequencies), in a sense, require no energy or external power, drawing only on the kinetic energy of the flowing mud – rotating in the same way a flapping flag freely oscillates in the wind. With this design, electric and hydraulic motors are never needed – not even for modulation, since changes in rotor speed can be effected by rapidly acting braking systems. Precious downhole turbine or battery power can instead be used, for example, to increase logging density and measurement types or to recharge backup power sources. In addition, our rotors and stators may be fabricated with just two or three lobes for much stronger signal levels not possible with existing four lobe designs. Such sirens, in fact, were and are our *modus operandi* in designing practical turbosirens.

4.3 Sirens in Series Operation

In Section 3 we proved mathematically that numerous high frequencies are available for strong FSK telemetry. For a given BHA, the P/ΔP ratio measuring signal strength entering the drill pipe assuming fully opened drillbit nozzles takes on ideal values of 1.0 as derived earlier for single reflections (detailed calculations show 0.96 – 0.97 when real geometric effects are considered). However, the ratio surprisingly increases to values near 2.6 for certain discrete frequencies exceeding 100 Hz, possible with multi-cycle constructive wave interference. Our model properly ignores dissipation within the BHA, which is permissible given its small dimensions. Once the signal propagates up the long drill pipe, attenuation takes hold and wave amplitudes will decrease irreversibly. To make use of these high frequency carrier waves, starting signal strengths must be improved – the higher the wave frequency, the greater the initial "boost" required. Two hardware solution approaches are possible.

Reducing rotor-stator gap, the first, offers only limited returns. At best, the created signal is finite, but the siren will clog with debris long before the maximum signal is created. We turned to a less obvious alternative, drawing on the wave nature of acoustic signals. Amplitudes are increased by stacking "sirens in series," with identical aligned turbosirens sharing the same rotating shaft. The method is proven experimentally, as disclosed in Chin [2], and videos with one, two and three turbosirens are available from the download link at https://we.tl/t-RM0j2ygvAD. The ten second video, "MWD Turbosirens in Series, Single, Dual and Triple Sirens (2024).mp4 [10]," is offered with other company literature. Our sirens need not operate simultaneously. At least one should actively rotate, while others may lie dormant until activated to overcome depth or mud viscosity impediments. In addition, they need not be close in proximity. Separations may be a foot or more apart, with particular sirens (corresponding to favorable siren source positions) activated as results in Figures 13 (a-i) dictate. Sirens in series signals are additive, drawing on constructive wave interference principles.

4.4 Turbosirens with Jamming Resistance

While the above section discusses signal additions needed to facilitate transmissions in highly attenuative environments, it does not address the problems associated with jamming and debris accumulation. These are worsened by the use of Lost Circulation Materials (LCM) deliberately introduced into the drilling mud to reduce unintended and dangerous oil and gas releases from the reservoir that rise to the surface. That this is still as problematic as it was decades ago is clear from recent publications like U.S. Patent Application Publication 2017/0130578 A1 [11], "Jam Clearing Process for Rotary Telemetry Tools," T.L. Skerry, assigned to Schlumberger Technology Corporation, Publication Date May 11, 2017 and U.S. Patent US 10,323,511 B2 [12], "Dual Rotor Pulser for Transmitting Information in a Drilling System," W.E. Turner, assigned to APS Technology, Inc., awarded June 18, 2019. These works, applicable to sirens and rotary valves, provide essentially "scissor-like" solutions that involve some mechanical complexity, which may not be entirely reliable in operations. However, our SWT research has uncovered the more elegant solution highlighted next in Figure 16.

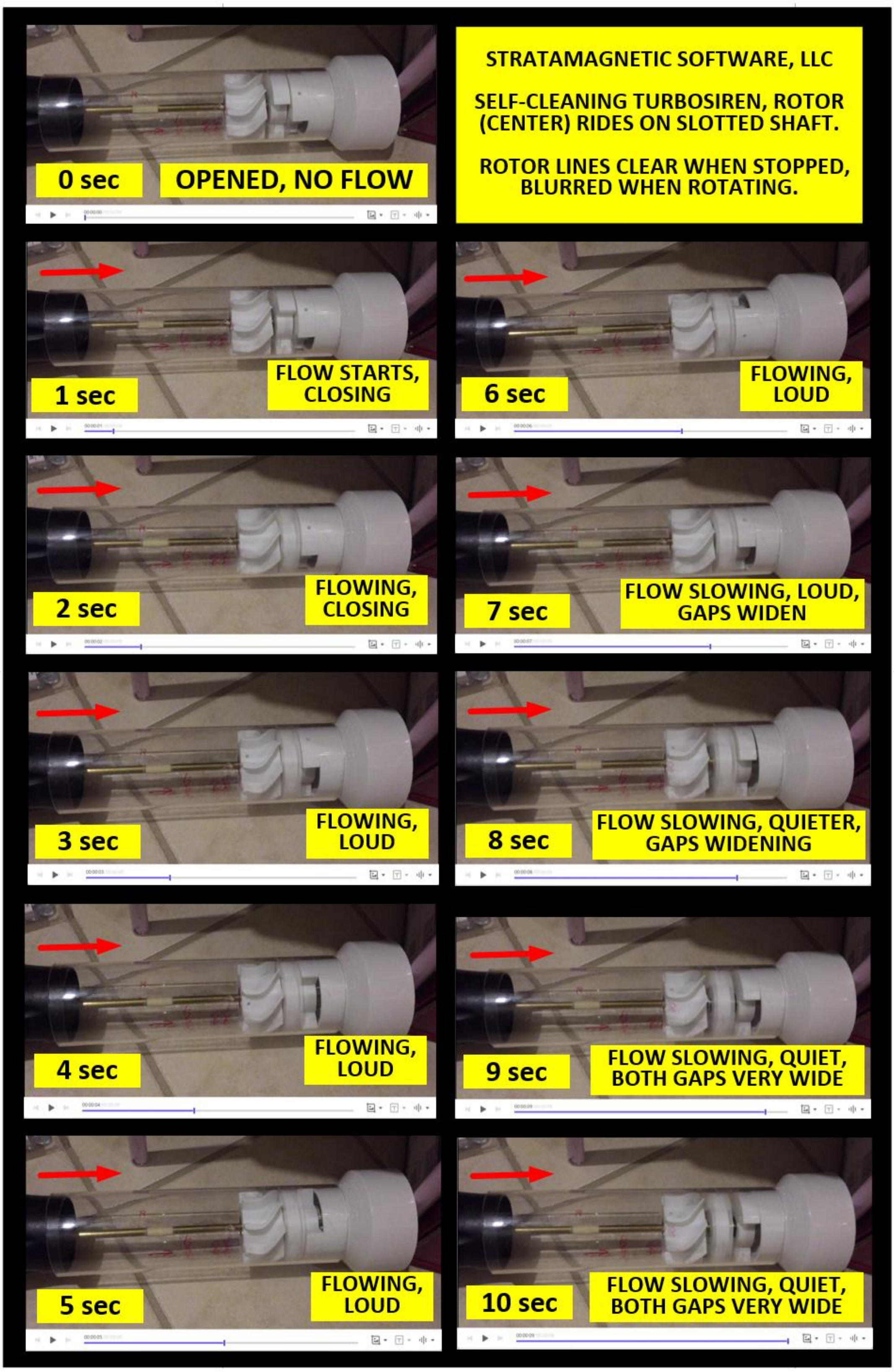


Figure 16 Self-cleaning turbosiren, turbine-rotor and siren rotor-stator gaps widen as flow slows.

Figure 16 reproduces frames from a ten-second “self-cleaning turbosiren video” taken one second apart. Wind tunnel air flows left to right, impinging first at the turbine stator, then the rotating rotor and finally the stationary stator. Unlike Figure 15, our turbine stator is *not* secured to the housing, while the siren rotor is *not* entirely anchored to the rotating shaft. Both are free to "ride" longitudinally along the shaft, in practice, free to move along a straight trench or channel guided by a *loose* "key and slot" anchor. At t = 0 sec, we have non-flowing conditions. Initial wide turbine-rotor and siren rotor-stator gaps are seen. From t = 1 to 5 sec, wind speeds accelerate, signal strengths (SWT sound volumes) noticeably increase, while the oncoming flow as expected pushes both turbine and rotor to the right to close both gaps. Interestingly, from t = 6 to 10 sec, our flow slows down and sound levels in the lab reduce as expected. However, both turbine and rotor move to the left, opening both gaps widely even as wind continues flowing to the right. In other words, instead of being "blown away" by wind, both "blow into" the wind, which would release any LCM accumulating near any gaps. This unanticipated result, defying common sense, is repeatable. It provides a simple aerodynamic means to reduce jamming susceptibility without major mechanical re-design or complexity. As of this writing, patent application is in progress, and forthcoming videos will be available to the general public.

5. Discussion: Reflections, Pump Noise Removal and Surface Signal Processing

Adequate surface signal processing, which includes downhole and surface reflections, desurger distortions and pump noise removal, is not possible without understanding the downhole environment. Events near surface facilities and bottomhole must be regarded and treated as an integrated system. Popular statistical filters, which may work in isolated instances, do not take advantage of the reflection-dominated physics, so that their limitations will not be well understood. A solid foundation begins with an understanding of downhole events, particularly those created by higher frequency sources with short wavelengths. Consider a siren operating in PSK mode. Depending on lithology and encoding particulars, random intervals of silence are found between oscillatory wave segments. When a pressure signal is positive at one side, for example, the opposite is negative, as previously discussed. These travel in opposing directions, with one reflecting at the bit and the other at the pipe-collar intersection. Needless to say, the resulting signal that propagates up the drill pipe is complicated, a consequence of multiple reflections with unknown reflection conditions and stretches of silence.

Positive pulsers are no better. A single plunger action, as for sirens, results in upgoing and downgoing waves, both of which are equally strong initially. Multiple plunger movements are executed with time; afterwards, what travels up the pipe is a "fuzzy" signal which must be "cleaned up" statistically, usually by optimizing some mathematical energy or error norm having little to do with reality. This problem cannot be solved without further assumptions. However, removing the underlying cause by using FSK telemetry will work. As shown in Figure 14, "frequency is frequency" and the effects of multiple reflections are already embedded in easily distinguished pressure traces. Piecewise-constant frequency snapshots propagating up the drill pipe are simple to interpret, acting as if they were created by a simple piston driver positioned at the end of a long conduit.

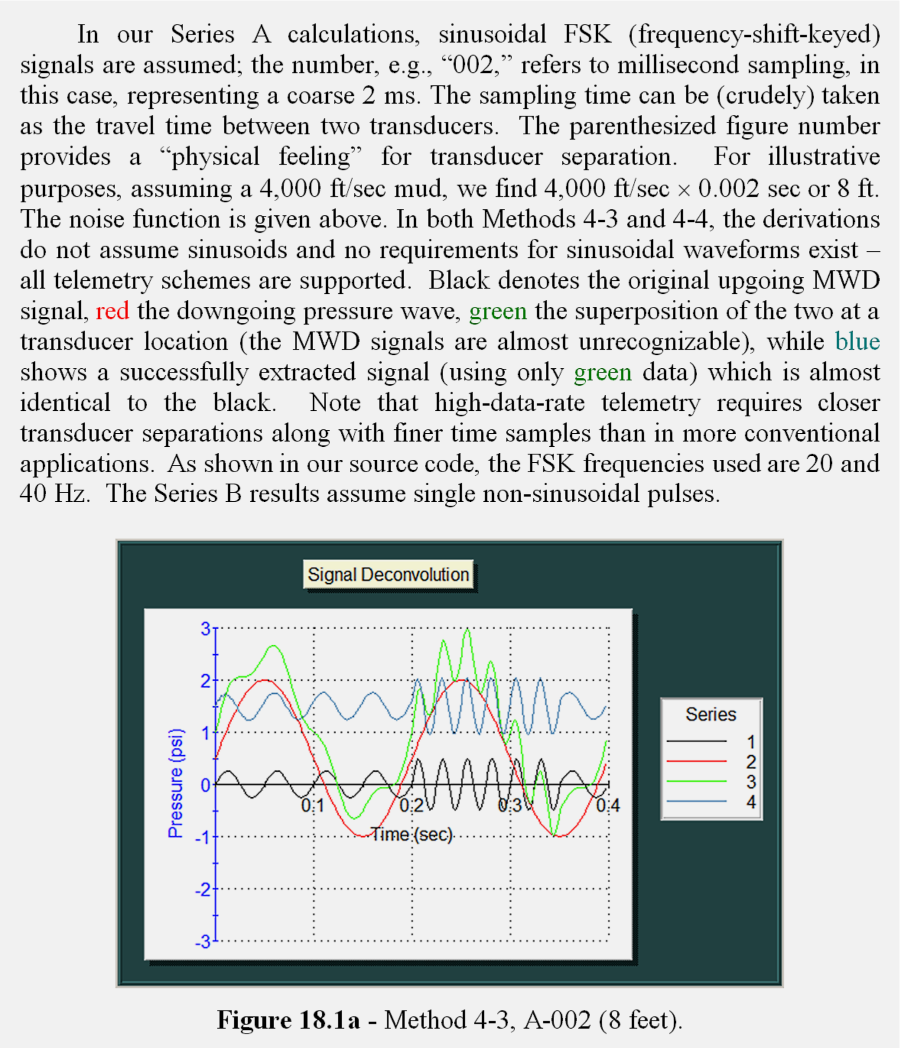
These FSK waveforms represent clean, unambiguous MWD signals we denote by $f_{MWD}\{x - ct\}$ where c is sound speed, x is space, t is time, and the function f_{MWD} denotes a general upgoing pressure wave. For now, we ignore the possibility of extraneous noise created by bit bounce, axial drillstring vibrations, or effects induced by turbodrill rotor and stator interactions. Two situations are possible. If there is no desurger, or it its bladder in damaged, the signal will propagate to the (solid) pistons directly and reflect without change in pressure polarity. Thus, at any standpipe point x and time t, the upgoing signal $f_{MWD}\{x – ct\}$ will be accompanied by a return pressure "$+ f_{MWD}\{x – c(t - t^*)\}$" from an earlier time, where the time delay t* is known from the surface sound speed and standpipe-to-pump distance. At the transducer location x, the measured (contaminated) pressure at time t is thus $P_{MEASURED}(x,t) = f_{MWD}\{x – ct\} + f_{MWD}\{x – c(t - t^*)\}$. This single-transducer "delay model" assumes that multiple reflections are not present, meaning that the drill pipe is long, the mud is sufficiently attenuative, or both, all situations that are not unrealistic. For this model, an exact, closed form, analytical solution is available. General "off the shelf" digital filters employing statistical methods assuming multiple reflections should be avoided. Our "analytical filter" is rapid and much more accurate; however, it cannot be used when multiple reflections exist. Fortunately, secondary reflections are likely to be weak. An extended delay model allowing general mudpump pulsations is also available, but requires dual transducers.

In the second scenario, a desurger with an elastic bladder is operable. Our upgoing $f_{MWD}\{x – ct\}$ will impinge at the bladder, where elastic effects cause it to reflect with severe distortions that cannot be characterized accurately. It will never "see" the mud pump. If we designate this general reflection by g(x + ct), the net measured signal is $P_{MEASURED}(x,t) = f_{MWD}\{x – ct\} + g(x + ct)$ where "g" is an unknown function. We will write $p(x,t) = f(x - ct) + g(x + ct)$ for convenience. Also, let "primes" denote derivatives taken with respect to arguments, while subscripts denote partial derivatives. Therefore, we have $p_x = f' + g'$ or $- cp_x = - cf' - cg'$. Now, differentiate p with respect to time, so that $p_t = - cf' + cg'$. Adding the two results leads to $f' = (cp_x – p_t)/(2c)$ which is known and independent of the unknown function g.

This result leads to usable signal processing formulas, recognizing that p_x is the pressure difference between two transducers separated by a distance Δx, divided by Δx. Analogously, p_t is the time derivative calculated from midpoint pressures at one time level, minus those at a prior time t – Δt, divided by the time difference Δt. Thus, f' is known and f can be computed by simple integration. When a data stream p_1, p_2, p_3 . . . is available, f is known to within a constant that can be set to zero for plotting purposes. This method applies to any form of upgoing signal, whether PSK or FSK telemetry. This simple "differential equation model" applies in the presence of distortive desurgers and strong pump excitations since both can be absorbed in the downgoing function g(x + ct). Excepting for the sound speed c, it is not necessary to know more about the desurger or pump. When downhole transmissions are "clean" using FSK modulation, as previously described, integration is unnecessary as changes in frequency are always readily discernible. This simplifies signal processing and reduces error rates significantly. This and the two transducer delay model are complementary. Both filters can be used for redundancy.

The "delay model" is used in communications and signal processing for general situations with multiple reverberations. Approximate statistical methods are used. We are able to provide exact solutions because we assume single reflections only, implicitly assuming that multiple reflections are nonexistent or weak. This breaks down at very shallow depths. The single transducer delay model also requires bandpass frequency filtering to remove pump pulsations while its dual sensor alternative does not. The "differential equation method" is developed in U.S. Patent 5,969,638 due to Chin [13] and evaluated in Chin [2]. Simple delay and differential equation models differ in one operational respect. The former requires a single standpipe transducer, a convenience that avoids tapping additional holes into a highly pressurized tubular. The latter requires at least two transducer ports. Since p_x represents a spatial derivative, Δx must be small in some physical sense. Acoustic LWT tests suggest a value of about 5% of a wavelength. And since wavelengths depend on excitation frequency, multiple standpipe holes must be tapped to accommodate the possibility that different carrier frequencies are used. This decreases the structural integrity of the standpipe. A solution is offered in U.S. Patent 5,515,336 due to Chin et al. [14], in which a long, flexible hydraulic hose is connected between two drilled holes, which are in turn tapped at multiple stations to provide a range of ports that may be used to provide pressure values for p_x evaluation.

The foregoing methods are treated extensively in Chin [2], which discusses single and dual transducer delay models, attenuation simulation and desurger distortion in Chapter 3-6, and differential equation models in Chapter 18. Numerous validation examples are given. We conclude this discussion with two representative calculations. In Figure 17, we demonstrate our extended delay model. The discussion shows that an assumed upgoing MWD signal (created by FSK modulation) in the presence of a larger downgoing red signal. The combined signal at the transducer location is given by the green line. The blue line, which represents information extracted from green data only, is surprisingly close to the black assumption. The method is extremely accurate.

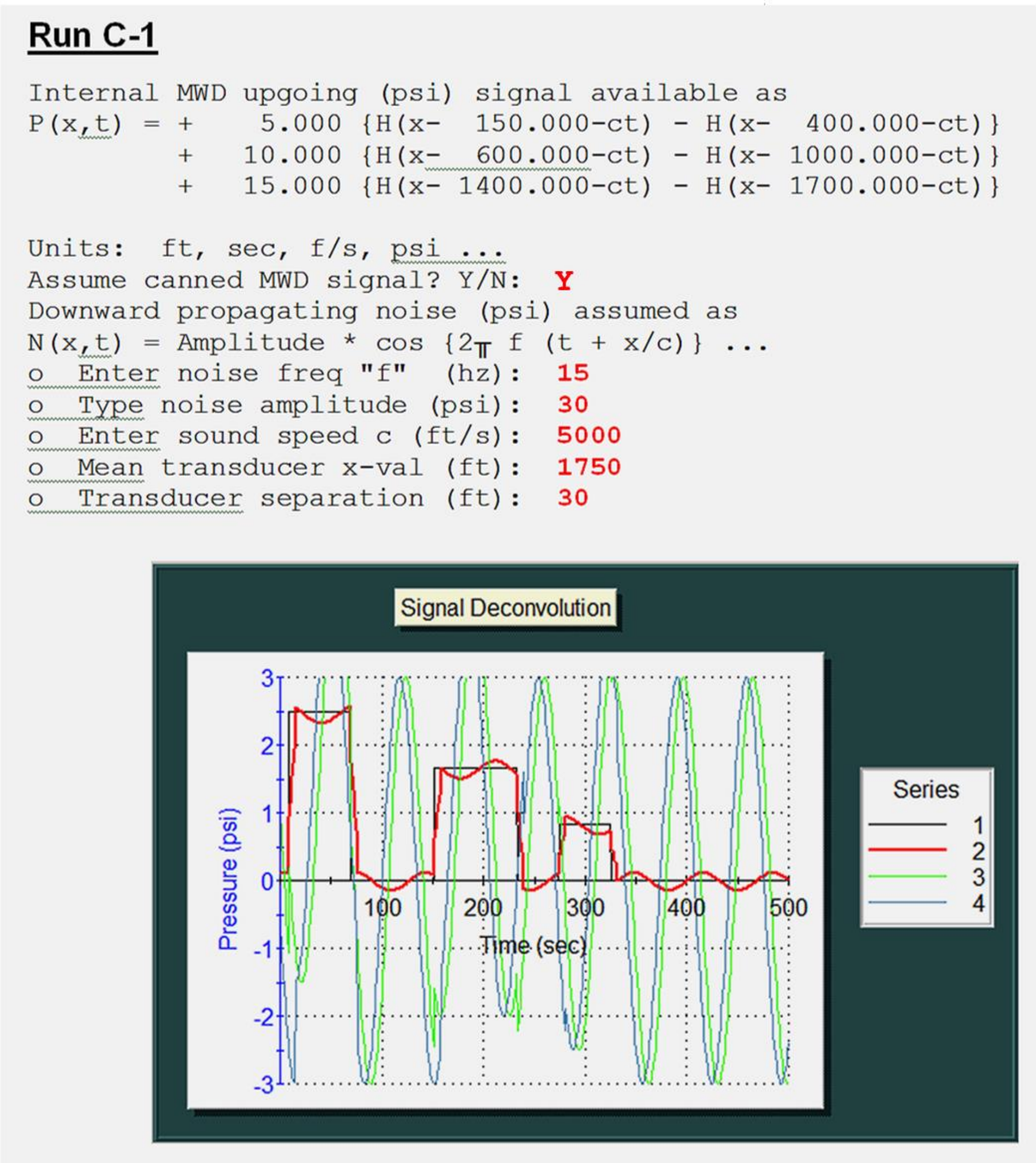


In our Series A calculations, sinusoidal FSK (frequency-shift-keyed) signals are assumed; the number, e.g., "002," refers to millisecond sampling, in this case, representing a coarse 2 ms. The sampling time can be (crudely) taken as the travel time between two transducers. The parenthesized figure number provides a "physical feeling" for transducer separation. For illustrative purposes, assuming a 4,000 ft/sec mud, we find 4,000 ft/sec × 0.002 sec or 8 ft. The noise function is given above. In both Methods 4-3 and 4-4, the derivations do not assume sinusoids and no requirements for sinusoidal waveforms exist – all telemetry schemes are supported. Black denotes the original upgoing MWD signal, red the downgoing pressure wave, green the superposition of the two at a transducer location (the MWD signals are almost unrecognizable), while blue shows a successfully extracted signal (using only green data) which is almost identical to the black. Note that high-data-rate telemetry requires closer transducer separations along with finer time samples than in more conventional applications. As shown in our source code, the FSK frequencies used are 20 and 40 Hz. The Series B results assume single non-sinusoidal pulses.

Figure 18.1a - Method 4-3, A-002 (8 feet).

Figure 17 Single transducer delay equation analytical filter example.

Next we illustrate the differential equation method. In Figure 18, a black upgoing traveling pressure wave consisting of three steps with successfully smaller pulse heights is assumed. It propagates against a noisy signal defined by the tabulated parameters. The blue and green lines, barely distinguishable from each other, are pressure traces obtained at each of two separated transducers. They are almost identical because signal to noise ratios are small. Nonetheless, the red curve is successfully extracted with simple, rapid calculations. Many MWD reflection cancellation patents, based on ad hoc math without wave equation basis, do not work well. Our examples provide convincing evidence that successful reflection cancellation is achievable using rigorous math models.



Run C-1

```
Internal MWD upgoing (psi) signal available as
P(x,t) = +     5.000 {H(x-  150.000-ct) - H(x-  400.000-ct)}
         +    10.000 {H(x-  600.000-ct) - H(x- 1000.000-ct)}
         +    15.000 {H(x- 1400.000-ct) - H(x- 1700.000-ct)}

Units:  ft, sec, f/s, psi ...
Assume canned MWD signal? Y/N:  Y
Downward propagating noise (psi) assumed as
N(x,t) = Amplitude * cos {2π f (t + x/c)} ...
o  Enter noise freq "f"  (hz):  15
o  Type noise amplitude (psi):  30
o  Enter sound speed c (ft/s):  5000
o  Mean transducer x-val (ft):  1750
o  Transducer separation (ft):  30
```

Figure 18.2a - Method 4-4, Run C-1.

Figure 18 Dual transducer differential equation method deconvolution example.

5.1 Extraneous Downhole Effects

Other upgoing signals originating from downhole exist, for example, those arising from bit bounce, BHA axial vibrations, and rotor-stator interactions in positive displacement turbodrill motors. Because they originate from the same location as the MWD signal, direction-based delay and differential equation filters will not apply. In practice, the use of bandpass filters is necessary to remove noise outside the frequency ranges characterizing the signal. PSK signal removal is less predictable given reverberant reflections and phase-shifting. FSK transmissions are desirable since acoustic fields with visually clear frequencies are amenable to simpler and accurate analysis methods.

5.2 Analog Acoustic Amplifiers and Filters

Finally we discuss the use of analog devices in field application. In the early 1990s, Halliburton drilling engineers presented the author with an unplanned opportunity arising from signal detection failure. Signals were too low for unknown reasons. Realizing that low frequency waves traveling through long conduits reflect at solid terminations with doubled pressures, the author removed the standpipe transducer and inserted one end of a fifty feet hydraulic hose. The transducer was then installed at the far end of the hose. Measured pressures should, but did not double. Undeterred, the hose was lengthened another fifty feet, at which point the signal *would* double as theory required. This “hundred feet hose” proved to be a field success, leading to U.S. Patents 5,459,697 and 5,535,177 due to Chin and Hamlin [15, 16].

Two lessons were learned. First, mathematical limits like “long” are not well defined and must be determined empirically, and second, a knowledge of physics can prove beneficial. To be sure, other analog amplifiers are available in older telephony literature, like *Electromechanical Transducers and Wave Filters*, from Mason [17] at Bell Telephone Laboratories, Inc. Elementary publications like *Acoustics, Schaum’s Outline Series* [18] and advanced monographs like *Theoretical Acoustics*, Morse and Ingard [19] are also both useful.

A literature search revealed an analog amplifier that may be useful in drilling. Consider harmonic plane waves of wavelength λ propagating through a conduit of given area, and then into a closed extension with length $\lambda/4$ and a halved area. Analysis shows that the pressure at the closed end equals four times the incident pressure. In practice, one might consider a very long hose attached to a standpipe port, with an extension $\lambda/4$ in length and half the original tubular area. A 100 Hz MWD signal in thin brine mud is associated with λ = 5,000 ft/sec/100 Hz or 50 ft. The extension would be 50 ft/4 or approximately 12 ft. This length would change as MWD frequencies change. Analog *filters*, as opposed to *amplifiers*, should also be evaluated for drilling potential. These include long conduits with open side pipe extensions, closed extensions, and extensions with spherical attachments as outlined in Seto [18] with more designs in Mason [17]. The potential of these long forgotten devices is yet to be realized.

6. Discussion: Historical Notes, Contextual Insights and Acoustic Subtleties

The first author had stated, early in this paper, how reviews are subjective and biased toward a writer’s experience and personal perspectives, and that it was necessary to understand an author’s background so that his writings can be taken in context. Insightful comments and questions were raised by the authors' colleagues that do not fall into the paper categories used above. These deserve special attention, and our responses are sometimes more situational than technical. Nonetheless, they explain why our technologies were not developed earlier, and are therefore relevant to readers. These interesting points are addressed below.

6.1 Oilfield Jargon and Illustrations

Readers familiar with our MWD work, say Chin et al. [1] and Chin [2], appreciate our use of precise terminology and drawings. In this paper, formal mathematics were kept to a minimum and certain illustrations, e.g., Figure 9, were deliberately informal. It was not our intent to delve into analytics and algorithms when we can productively introduce important new ideas more simply. In the oilfield, many improvements to MWD are introduced by field workers who contribute by making hardware changes. Thus, it is necessary to explain more abstract concepts by simpler and more direct examples. We adhered to the old adage that, if one truly understands a difficult problem, one should be able to explain ideas with simple illustrations in lieu of equations. Toward this end, we abided by still another wise saying, namely that "a picture is worth a thousand words." A second case in point is our unconventional use of the terms "hydraulic" and "acoustic," whose definitions are available in scientific references. This terminology was used only for consistency with "oilfield jargon," that is, conversational language common among "roughnecks" with less exposure to formal fluid mechanics. Unfortunately, this usage has been universally adopted among technical personnel over the years that it cannot be avoided without introducing confusion. Thus, our explanations in the main text are augmented with unambiguous differential equations in order to reduce any misleading associations.

6.2 Very Long Waves and Cutoff Frequencies

Many acoustics papers indicate difficulties in high data rate communication over long distances, which may arise for two different reasons. The first is irreversible thermodynamic attenuation, which cannot be avoided; we solve this problem by using efficient, low-energy, self-spinning, "turbosirens in series" signal superposition, selecting enough sirens as is necessary to overcome any anticipated dissipation. The second reason arises from "cutoff frequencies" found in the *tens* of Hz, "meaning that high-frequency signals cannot be transmitted over long distances at all." How do we reconcile this with our claim that *hundreds* of Hz should be doable?

Such problematic transmissions, in fact, do *not* exist. We refer readers to Chapter 9 of the classic M.I.T. book *Theoretical Acoustics*, by legendary Professors P.M. Morse and K.U. Ingard, from McGraw-Hill Book Company, New York, 1968. Quoting from their text, "When a sound wave is transmitted along the interior of a tube, and when the wavelength is large compared with the transverse dimensions of the tube, the fluid motion is predominantly parallel to the tube axis, and the wave motion is very nearly one-dimensional." Later in the chapter, the authors' Equation (6.2.4) is identified as the classical wave equation "$\partial^2 P/\partial t^2 - c^2 \partial^2 P/\partial x^2 = 0$," where c is the sound speed in the medium and P is pressure. This has general upgoing and downgoing solutions of the form $P(x,t) = f(x - ct) + g(x + ct)$ where x is the axial coordinate and t is time. These are the equations underlying the "six segment waveguide" examples in Figure 10, Figure 11, Figure 12 and Figure 13. Finally, in our earlier section "Two observations impacting MWD research," we cited experimental proof showing that waves in the 50-100 Hz range exist in conventional drilling channels. In the LSU experiment, the wavelength λ = c/f ≈ (5,000 ft/sec)/50 Hz = 100 ft >> 3 in (diameter) easily satisfies the "long wave" criterion, so that our observed wave propagation is in fact very real.

Section 9.2 of *Theoretical Acoustics* also studies "higher modes" in ducts. According to the authors, "These higher modes of wave transmission (depending also on transverse coordinates y and z) have phase velocities which are greater than the velocity of sound c in free space. As the frequency is decreased, the phase velocity of each higher mode increases, to become infinite at some cutoff frequency characteristic of the mode considered. Below the cutoff, true transmission cannot take place for this mode; the wave attenuates rapidly. *Thus, at low frequencies, only the plane wave, the fundamental mode, is transmitted*." The italicized text, we emphasize, can be misleading. As the book correctly points out, strictly speaking, one-dimensional wave propagation is guaranteed when λ greatly exceeds a typical transverse dimension. Since λ = c/f, this is possible if "f is very low," but propagating waves will also be found when "f" is high, for example 500 Hz, and the corresponding "c" is much larger, say 5,000 ft/sec. In this case, the inequality λ = c/f ≈ (5,000 ft/sec)/500 Hz = 10 ft >> 3 in (diameter) still holds, and so, we therefore expect to find that propagating waves do exist. The authors do state that, "At higher frequencies some of the higher modes also are propagated, and these additional waves must be included in our calculations." In conclusion, for MWD transmission, "plane waves," which depend on "x" only (and not y and z) *always* arise from positive pulser piston and siren blockage and negative pulser flow dumping. Again, "P = f + g" one-dimensional solutions, which include all transmitted and reflected waves, are *always* guaranteed and found whenever wavelengths greatly exceed typical pipe diameters. This assumes that their initial amplitudes (created by enough "turbosirens in series" elements) are able to withstand the thermodynamic attenuation encountered along lengthy travel paths going uphole. Numerous calculated one-dimensional examples are pursued in the book *Acoustics* by Seto [18].

6.3 Why Now and Not Much Earlier

Some in outside research organizations understand that turbosirens can achieve high-speed rotations in hundreds of Hertz ranges. A typical spectrum analyzer trace appears in Figure 19, but much higher frequencies are possible since rotation rates are directly proportional to flow rate. Several have asked, (1) how one might implement a high-speed data signaling scheme, and (2) why focused research such as ours has not appeared until now, given that "turbosirens have been around for more than *thirty* years."

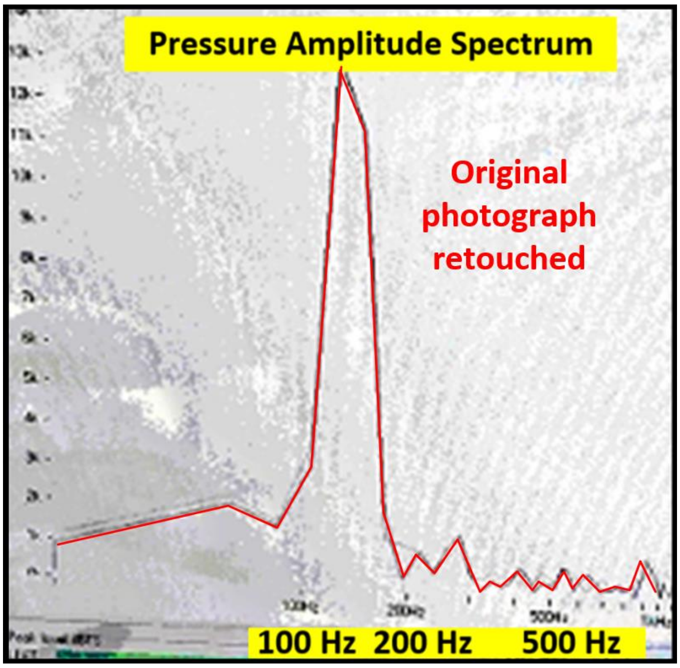


Figure 19 Measured amplitude spectrum from Figure 16.22 of Chin [2].

We correctly note that the first author invented Halliburton's turbosiren in U.S. Patents 5,586,083 [8] and 5,740,126 [9]. Prior to 1996, self-spinning sirens did not exist. These and related patents, however, did not address modulation schemes. Modulation schemes were only described in a recent 2024 patent application, calling for consistently rapid braking systems. One possibility is the use of electro-magneto-rheological brakes, in which changing electromagnetic fields (almost) instantaneously adjust fluid viscosities to induce (almost) infinite viscosities, for example, as described in U.S. Patent 7,082,078 [20] due to Fripp, Skinner and Chin. Other circuit driven brakes or motor drives are possible for FSK use. In any event, very rapid *high-to-low* frequency changes are effected by such braking, while rapid *low-to-high* frequency changes are naturally provided by high-torque rotors inherent in our use of long, highly cambered, closely spaced turbine blades. Finally, whereas conventional FSK approaches might arbitrarily select, say "12 Hz and 24 Hz," or "0 Hz and 12 Hz" in a Schlumberger siren application, our "Intelligent *i*FSK" strategy chooses candidate frequencies from properties like those in Figure 12, utilizing close frequency pairs corresponding to neighboring amplitude nodes and anti-nodes. Such waveforms are easily identified and facilitate rapid signal processing. Our rotors always rotate in one direction, even when braking is applied, thus enhancing data rate by reducing times spent in low rotation rate zones. Surface frequency selection methods are described in a recent patent application. This is yet to be field tested, given the high costs involved, and we are presently searching for industry partners.

The second "unavoidable" question is more interesting. Many ideas, developed over thirty years, at several leading companies no less, have not led to results until now. *What were the problems and how were these resolved?* The answers are complicated, with our problems being more situational than technical. At Schlumberger, realizing that rotating, blunt body, separated flows could not be studied mathematically, the author would stumble upon wind tunnel modeling during one singular lunch hour – the "stable closed" character of its *mud* sirens was rediscovered and replicated using a card-board siren positioned in a poster-board tube with clean blowing "*shop* *air*." In other words, sirens naturally jam even when debris is not present. The widely recognized "stable open" siren, with downstream rotors, was inexpensively and rapidly designed in two week's time. Schlumberger's very secretive 1981 invention finally sought patent protection in 1986, and was awarded U.S. Patent 4,785,300 in late 1988.

An even more closely guarded trade secret was the company's use of "short wind tunnel" (SWT) testing, a novel practice inadvertently disclosed in later publications undertaken at its Cambridge, England research division. In the meantime, the author had left the company, and vigorous litigation had prevented him from engaging in any MWD activities until he joined Halliburton as MWD Manager in 1992. Thus, ten years had elapsed. Here, the "long acoustic wind tunnel" (LWT) was developed, together with the author's "turbosiren," although somewhat accidentally, in U.S. Patents 5,586,083 and 5,740,126. Despite intense interest and high commercial potential, the turbosiren at the lower portion of Figure 15 was never tested – the model shown was fabricated without bearings, seals, housings, or any electrical connections to measurement devices. At the time, a leading management consulting company recommended that Halliburton terminate such research – the company did so, and the author would instead work in formation testing and rheology, areas to which he would significantly contribute. Patent applications were pursued to prevent present and future competitors from applying the technologies.

It was not until 2015, almost twenty years after the first 1996 turbosiren patent, that Xiaoying Zhuang (second author and Chinese-English interpreter) talked with Professor Wenxiao Qiao at Beijing's China University of Petroleum about our discoveries – who would, in turn, introduce us to Sinopec's Research and Development group in Southern China. Sinopec would fund its own internal MWD activities in this area, while the first author and Jamie Chin (third author, now with Hong Kong University) focused on detailed experiments related to flow rate, signal strength, rotation rpm, torque, and "sirens in series" acoustic pressure wave superposition. These results would see publication only in our second MWD book [2]. This represented our *only* prior disclosure of turbosiren results. We had published just two other MWD papers over the years, namely, Su et al. [21] and Su et al. [22], both of which described China National Petroleum Corporation's (CNPC) high data rate developments and its long acoustic wind tunnel facilities, long before our Sinopec funded turbosiren work was pursued. Thus, while the author's MWD involvement extended some thirty years, with numerous patents acquired in the intervening time, noticeable hardware progress was lacking even as good ideas accumulated slowly. The disruptive roles played by accidental discovery in the laboratory, e.g., from SWT, to LWT, to turbosiren self-rotation, to aerodynamic self-cleaning and more, cannot be deemphasized. Without the convenience and rapid learning offered by inexpensive test facilities, these important inventions could not have been anticipated from mathematics alone.

6.4 Other Relevant MWD Siren Research

The literature is rich with articles on MWD methods, however, paper length considerations preclude our detailed review. We have therefore omitted discussions of other siren developments, although some remarks are deserved. In fact, numerous attempts at improved siren and rotary shear designs have been made, and attributed to companies like APS, BakerHughes, Calmena, CNPC, Evolution Engineering and Geolink. However, none are self-spinning, and several designs jam because "stable closed" rotor designs, rendered obsolete by Schlumberger's U.S. Patent

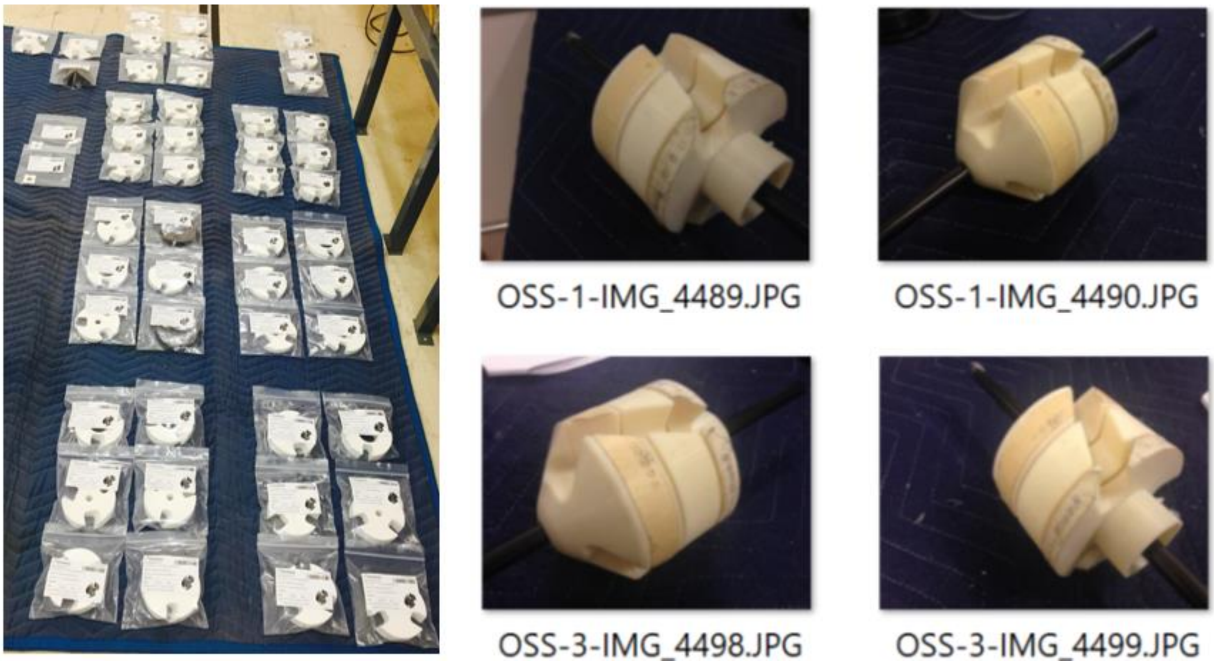
4,785,300 for "stable open" downstream rotors, were unwittingly used. Further, few papers have disclosed new approaches to signal processing and reflection cancellation, let alone physics-based *i* FSK. The great majority assume ideal sinusoidal waveforms when realistic oscilloscope traces like those in Figure 14 should have been studied. Others invoke standard least-squares filtering algorithms, without focusing on truly relevant physical issues related to direction-based processing. Although we introduced our own "six segment waveguide model," published in Chin et al. [1] and Chin [2], we deliberately left out math details in the original publications. In this paper, we explained for the first time, how our new high-frequency results in Figure 12 can be used to select optimal frequency pairs for "Intelligent FSK." In summary, this paper does not address math models and algorithms, choosing instead to describe key historical milestones and misleading judgments so that readers can more readily grasp the "big picture" needed to truly advance the art. In closing, we acknowledge the recent contributions in "Experimental Study of High Speed Shear Valve Pulser Telemetry System in MWD" due to Wang et al. [6]. The paper describes an encouraging rotary shear valve system operating at 36 Hz with a bit rate of 12 bps at 3,000 meter depths. Also, the newly developed "sandwich siren" funded by GE Oil & Gas, BakerHughes and Prime Downhole Manufacturing deserves special attention, providing high-torque, self-spinning features, appearing in several patent publications to be discussed later in this paper.

6.5 Additional Historical Notes

While this paper reviews the development of MWD siren technology over the years, it was not intended to and does not summarize our 2014 and 2018 books. Much of the present write-up is new and based on 2024 observations, as follows. (1) The "six segment waveguide" (see Figure 10 and related discussions) first published in 2014 discussed calculated results up to 50 Hz, shedding insight into Schlumberger capabilities (then and now) limited to 24 Hz carrier frequencies. In this paper, we omitted derivations and math discussions. Our Figure 12, in contrast, pursues calculations up to 5,000 Hz, only now recognizing that very, very high frequencies can be effectively used for high bit rate "Intelligent *i*FSK" modulation. (2) High frequency signals are subject to irreversible thermodynamic attenuation. The obvious use of "turbosirens in series" signal superposition would support very high frequency operation, of course, however this convenient approach was not anticipated in our 1996 and 1988 turbosiren hardware patents. Only with Figure 12 results did the implications and important role of self-spinning, low-power sirens become evident, suggesting that we treat "Intelligent *i*FSK" and turbosiren design as an integrated technology. (3) The disruptive role played by Lost Circulation Material (LCM) in MWD operations is well known, and represents an ongoing problematic issue, for instance, addressed in U.S. Patent 10,323,511 B2 (APS Technology) and U.S. Patent Application 2017/0130578 A1 (Schlumberger). These inventions provide complicated mechanical means to dislodge jammed debris. We have addressed debris removal using the new and novel method in Figure 16, in which turbine-rotor and rotor-stator gaps automatically separate and widen when mud flow slows down. This effect takes advantage of self-induced aerodynamic effects drawn from MWD short wind tunnel (SWT) experiments, and has not yet been published in any form; however, intellectual property protection was recently sought. (4) As a final example of new, unpublished contributions, we cite our proposal for advanced braking as a means for rapid modulation. In the new approach, *fast-to-slow* rotations may be accomplished using electro-magneto-rheological brakes, servo-motors or other stepper motor methods. However, *slow-to-fast* rotations are obtained naturally, employing the high torques inherently built into our cambered turbosiren blade designs. In summary, the present paper provides numerous contributions to high data rate telemetry not discussed in our two prior MWD book publications.

6.6 A New Self-Spinning “Sandwich Siren”

While the turbosiren in Figure 15 is described extensively in this paper, a more efficient self-spinning siren was actually developed by the first author and his team during 2012-2020. This work, supported by GE Oil & Gas, a subsidiary of General Electric, Baker Hughes and Prime Downhole Manufacturing, is presently protected by U.S. Patents 9,850,754 [23]; 10,145,239 [24]; 10,156,127 [25]; 10,273,801 [26]; and 10,808,505 [27]. Its design completely differs from the “turbine stator – siren rotor – siren stator” configuration in Figure 15, instead taking on a simpler single “stator-rotor-stator” build, dubbed “the sandwich siren” for obvious reasons. An example of a sandwich siren and test setup is shown in Figure 20, although we caution that not all sandwich siren shapes take the form displayed below (for additional shapes, refer to the above cited patents).



OSS-1-IMG_4489.JPG OSS-1-IMG_4490.JPG

OSS-3-IMG_4498.JPG OSS-3-IMG_4499.JPG

Figure 20 Example “sandwich siren” prototype and wind tunnel test array.

This author’s design rationale was unusual. The signal due to two traditional Schlumberger sirens placed in series normally requires two separate “stator and rotor” sirens placed side-by-side along the same rotating shaft. In a sandwich siren, a first signal would be created upon mud impingement at the first upstream *stator-rotor* pair. Flow also passes through a downstream *rotor-stator* pair, so that the net signal is twice that of any single pair alone. That is, the “rotor is used twice” to create a doubly-strong signals. The expected pressure wave superposition was verified experimentally in numerous acoustic (SWT) tests for many geometric designs. Three reasons suggest that sandwich sirens may *not* see common application in the near future. First, the design principles needed to produce self-spinning torques are not obvious, and require labor intensive case-by-case testing. Rotors and stators need special “trial and error” aerodynamic contouring, and geometric changes arising from unpredictable metal erosion cannot yet be anticipated. Second, a significant limitation relates to Lost Circulation Material (LCM) debris tolerance. A self-cleaning capability similar to that in Figure 16 is not available, so the ability of sandwich sirens to recover from debris jamming is not optimistic without the use of complicated mechanical scissor-like fixes. And third, the ownership status of the sandwich siren is presently embroiled in litigation among several companies (not related to this author’s activities) and the present status and outcome are as yet not predictable.

7. Conclusions: Closing Remarks, High Data Rates on the Horizon

In summary, we first showed convincingly using rigorous waveguide models that very high carrier frequencies can be used in conventional drilling channels. Our math did not assume that such frequencies existed, nor did the equations assume they did not. Our analytical model simply solved a general formulation using exact methods, to produce readable color plots for “Drillpipe P/ΔP Signal Strengths” versus Source Position and Frequency. These surprisingly identified numerous *close* pressure peaks and valleys useful to FSK telemetry, and in particular, in frequency ranges far beyond the 12-24 Hz used in conventional siren telemetry. They are attributed to the increasing numbers of constructive wave interference events possible as maximum target frequency increases and wavelength decreases. These frequencies should *not* be misinterpreted as eigenvalues in conventional waveguide problems (that is, “separation of variables” formulations) because we have *not* solved any eigenvalue problems.

We have outlined and designed a fully integrated system, consisting of (1) low power, self-spinning, self-cleaning turbosirens, (2) “Intelligent *i*FSK” building on physics-based use of frequency pairs, with each close frequency associated with easily identified high or low pressure amplitude peaks, (3) accompanying surface procedures in continuous monitoring of selected frequency pairs, (4) improved modulation where rapidly-acting brakes decelerate rotations while naturally high rotor torques increase rotational speed, and (5) innovative materials-based improvements to component fabrication and testing. Our approach, of course, represents a new “top, down” revisit to mud pulse telemetry, and we expect resistance from organizations saddled with large existing tool inventories and client bases. However, changes are needed to an industry that is, at best, mired in a low 1-5 bps data rate range, and perhaps disruptive changes are best borne by highly driven newcomers to Measurement While Drilling.

Why were our results not discovered earlier? The answers are at least two-fold. First, existing sirens and rotary shear valves require electric or hydraulic motors, which are mechanically incapable of producing higher rotation rates. Second, even if high frequencies were possible, signal strengths are too low to be detectable at the surface. In response, we developed self-spinning turbosirens that effortlessly create signals in the 300-500 Hz range, and possibly greater, drawing only on the kinetic energy of flowing drilling fluid without requiring external power. If selected frequencies are prone to attenuation, say due to mud damping or lengthy travel paths, practical hardware solutions are found in “sirens in series” pressure superposition, again conveniently doable without motor drives or external power.

This said, stringent frequency constraints and low amplitudes in competitor tools, and particularly positive pulsers, bring to mind the story of the proverbial blind man who “could see no farther than his walking stick." Our software and hardware discoveries would extend our vision in unforeseen ways. They demonstrate that useful high frequencies do exist, and that clean FSK telemetry, together with intelligent frequency pair selection, will support rapid and efficient mud pulse telemetry. Added costs incurred in producing higher strength signals are non-existent. Again, turbosirens and "turbosirens in series" do not require conventional power and motors, drawing only on the energy freely available in the flowing drilling fluid. Nor are motors necessary for modulation, as rapidly acting "brakes in series" with electro-magneto rheological components or smart electric drives are much more effective.

Our self-cleaning turbosiren also reduces significantly the likelihood of Lost Circulation Material (LCM) jamming without introducing mechanical complexity to basic turbosiren designs, such as those given in Chin and Ritter [8, 9]. Data rate is, in a sense, further enhanced, since non-productive time (NPT) is reduced. To achieve high data rates, rapid modulations are needed, preferably without using electric or hydraulic motors, but using electro-magneto-rheological brake systems as outlined in U.S. Patent 7082078 due to Fripp, Skinner and Chin [20], or possibly special servomotors and stepper motors. These brakes can be turbine or battery powered, by cleverly connecting alternators to rotating turbosiren shafts to generate electricity.

We further emphasize that all sirens in a turbosiren array need not rotate simultaneously. For example, consider three turbosirens separated by, say 2-3 feet each. At shallow depths, only one is activated for telemetry purposes (the others are used in case of mechanical failure). At deeper locations, or perhaps as mud content changes affect attenuation or sound speed, additional signal strength may be required. If so, a second turbosiren may be activated from those in waiting, selected based on a location which contributes best to constructive wave interference (e.g., see Figure 12). A third rapidly spinning siren, temporarily playing a turbine-like role, might be used to charge a draining downhole battery.

Because turbosiren torques are strong and act continuously, significant *abrasive* wear will result. Complementary research into wear-resistant materials will be important. This effort should also address *erosive* mud wear at rotor tips and stator roots, especially since very high frequencies and correspondingly high rotational speeds are easily achieved. The use of "brakes in series" will offer needed redundancy and reduced wear per unit, thus increasing both reliability and life span, while minimizing *vibratory loads* by supporting the shaft at multiple points. These loads can be determined experimentally or by finite element analysis.

For erosion analysis, SWT flow visualization offers useful clues to related impacted areas. However, the final location and rates of material loss at worn areas must be determined experimentally using actual mud with erosive sand. We have found that 3% sand content with mud flowing five minutes provides useful information when metal prototypes coated with epoxy paint are used. Wear patterns consistent with recovered damaged models from the field are always found. Fortunately, this does not require expensive and inconvenient mud pump facilities – simple "parking lot, closed flow loop" fixtures suffice, operating for hours if not days at a time. Pressurized flows are not necessary and any leakage is manageable. Erosion, abrasion and vibration problems can be minimized with simple methods. Several partners skilled in titanium and alloy materials research have been identified, with complementary aerospace and 3D printing experience. The latter is extremely important to MWD siren and turbine fabrication. For example, our self-cleaning turbosiren should work effortlessly in vertical wells, however, turbine stator and siren rotor lifting will be greatly enhanced by buoyancy effects if these are fabricated with single-piece porous titanium alloys. In general, of course, porous rotor materials are preferred over solid denser designs because of reduced mechanical inertial loads.

We emphasize that SWT results for torque, pressure and rotation rate results obtained in air may be rescaled for mud use at all densities and flow rates, as explained in Chin [2], however, the same does not apply to component viscous drag in the streamwise direction. Similarly, LWT acoustic phenomena related to reflection patterns, and constructive and destructive wave interference can be studied successfully by rescaling lengths according to sound speed as described. However, wave attenuation and damping coefficient prediction are not possible, and detailed experiments will be necessary. Our overall and prevailing philosophy is simple – learn from numerous inexpensive, rapid and convenient experiments, so that field applications and real hardware experiments can be designed in a truly cost and time effective controlled manner. Further, physical principles must always take precedence over design convenience. The industry's decades-old "build now, think later" approach has proven unproductive thus far.

Different logging requirements dictate variable data rate usage, suggesting the need for specialized turbosirens targeting different applications. This is often the case in engineering, for example, 100 and 500 HP turbines require different blade designs. We emphasize that not all "turbine stator, siren rotor and stator" combinations will self-spin, and not all self-rotating sirens will self-clean. While the concepts behind turbosiren design are taught in the patents and books, working prototypes often require multiple design iterations which may or may not be successful. It may be preferable to develop a single versatile design that is rapidly configurable for multiple rotation rate and flow speed requirements. Our high-camber, high torque design operates at high rotation rates for all flow rates, slowing as needed using rapidly acting braking. This approach reduces the need for labor-intensive, time-consuming and expensive redesign, re-testing and continual re-manufacturing. Our efficient SWT/LWT methods support physics-based rescaling, so that tools can be easily designed for use in boreholes having arbitrary diameters.

In closing, we reiterate a final important point: our detailed waveguide analysis considering signals as high as 5,000 Hz is not restricted to any type of mud or drill string length. The waveguide analysis applies to the lower BHA and annular region surrounding the collar where, owing to its limited extent, attenuation is not significant. The strategy is this. If 5,000 Hz is actually pursued, the pressure at the bottom entrance to the drillpipe may reach 2.6 times the best poppet performance at low frequencies. What happens after the pressure wave enters the drillpipe is not addressed by our waveguide analysis, but is separately covered by turbosiren application. Basically a strong entry signal is required, and as many "turbosirens in series" are used as are needed, to provide pressure superpositions explained and proven experimentally in Chin [2]. These ideas are covered in ten different expired Halliburton patents previously awarded to the first author, plus several other new innovations recently developed and explained in detail in the present paper. None of our ideas are utilized in poppet valve, negative pulser, conventional siren or rotary shear valve applications, which are not able to achieve high frequencies or high signal strengths. We believe the reasons are related to high development costs, lengthy times and extensive tool inventories. However, mud pulse telemetry has continually demonstrated its practical advantages over wired pipe, electromagnetic, and "banging the steel pipe" acoustic methods, and we hope that our new ideas and technology integration will contribute to its future improvements.

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Author Contributions

Wilson C. Chin contributed to overall conceptualization, writing, and math model, technology and computational development. Xiaoying Zhuang actively participated in short and long wind tunnel development at China National Petroleum Corporation and Sinopec Corporation. Jamie A. Chin contributed to data acquisition and analysis for several turbosiren prototype designs offered in Chin [2].

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Self-rotating, self-cleaning turbosiren design and testing, “Intelligent *i*FSK” and algorithms for delay and differential equation signal processing methods were funded by Stratamagnetic Software, LLC internally. All cited United States patents have expired and were supported by Schlumberger and Halliburton Energy Services. We have recently applied for intellectual property protection for turbosiren jamming reduction, advanced “Intelligent *i*FSK” telemetry, braking systems, and inclusion of these developments as an integrated system offering with low power, self-spinning, turbosiren features in addition.

Competing Interests

No other present conflicts of interest are declared.

References

1. Chin WC, Su YN, Sheng LM, Li L, Bian HL, Shi R. Measurement while drilling signal analysis, optimization and design. 1st ed. New York, NY: John Wiley & Sons; 2014.
2. Chin WC. Measurement while drilling: Signal analysis, optimization and design. 2nd ed. New York, NY: John Wiley & Sons; 2018.
3. Stratamagnetic Software. Company Brochure [Internet]. Houston, TX: Stratamagnetic Software, LLC.; 2024. Available from: https://we.tl/t-RM0j2ygvAD.
4. Stratamagnetic Software. Software and MWD Technical Proposals [Internet]. Houston, TX: Stratamagnetic Software, LLC.; 2024. Available from: https://we.tl/t-RM0j2ygvAD.

5. U.S. Patent 5,583,827. Measurement-while-drilling system and method. Alexandria, VA: U.S. Patent; 1996; US5583827.
6. Wang ZM, Lu HT, Yao XJ, Li H, Jia JB. Experimental study of high speed shear valve pulser telemetry system in MWD. Proceedings of the 5th International Conference on Intelligent Control, Measurement and Signal Processing (ICMSP); 2023 May 19-21; Chengdu, China. Piscataway Township: IEEE.
7. U. S. Patent 4,785,300. Pressure pulse generator. Alexandria, VA: U.S. Patent; 1988; US4,785,300.
8. U.S. Patent 5,586,083. Turbosiren signal generator for measurement while drilling systems. Alexandria, VA: U.S. Patent; 1996; US5,586,083.
9. U.S. Patent 5,740,126. Turbosiren signal generator for measurement while drilling systems. Alexandria, VA: U.S. Patent; 1998; US5,740,126.
10. Stratamagnetic Software. Video: MWD Turbosirens in Series, Single, Dual and Triple Sirens [Internet]. Houston, TX: Stratamagnetic Software, LLC.; 2024. Available from: https://we.tl/t-RM0j2ygvAD.
11. U.S. Patent Application No. US 2017/0130578 A1. Jam clearing process for rotary telemetry tools. Alexandria, VA: U.S. Patent; 2017; No. US 2017/0130578 A1.
12. U.S. Patent 10,323,511 B2. Dual rotor pulser for transmitting information in a drilling system. Alexandria, VA: U.S. Patent; 2019; 10,323,511 B2.
13. U.S. Patent 5,969,638. Multiple transducer MWD surface signal processing. Alexandria, VA: U.S. Patent; 1999; US5,969,638.
14. U. S. Patent 5,515,336. MWD surface signal detector having bypass loop acoustic detection means. Alexandria, VA: U.S. Patent; 1996; US5,515,336.
15. U. S. Patent 5,459,697. MWD surface signal detector having enhanced acoustic detection means. Alexandria, VA: U.S. Patent; 1995; US5,459,697.
16. U.S. Patent 5,535,177. MWD surface signal detector having enhanced acoustic detection means. Alexandria, VA: U.S. Patent; 1996; US5,535,177.
17. Mason WP. Electromechanical Transducers and Wave Filters. New York, NY: D. Van Nostrand Company; 1942.
18. Seto WW. Acoustics, Schaum's Outline Series. New York, NY: McGraw-Hill Book Company; 1971.
19. Morse PM, Ingard KU. Theoretical Acoustics. New York, NY: McGraw-Hill Book Company; 1968.
20. U.S. Patent 7,082,078. Magneto-rheological fluid controlled mud pulser. Alexandria, VA: U.S. Patent; 2006; US7,082,078.
21. Su Y, Sheng L, Li L, Bian H, Shi R, Chin WC. High-data-rate measurement-while-drilling system for very deep wells. Proceedings of the 2011 AADE National Technical Conference and Exhibition; 2011 April 12-14; Houston, TX, USA. Houston: American Association of Drilling Engineers.
22. Su Y, Sheng L, Li L, Bian H, Shi R, Zhuang X, et al. Strategies in high-data-rate MWD mud pulse telemetry. J Sustain Energy Eng. 2014; 2: 269-319.
23. U.S. Patent 9,850,754. High speed telemetry signal processing. Alexandria, VA: U.S. Patent; 2017; US9,850,754.
24. U.S. Patent 10,145,239. Flow modulator for use in a drilling system. Alexandria, VA: U.S. Patent; 2018; US10,145,239.

25. U.S. Patent 10,156,127. High signal strength mud siren for MWD telemetry. Alexandria, VA: U.S. Patent; 2018; US10,156,127.
26. U.S. Patent 10,273,801. Methods and systems for downhole sensing and communications in gas lift wells. Alexandria, VA: U.S. Patent; 2019; US10,273,801.
27. U.S. Patent 10,808,505. High signal strength mud siren for MWD telemetry. Alexandria, VA: U.S. Patent; 2020; US10,808,505.