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Paper Title: **Development & Application of Versatile and Economical 3D Rotary Steering Technology**

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Abstract
Rotary steering technique has seen a dramatic resurgence driven by the need to design and plan more complicated directional wells. The evolution of directional drilling trajectory control techniques from conventional rotary assemblies through steerable motors to full 3D rotary steering control systems, in addition to the corresponding evolution of survey and logging methods, has been equal to the challenge of these more complex, designer and extended reach wells. However, the development cost and running cost of most of these systems has prevented wide spread utilization of rotary steering technology. The benefits of 3D rotary steering continue to be widely documented, however, its use is being restricted to difficult well profiles: this constraint is the direct result of the high cost of running these systems. The multiple benefits of rotary steering such as smoother wellbores, improved hole cleaning and faster rates of penetration are equally applicable to more conventional directional well profiles.

A simple, lower cost rotary steering system has been developed which will allow the technology to be applied on most directional wells worldwide. The majority of the existing 3D devices are complex and have between 1,800 and 4,000 line item components integrated into a typical rotary steerable system. This new device has fewer than 60 line item components and is fully compatible with any wellbore survey and logging devices. The tool development process was initiated with two objectives in mind; simplicity and drilling system compatibility. Low manufacture and low operating costs were identified as specific design goals, thus making more directional wells accessible to rotary steerable technology. Secondary objectives that were met, included ease of rig operation and remote location serviceability. Field trials of this new system have begun and several specific well applications have now been documented.

Introduction
Modern 3D Rotary Steerable Systems ("RSS") were first commercially run in the mid 1990's with Baker Hughes' development of the Autotrak system and Amoco's pioneering work on a short radius system known then as the "Sidewinder" tool. Since then, various other Rotary Steering concepts have been investigated and several systems are now commercially available. All of these tools are extremely complex. Complexity adds cost which reduces the number of cost-effective applications. This, in turn, stifles the growth of the technology. A new company has developed a lower cost RSS which should dramatically increase the number of available cost-effective applications. The patent, PCT (GB96/00813), J. Chance-S. McLoughlin, was filed in April 1995 describing a gravity-oriented system, which applies internal offsets utilizing an "eccentric sleeve". The development of this system followed an arduous path as an idea and a spark between two individuals, which finally became a functioning RSS.

1. Steerable System Evolution
The benefits of 3D rotary steering began to be documented in the late 1990's with the

introduction of the Baker Hughes Autotrak system. However, rotary control of inclined wellbores has been in practice since the inception of directional drilling. Deflection and control techniques for inclined wellbores have evolved over the years. This evolution (figures 1 & 2) continues as we emerge from steerable mud motor/MWD applications back into complete, 3D, rotary control. Early systems utilized magnetic single shot survey equipment, whipstock and/or jetting technique along with rotary (build, drop or hold) bottom hole assemblies. Later, straight motors and bent subs became the deflection tools of choice to run with these “kick-off” or “correction” bottom hole assemblies. Steering tool, wireline survey techniques allowed for continuous toolface updates prior to MWD evolution of the 1980’s, where slower toolface updates were tolerated to remove electric wireline cable from the drilling operation. Today, surface adjustable bend, steerable motors combined with MWD survey methods allow for deflection and “rotary” drilling from kick-off to TD, with complete 3D control.

Steerable motor deflection and control have proved extremely effective for most directional applications, however, the benefits of 100% rotary controlled wellbore sections are becoming clearer. These benefits include, smoother wellbores, improved hole cleaning and faster rates of penetration. These improvements are primarily the result of removing motor “sliding” from the drilling operation. Several authors have documented the potential hazards of steerable motor drilling and much data and example can be cited where inclined wellbores benefit from continuous drillstring rotation.

Pressure While Drilling (PWD) measurements of the late 90’s confirmed hole cleaning problems while “sliding” with a steerable motor then alleviated through drillstring rotation. 2D rotary stabilizer systems, which control only inclination, brought renewed interest in the late 1980’s to drilling with rotation and restricting the use of steerable motors, especially in high angle and ERD well applications. Elimination of “sliding” with steerable motors, through the use of these 2D stabilizers, worked effectively in many cases where azimuthal control was not critical. However, full 3D control of both inclination and azimuth, with 100% rotation, was not attained until the late 1990’s, with the introduction of RSS.

2. Rotary Steering Basics

Most RSS devices require a stable platform from which to apply an offset or force to the wellbore wall. Typically, they utilize some form of instrumented, “non-rotating” housing as the platform from which to apply the offset or force. “Non-rotating” does not normally mean that the outer “sleeve” device never rotates with the drillstring, but that it is de-coupled from the rotation of the drillstring in such a manner as to prevent actuation mechanisms from having to work at a rate equal to drillstring RPM. We characterize such devices as “static”.

Furthermore, most of the existing 3D RSS use accelerometer packages to monitor the attitude of the platform so that a correct determination on the direction of the force vectors to be applied can be made. Once the housing or platform is stable or stable enough to determine orientation, then a force must be applied to deflect the bit in the desired direction. This is accomplished by applying a force to (sometimes even bending) the mandrel/shaft connected to the bit. Several tools utilize pistons or pads that are forced in/out of the housing in order to supply the deflecting force. Other tools use internal forces that flex the mandrel for a more “point-the-bit” system.

A few devices use alternative methods for deflecting the drillstring and achieving directional control. These tools do not have a de-coupled sleeve type device, with an internal mandrel and they rely upon rapid electro-mechanical actuation to keep the vector forces in synchronization with drillstring rotation. Perhaps unsurprisingly, these tools have high capital and running costs and suffer from maintenance and longevity issues. We characterize such devices as “dynamic”.

The many advantages of RSS are well documented. Examples are emerging where well profiles are being drilled that could not have been possible without rotary steering. Extended reach drilling examples exist that give enormous credit to rotary steering systems. These successes are made possible primarily due to these systems' ability to provide 100% drillstring rotation while maintaining accurate 3D directional control.

3. Existing Systems/Complexity

Most RSS existing in the market today are extremely complex. The engineering and science used to develop these tools is truly outstanding and a marvel to watch in action. They are not, however, without faults. Several examples exist in recent publications whereby the RSS performed as per the required task but trips were required due to failure. Such is the price of progress. These systems provide for two-way communication, variable "bend/push" control and include directional package feedback circuitry with auto correction software features. These are indeed interesting and complex systems. Unfortunately, they are also expensive to build and expensive to maintain, which requires the service company to charge enormous dayrates in order to make the system financially feasible. This forces the tools into a niche market of the most difficult wells where complex well engineering and favorable economics dictate a requirement for a rotary steering system. Most likely, if a piece of drilling technology is applicable in an extended reach well, it is probably – if the price is right – equally applicable to normal directional wells.

The fallout in this market place is tremendous. Our research has shown that over 25 devices have been patented on the broad subject heading of rotary steerable systems. Of those patents, attempts have been made to build approximately half of those tools. Of those 12 efforts, approximately half died at the laboratory or field trials phase of operation. The final 25% are proceeding with their commercialization plans and enhancements. Enhancements typically take the form of (1) simplification – we understand that one service company has reduced its parts count by over half, (2) improvement – performance or cost reduction, e.g. the RST development had 22 major design changes between prototype and "pilot"series (3) size reduction and expanding the capability of a particular tool, e.g. one tool with valve mechanisms has issued four patents on valve improvements which coincide with their field findings, thus expanding the range of drilling fluids which can be used with it.

Of particular interest may be the observations we have made and lessons we have learned to date: complexity is fine – but it comes with a cost – capital and also in terms of reliability. A VW bug will get you there a lot cheaper than a Ferrari. Simple is good! Modularization is difficult to design and very difficult to implement. Keep the design integrated. There will be less software and hardware difficulties. Protocols will not need to be the downfall of the design. What works in the lab might not work downhole. Our experience suggests that when the design gets to look too complicated, it probably is: there are only three elements to a design (1) what shape it is (2) what material it's constructed from and (3) what tolerance that particular part has. So, it's really quite simple.

The ability to rotate the drillstring 100% of the time, while maintaining complete 3D control over inclination and azimuth, is a benefit to ALL directional wells. Elimination of "sliding", improved hole cleaning, faster rates of penetration and smoother well profiles are benefits that are equally applicable to all directional wells. Industry attention is now turning to using RSS for applications other than ERD wells. However, high system running costs are preventing widespread adoption and utilization of the technology. The requirement then, is for a RSS that performs this basic ability, but is not complicated by other, non-essential functions.

4. Tool Development Process

A tool has been built, following an arduous development process, which meets the requirement for continuous drillstring rotation with 3D directional control. The tool was developed as an enhancement, which loosely used a conceptual "bit-walk" correction tool of the 1970's and the addition of years of experience with more modern directional technology gained in the 1980's and into the 1990's. The patent was filed in

April 1995, combining some unique features into the "bit-walk" tool to make a fully 3D rotary steerable system. Financial, technical, legal and other challenges were confronted daily during the 3 year development process, as an independent team of directional drilling specialists and a bona fide rocket scientist persevered to bring a new and unique technology into commercialization.

The patent described a device that consisted of a weighted housing for creating a stable platform from which to leverage a rotating mandrel which transmits all torque, weight and flow to the bit, and an eccentric inner sleeve or "cam" that causes the mandrel, and thus the bit, to rotate off center thus deflecting the wellbore. Following patent application, the idea was revealed to all of the major directional drilling service providers and many other companies who were potential sources of development funding. An idea with patent pending status did not stimulate huge interest from these companies. The old "not invented here" syndrome also appears to have played a role as most of the major companies were attempting to develop a rotary system in-house. An initial funding in the amount of a $250,000 line of credit was secured from an entrepreneur and industry figure head and started things rolling. The founding partners continued to work as directional drillers to support themselves over the next two years. Funds were spent on further patent fees and a feasibility study. The study confirmed the viability of implementing this technology on a commercial basis. Progress continued at a slow pace, mainly due to the principles working in various parts of the world as directional drillers. Engineering concepts were discussed and cursory evaluations were made to verify engineering validity, but not much meaningful progress was made. Philosophical development ideas were often discuss during this period. Conscientious efforts were going to be made to keep the cost of the tools down and maintain tool applicability to most directional wells. Financial constraint and common sense led to a decision to build the 12-1/4" hole size tool first. A market existed and 12-1/4" tools should be easier to build than other, perhaps more popular hole sizes due to radial space availability. It was also felt that the learning curve would best be served in the 12-1/4" tool size.

A decision was reached in May of 1997 to spend 100% effort progressing the tool development. Deciding to stop employment and spend one's savings on a fledgling tool development project is a difficult decision but one that must be made in order to move the project forward at any sort of acceptable pace.

Progress on development now moved much more rapidly. Besides the need to find additional cash, a never-ending job at start-up, the next step involved the engineering and development of "machine-shop" drawings. The oilfield of 3rd quarter 1997 was booming and finding engineering assistance on such a fledgling development project proved to be a difficult task. Fate took us to the space industry where we were able to find extremely talented and innovative engineers who had time to work on an oilfield product. This is where great efforts were expended aimed at keeping costs down. Material selection, maintenance considerations, "off-the-shelf" vs custom component selection were just a few of the areas that were constantly worked in order to keep the capital and running cost of the system down. The tool was to be developed as simply as possible with a focussed effort to keep in mind future field operations and the ultimate application of the product. Every angle of future field operations was analyzed to make sure that what was ultimately developed would be field applicable. Very few efforts were expended to increase tool functionality, as the requirement of 100% rotation with accurate directional control was the primary focus.

Actuation mechanisms including, but not limited to, hydraulic, electronic, linear and ballscrews were discussed and evaluated. Cam configurations, power requirements, electronic system and sub-system logic control mechanisms and high temperature components had to be selected. Bearing selection was treated with extreme care and advanced testing, some in conjunction with bearing manufacturers has been implemented in order to improve longevity and enhance reliability.

Downhole power sources and battery packaging received a great deal of attention. Directional engineers worked closely with electronics experts to provide seamless rigsite operational characteristics. Saving rig time was of paramount importance and a patented frequency modulated communications method was established which provided for communicating toolface accuracy to within 2 degrees within a 3-1/2 minute time frame. Problematic drilling scenarios were also considered; differential sticking was discussed and the tool was configured to be short in length with minimal contact area: air-flush and under-balanced drilling was considered as being a necessary environment for the tool to be able to function in and the tool has been designed to be compatible with all existing drilling environments. The major limitation, to date, is temperature, where our electronics confines the tool to a maximum operating environment of 150°C: electronics is now being planned to take this to 175°C.

Above all, the possibility of creating a directional device, which was fully serviceable on the rig-site, with a minimum of specialized equipment, drove the team to create a simple device. The concept of a fully field serviceable directional drilling tool has never been considered until now: the principal limitation being the requirement for bearing pullers and break-out benches. Once the connection on the mandrel on the RST tool has been broken at the rig-floor, the entire tool can be dis-assembled. Full field repair should be possible within 12 hours. This is of particular interest to those operators with operations in the more remote locations.

Early contracts were reached with electronics developers and most suppliers of parts. This enabled accurate predictability of ultimate manufacture cost and ensured low repair and maintenance cost. Specific modifications to design were made to specifically enhance field serviceability and to keep the cost of repair and maintenance down. One significant modification to the inner sleeve simultaneously reduced tool oil volume while also allowing field interchangeability of dogleg severity through rig changeable eccentric sleeve offsets placed at alternate ends of the inner sleeve. Electronics and batteries were packaged for easy access without breaching the tool's oil reservoir. Mandrel bearings were packaged to allow field accessibility. Circuitry was engineered to prevent battery drain while waiting for the tool to be picked up on the rig. The ultimate "field friendliness" and robust nature of the tool was the product of detailed examination on field applicability at all steps along the way.

Two prototype tools were assembled and bench tested in January of 1999. All downhole tool designers understand that a tool functioning perfectly on the bench does not translate into perfect functionality downhole with either reliability or application. We strongly felt that before placing the tool into a commercial wellbore, we needed to confirm general reliability and demonstrate actual robustness of the tool in a realistic downhole environment. Initial downhole testing was completed in February of 1999 at the Amoco Catoosa test facility. Enough footage was drilled in relatively hard drilling conditions to verify basic tool functionality, determine that the tool had some degree of survivability downhole and encouraging data was obtained regarding directional response.

In late June of 1999, a major operator contracted RST to run the tool in the first ever commercial application of the technology. Twelve runs on six wells, with various operators, were ultimately completed with the prototype technology, and during this time, work commenced towards identifying failure modes and implementing solutions. These solutions would ultimately be incorporated into the next, "pilot series" version of the tool. Protracted negotiations were begun in January of 2000 with a machining and tool manufacturing partner to finance and build eight of the improved "pilot" tools. 22 major design changes were implemented in the new design, some obvious, some not so obvious Several scheduling and manufacturing hurdles were overcome during the manufacturing process, ultimately delivering the first pilot tools in November 2000. Eight tools have now been manufactured for commercial application.

5. System Functionality

RST's RSS provides a basic tool offset function in a compact, reliable package. The package is fully compatible with all other downhole drilling tools and functions and poses NO LIMITS to normal drilling practices, or the optimization of drilling parameters. It is probably the only directional drilling tool which can claim this. The functionality of the tool is such that it dovetails extremely well with existing drill-floor jargon and operations and thus is easily integrated into the rig environment - this leads to rapid acceptance of the RST tool on the part of the drill-crew and the directional drillers.

This basic functionality can be combined with other, high tech BHA equipment in a "fit-for-purpose" application. The tool consists of a "non-rotating", gravity oriented "smart sleeve", through which a rotating, load bearing, mandrel runs, connecting to the bit and drillstring. (Figures 3 & 4) The mandrel is isolated from the "smart sleeve" by axial and radial bearings. Bearing isolation is important in order to allow the smart sleeve outer housing to create a stable platform from which to deflect the drillstring.

The "smart sleeve" has an eccentric inner sleeve which, when rotated relative to the weighted, outer housing, will offset the mandrel in a specific toolface direction. Smart sleeve is buffered axially through shock absorption mechanisms and radially though the use of marine grade bearings.

This toolface direction is communicated to an electronics package via simple rotary command communication on demand. The command sequence takes a constant 3-1/2 minutes and takes place with the pumps on, while simultaneously reciprocating and rotating the drillstring – the lessons in differential sticking learned from stationary MWD surveying were very well learned and understood. The tool can be instructed to offset the mandrel in a preferred specific toolface direction or commanded to enter preset programs, where the tool cycles through a series of changing toolfaces. These programs are used to break dogleg severity trends of oriented drilling to precisely maintain a prescribed directional plan.

Mechanically the toolface is oriented by actuating movement of the inner sleeve/cam assembly via rotating a ring and pinion gear system which locks/unlocks the eccentric sleeve to/from the weighted, outer housing. A brushless DC motor powered by lithium C cell batteries rotates the pinion gear. Oilfield application of these small, high powered electric motors is relatively new, however, an all industry feasibility study conducted by 12 major operators in 1995 proved their viability and several resulting downhole applications have recently proven successful.

The tool is designed to be completely field serviceable. We recognized early in the tool development that the remote nature of the drilling business, where service facilities are scarce and the cost of transportation is high, demanded a tool that requires little, or preferably no maintenance. Accordingly, much of the design effort was focussed on the ability to service the tool in the field. The rig footprint is small, consisting of two tool baskets and a 4 x 8-ft. toolbox. Batteries, electronics, cam sections and bearings are all field serviceable without draining the internal hydraulic reservoir. These constitute the major wear, adjustment and consumable components of the tool. Every external bolt on the tool is encapsulated or backed-up by snap rings, helping to prevent bolt back-off and minimize damage to critical mechanical parts. The mandrel, which transmits all the torque and weight to the bit, rotates in marine grade radial and thrust bearings that are rigsite replaceable. The mandrel is a two piece assembly that is coupled by a Grant Prideco XT39 connection: this is a modified stub-acme profile, which gives high-torque loading characteristics and high reliability in the field.

The tool electronics and batteries are housed in the non-rotating, weighted housing. This means that the electronics assembly is not subject to centrifugal forces during drilling, and provides the electronics with a much smoother ride. In addition to receiving surface RPM commands and driving a motor to control cam orientation, the electronics also record large amounts of diagnostic data. Many diagnostic parameters including motor current, battery voltage, and housing orientation are recorded. Once back at the surface, this information is downloaded to a laptop computer for on site and post-job analysis.

6. Versatility

The tool may be run as a "stand-alone" system, requiring only the simplest of survey methods to monitor hole position, or the tool may be combined with other downhole technologies for an effective high tech, fit-for-purpose system. The largest interest in tool application has been for elimination of steerable motors on wells where sliding is next to impossible and/or extremely time consuming. These include the larger reach, more expensive offshore wells.

The tool is remarkably versatile in configuration, the eccentric inner sleeve cams, that offset the bit, may be placed in a variety of positions on the tool. Thus the tool may be configured, as a more "point" system by placing one offset cam at one end of the tool, with the other end being formed around a "concentric" cam section, or it may be configured as a more "side-force" system by placing offset cams at both ends of the tool. Other variables may also be used to effect tool response, such as, bit type, stabilizer gauge, stabilizer position and drill collar rigidity.

Extensive efforts towards developing a BHA model are ongoing as of Q1 2001 which will more precisely determine the optimum configuration for any given application. These efforts should also more closely define the operating envelope of most effective tool operation. A major operator in Houston is undertaking these efforts on our behalf.

7. Data & Application

The first commercial application opportunity was drilled in July 1999 for a major operator, offshore California, after only three previous, short, test runs of the prototype tools at the Catoosa test rig facility. One of the biggest challenges on this ERD well was directional control of a long, 12-1/4" tangent interval. The 15,000 interval would traverse several formations with varying degrees of drillability. The well would reach a point of "negative weight" approximately 1/3 of the way into the tangent interval, making sliding a motor difficult, if not impossible. The operator ran rotary assemblies, with adjustable gauge stabilizers and specialized bits to control both inclination and azimuth for several thousand feet with success. The wellbore drifted right and the rotary steerable tool was placed in the hole at a toolface position of 60 degrees left of high side, the tool drilled 125 ft., turning and building the wellbore at 3.1 deg/100 ft. The RST tool was used to drill a further 493-ft., gathering tool response and diagnostic data, confirming the tool's ability to steer a wellbore in three dimensions. (Figure 5)

Additional high angle runs, offshore, in commercial application, have confirmed good lowside orientation of the outer housing. Data from high angle wells shows 15 degrees average housing roll in the direction of drillstring rotation. Ongoing bearing improvements should enhance housing stability and increased run experience will allow for the user to compensate for housing roll when setting toolfaces. We are not sure yet of the lower limit of hole angle at which weighted, outer housing orientation will remain effective. Current thinking is that 40 degrees will provide confident lowside orientation and enable effective toolface control. Figures 6 & 7 show examples of reliable housing orientation while drilling in two 80-degree wells.

The tool has proven robust, however, during the prototype runs, untraceable alteration of the cam position with respect to the outer housing was observed. A phenomenon, which was given the name "backdrive", was observed where the mechanism lost its toolface orientation slowly, over several hours of drilling. Data recovered from the prototype series runs showed this to be an extremely slow process. We had no quantitative data to prove the forces that were encountered downhole, and we assumed that vibration or very high drilling forces were causing the problem. The problem was that the tool would become "lost" during drilling, and would not recognize that it was not in the correct orientation. This was explained by one of our clients' drilling supervisors as the "tool having Alzheimer's". We subsequently altered the software to detect this movement and automatically correct for any unauthorized movement during drilling, i.e. the system self-checks and corrects for any unwanted orientation deviations. Figure 8 is data from downhole demonstrating detection and automatic correction of the movement.

In addition to the electro-mechanical problem highlighted above, a purely mechanical issue concerning the bolt pattern and load spread of the downhole electric motor lead us to reconfigure the motor "footprint", change the bolt type, length and head configuration No problems have occurred with the transmission on any of the initial four pilot tool runs.

Figure 9 demonstrates downhole commands issued through rotary control at surface. Note the mandrel RPM changing with time, followed by the toolface angle changing position while still downhole. We have been over 85% successful at communication downhole. The figure shows examples of these commands being given and detected at over 21000' MD. Inclination, CAM positions and outer housing orientation are all recorded in downhole memory. Future tool versions may include a simple MWD tool, still fully compatible with all other MWD/LWD systems, that transmits these three measurements. This would provide real-time, positive indication of toolface position and directional response.

Figure 8 demonstrates Inclination & Azimuth data changing predictably with changing toolface orientation of the tool. The tool is shown entering one of the preset toolface programs and cycles through 3 rotations of 360-degree variable toolfaces. Note the inclination and azimuth data changing predictably with toolface setting. The magnitude of the changing dogleg is proportional to the cam offsets, which are selected prior to running in the hole.

Conclusions

The benefits of rotary steering wells are now well documented. Elimination of motor "sliding" has many advantages – both tangible and intangible. These benefits primarily exist because rotary steering systems allow for continuous pipe rotation with accurate 3D directional control. However, most RSS available today are complex, expensive systems. One recent assessment indicated that only 15% of the North Sea offshore rigs could afford to run a rotary steerable system. This limits the use of rotary steering technology to only the more expensive wells which "require" the technology. It also serves to stifle widespread use of the RSS's , prolonging the use of steerable motor technology. A new company has designed and built a less complicated commercially available rotary steerable system in 12-1/4" hole size.

The design process began out of a previously proven "bit walk" technology of the 1970's and incorporates many of the newer downhole technologies of the 1990's. A small, focussed team of directional drilling specialists and engineers persevered against slim odds to bring the technology through design, development, testing and into commercialization.

The tool is simple, combining less than 60 components into a unique package for an effective, low cost rotary steering alternative. Data shows the tool to be effective at controlling inclination and azimuth in high angle wells. The simplicity of design, low maintenance costs and remote service capability combine to make the system economically feasible for most high angle directional wells around the world.

Acknowledgements

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Nomenclature

3D = three dimensional
2D = two dimensional
RSS = rotary steerable system(s)
PCT = Patent Cooperation Treaty
MWD = measurement while drilling

PWD = pressure while drilling
BVI = British Virgin Islands
RST = Rotary Steerable Tools (the company)
BHA = bottom hole assembly
RPM = revolutions per minute
TD = total depth
ERD = extended reach drilling

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Drilling Tool Type	Deflection Tool Type	Well Inclination	Survey Method
D500 Single-Lobe Motors	Bent Sub	25-35 deg Type I, II, III Wells	Singleshot
Multi-Lobe Motors	Bent Sub	25-55 deg Type I, II, III Wells	Steering Tool
Steerable Motors	Adjustable Bent Housing	25-90 deg Type I-III & Horizontal Wells	MWD / LWD
Dynamic Rotary Steerable Tools	Pistons or Paddles	25-90 deg Type I-III Horizontal & ERD Wells	MWD / LWD
Static Rotary Steerable Tools	Circumferential Forces	25-90 deg Type I-III Horizontal & ERD Wells	MWD / LWD

Figure 1

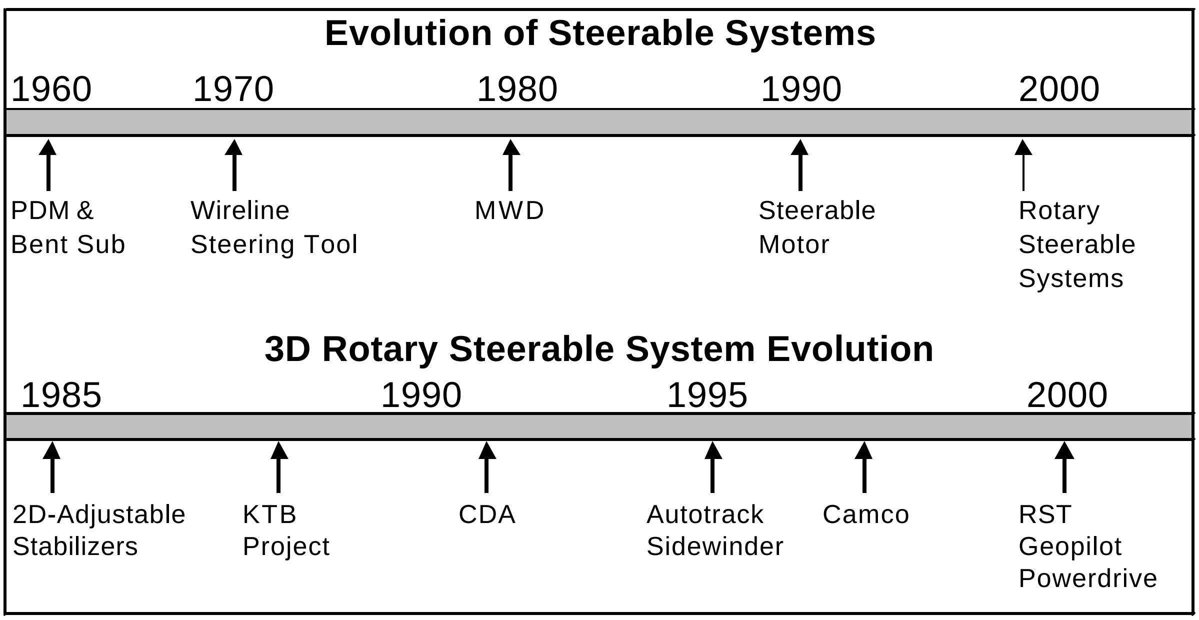

Figure 2

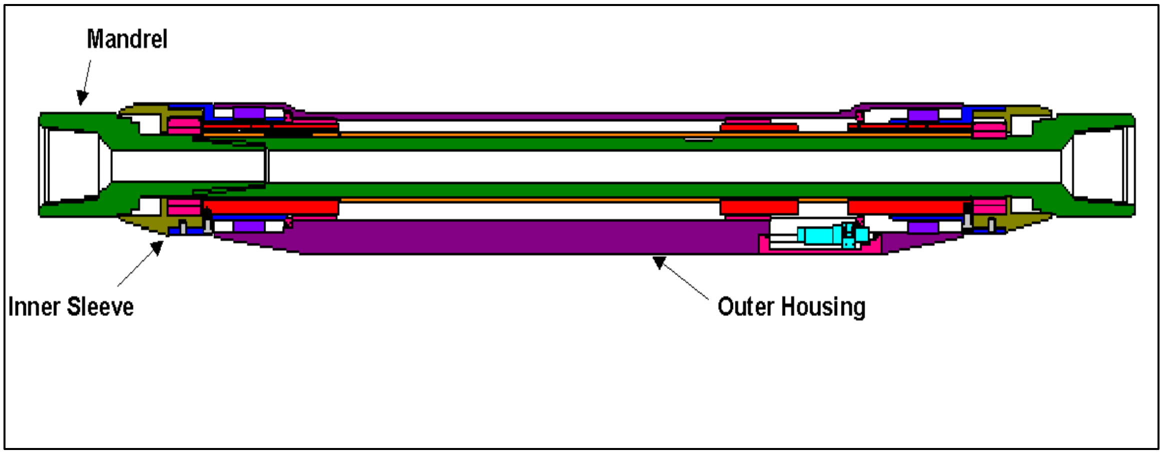

Figure 3 – RST Schematic

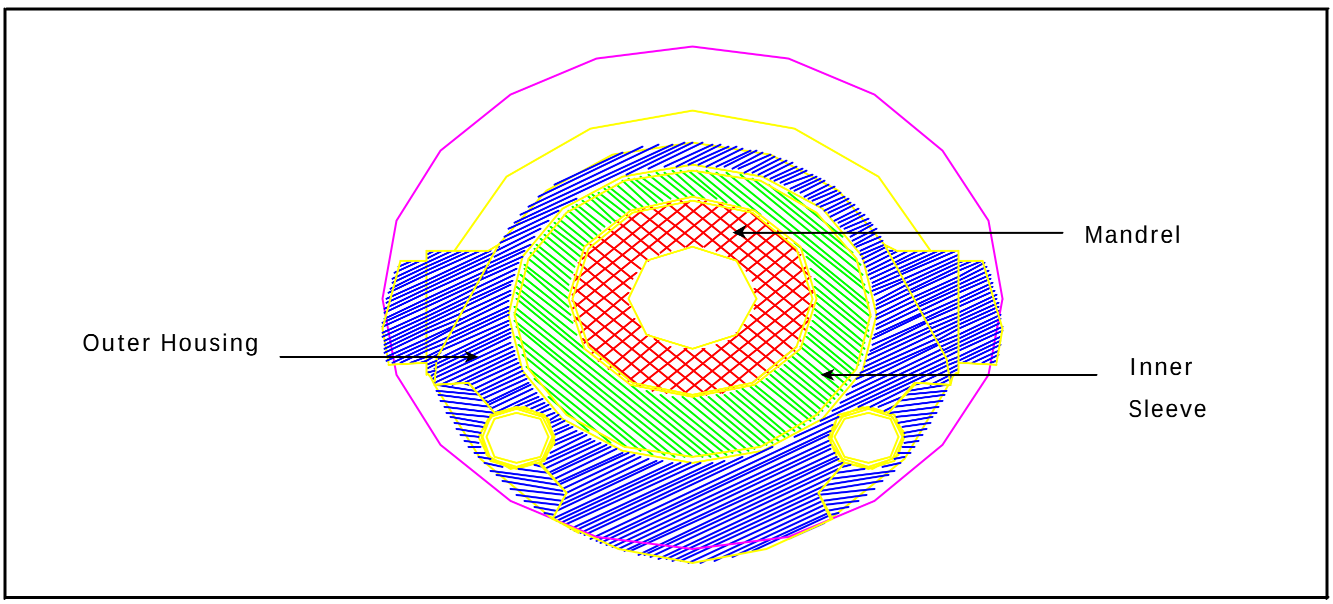

Figure 4 - RST Cross Section

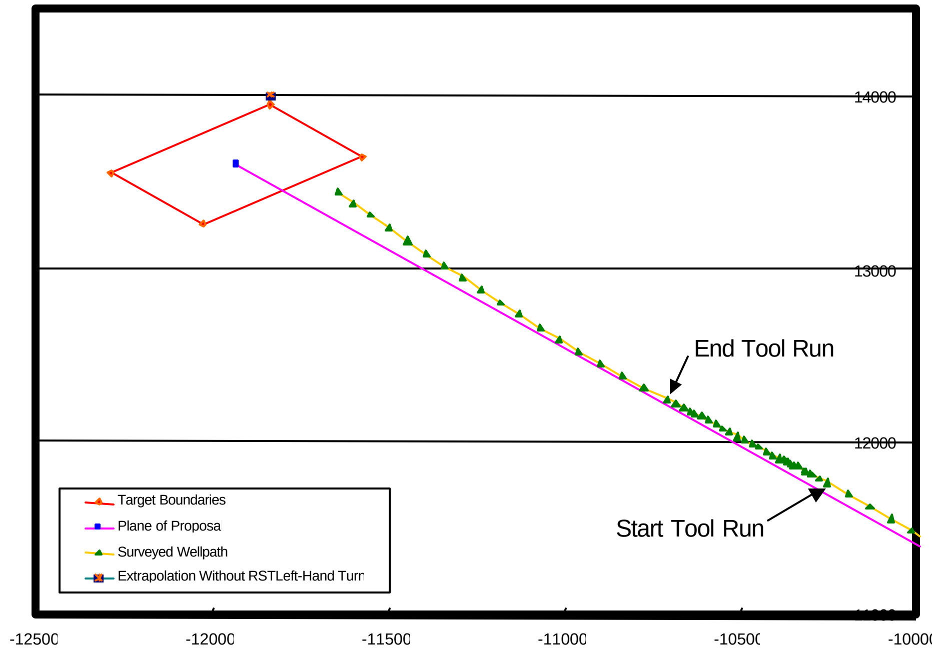

Figure 5 - Confirmation of Left Hand Turn Imparted by RST Tool

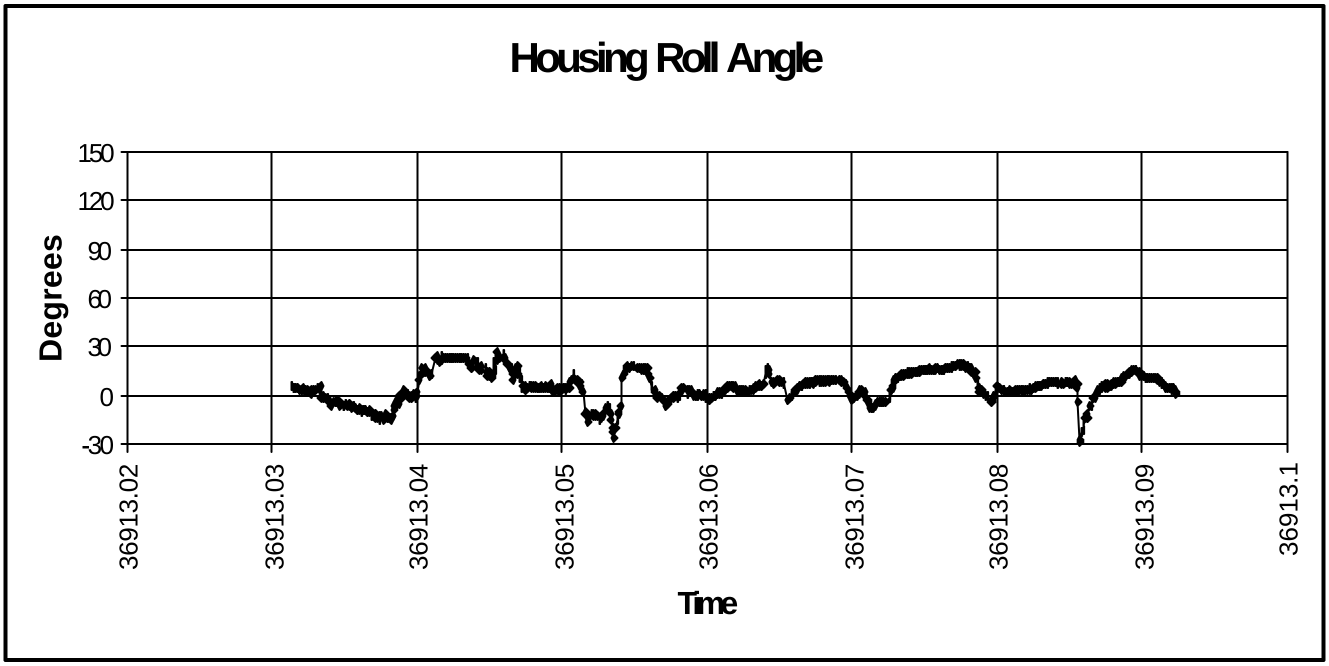

Figure 6

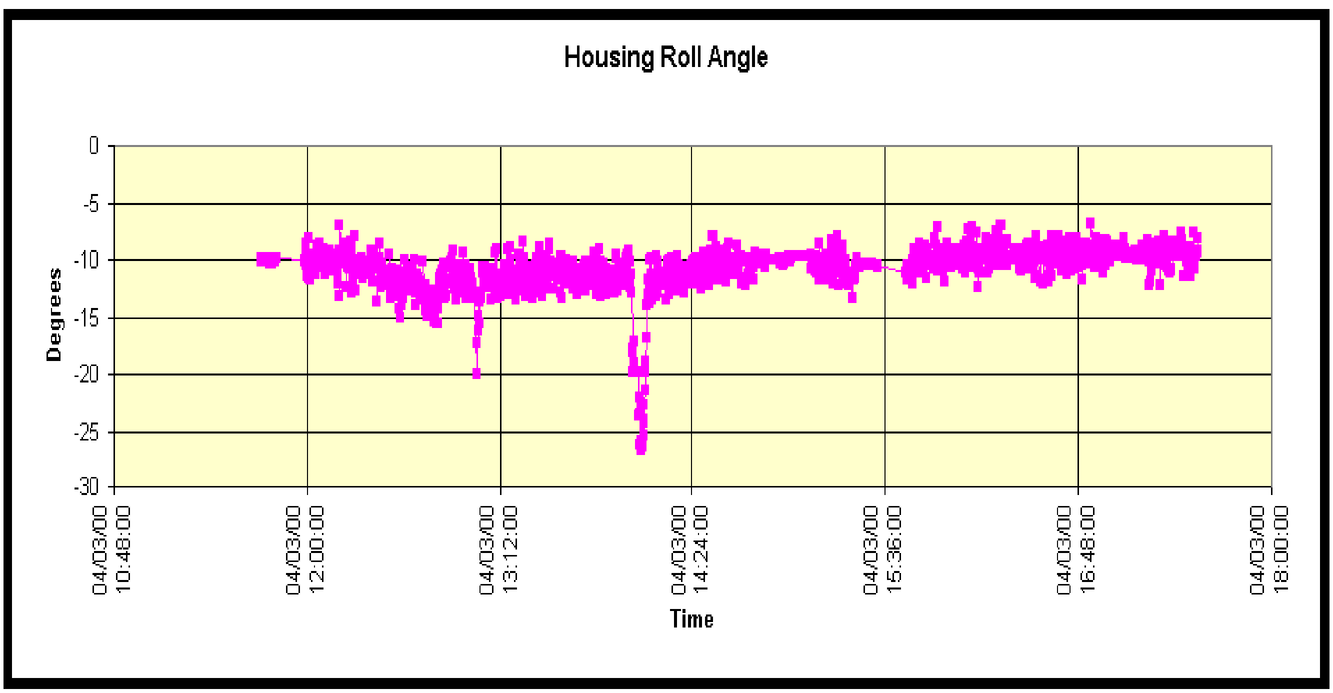

Figure 7

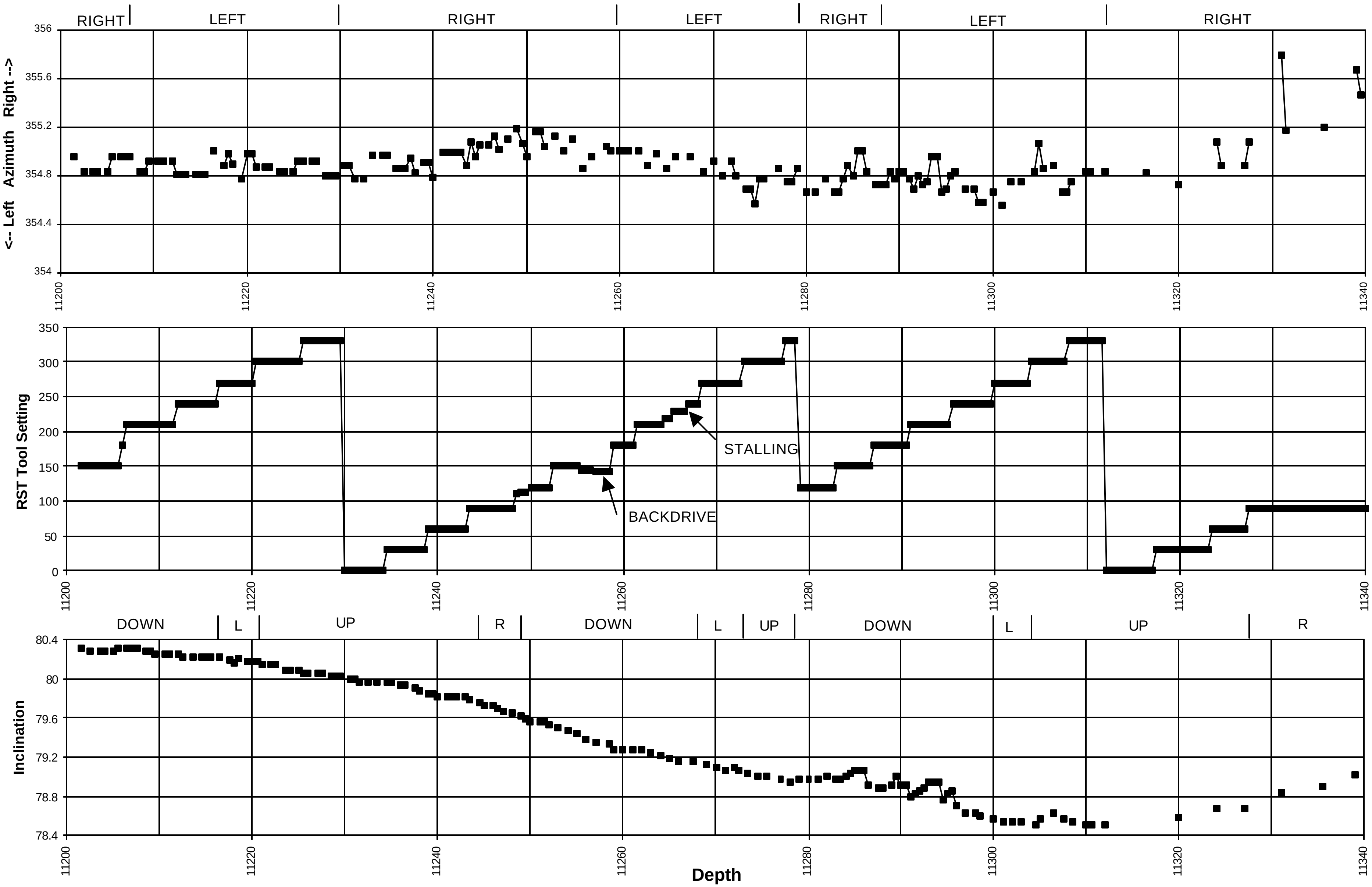

Figure 8 Auto-rotate Data Showing Wellpath Following Toolface Setting

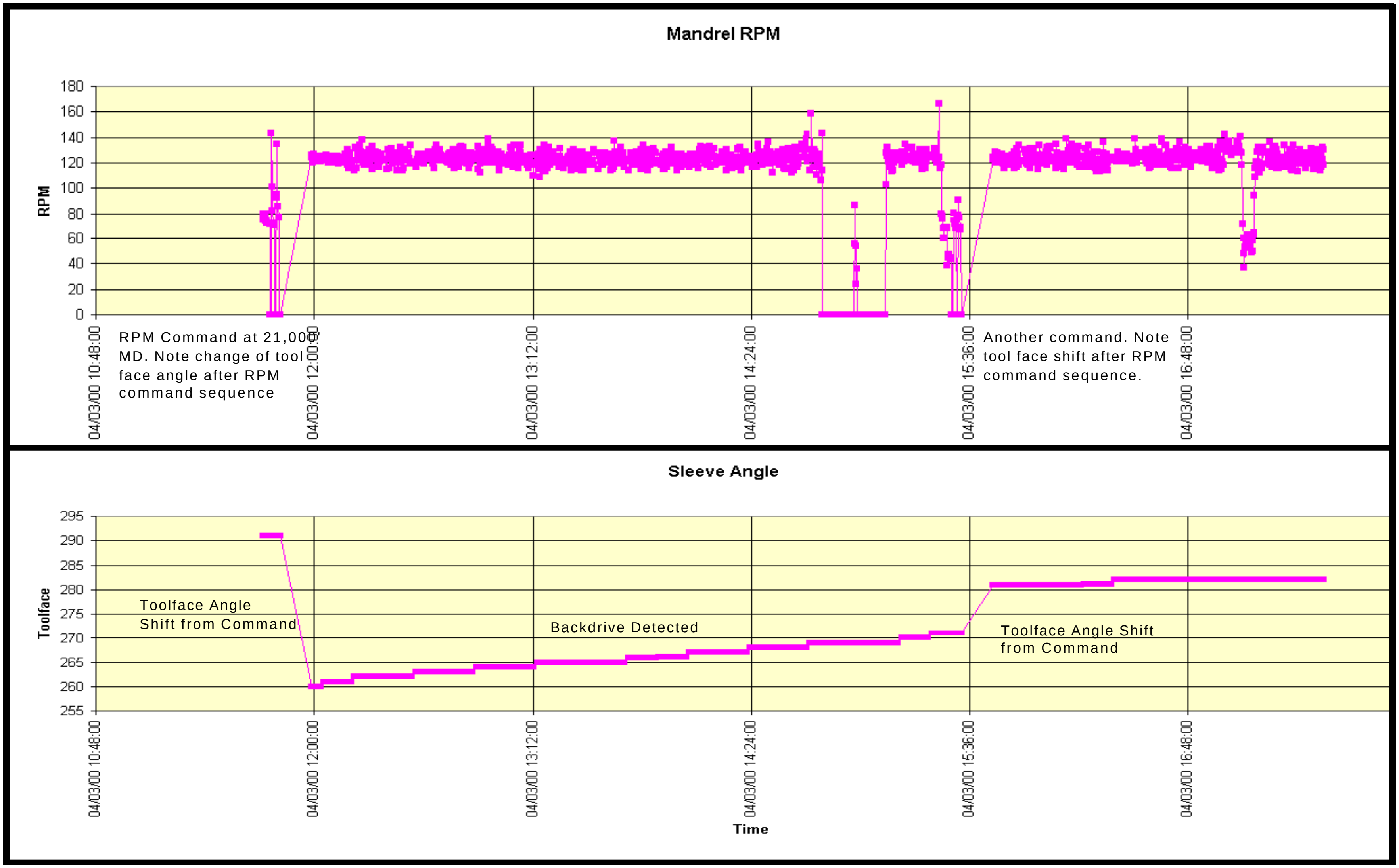

Figure 9 - Toolface Angle Shifts in Response to RPM Commands