55th General Meeting
30th & 31st of March 2022
Virtual Conference

Wellbore Positioning Technical Section

The Industry Steering Committee on
Wellbore Survey Accuracy (ISCWSA)

Inertial Navigation:
For Precise Wellbore Survey

Or - “Back to the Future”

Current Applications We Serve With INS:

Metrology – remote or manned

Marine construction – field development, optimal survey solutions

Subsea survey and positioning – buoy set, out of straightness, sparse LBL

Land survey – seismic, civil engineering

Dynamic Positioning (DP) – tightly coupled system integration for deep water HP/HT drilling

Well Bore Survey – Pure inertial navigation, data logging and re-processing

Near Term Technology Developments:

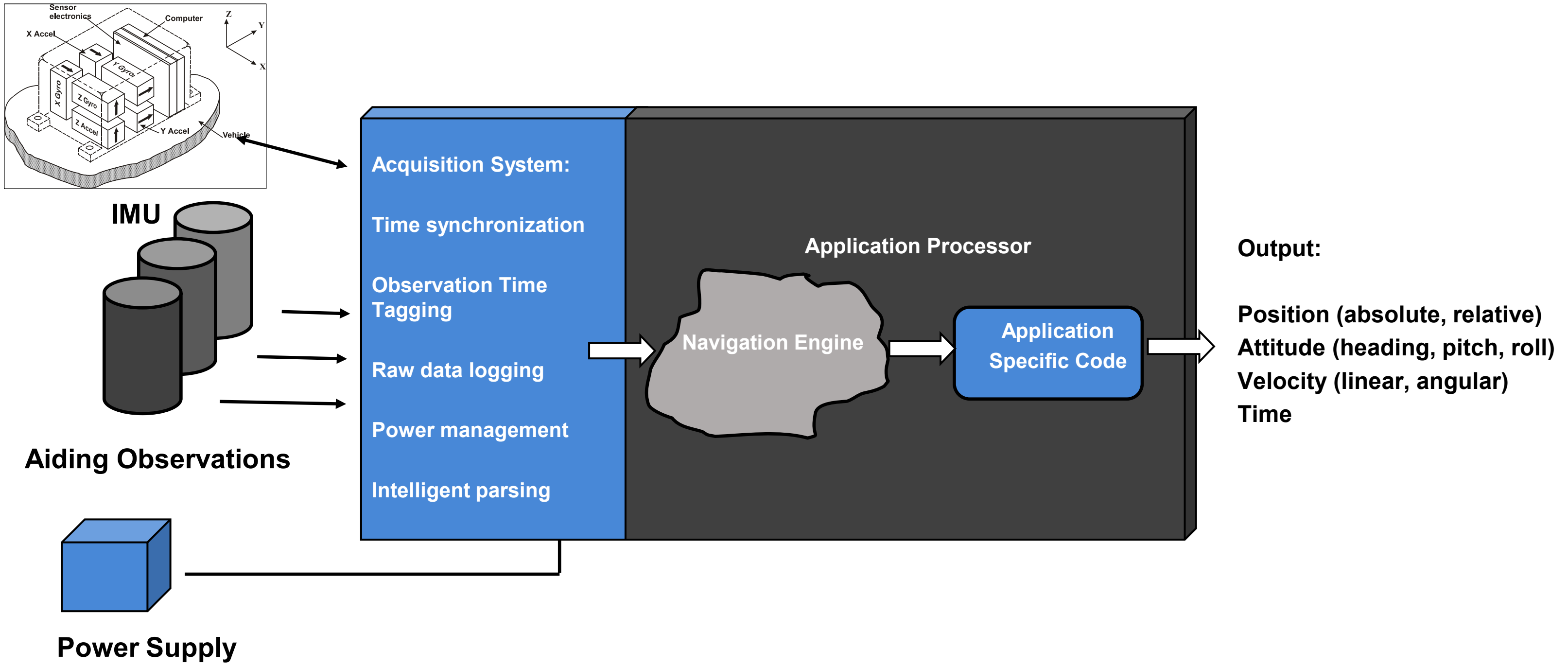
Inspection, Repair, and Maintenance (IRM) – pipeline inspection, asset inspection

Asset Integrity Management - automated change detection through life of field

Augmented reality – automated feature/location detection and identification

Application Knowledge

Zupt has a fully mature, tightly coupled "Navigation Engine" – we refer to this as "EQ":



Navigation Engine

Sensors

The sensors we have or are currently interfacing into a version of our navigation engine (EQ):

Inertial Sensors:

RLG – Sagem Sigma 30/40, Kearfott T24/T16, Honeywell GG1320, Northrop LN100, Thales, etc.

FOG – Northrop LN270, Optolink, Fizoptica, Tamagawa, GEMRAD, Civitanavi, iXBlue, etc.

DTG – Atlantic Inertial, Kearfott, Northrop G2000, etc.

HRG – Sagem/SAFRAN, Northrop (Delco), etc.

MEMS – Analog Devices, Honeywell, Silicon Sensing, Sensonor, MEMSense, XSENS, Microstrain, Advanced Navigation, Physical Logic, etc.

Aiding Sensors:

GNSS – Generic GNSS, C-Nav 3050, Veripos LD5/LD6,

USBL – Sonardyne Ranger, Scout –Kongsberg HiPAP 502, 352(P)

DVL – Teledyne RDI Workhorse/Pioneer, Nortek DVL1000, Rowe SeaPILOT, LinkQuest Navquest

LBL – Sonardyne 6G, 6+, Mk5, Kongsberg cNODE/Cymbal, Proserv NASNet

Depth – Paroscientific Digiquartz, Keller AG PA10LX, strain gauge

Image – Sony Pregius sensors, Laser line

LiDAR – Hesai, Waymo, Oyster, Slick, etc.

Ferranti Inertial Navigational Directional Surveyor - FINDS

Baker Hughes INTEQ ~1979

Advantages:

1,000:1 accuracy - actual accuracy is operator dependent;

Disadvantages:

Tool diameter 10 5/8”

13-3/8" casing and larger;

No downhole communications

Battery powered

Temperature limited

The system only measures North, East and Vertical. Along hole depth, inclination and azimuth have to be back-calculated using a method which may introduce uncertainties

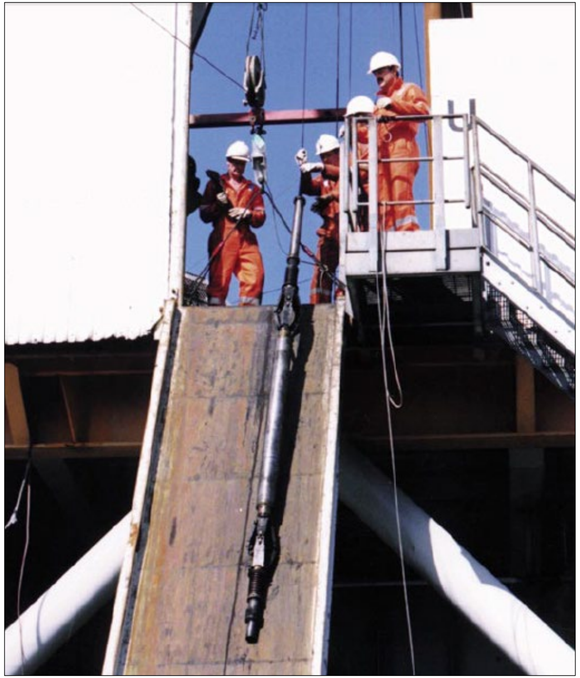
Way back when – “FINDS”

Ring Laser Inertial Guidance Surveyor (RIGS) - Baker Hughes INTEQ 1990's

Cable aided inertial navigation

RIGS Specifications	
Diameter	5.25 in (13.3 cm)
Length	14.8 ft (4.51 m)
Temperature Rating	212 °F (100°C) [302°F(150°C) for 1 hour from 77°F (25°C) start]
Heatshield 5.875" O.D.	18,000 psi at 500°F (1,241 bar at 260°C)
Pressure Rating	15,000 psi (1,034 bar)
Heading Alignment Time (+/-.15 degrees true north)	10 minutes 30 degrees latitude (24 minutes 70 degrees latitude)
Maximum Inclination	No Limit
Maximum Acceleration (linear) (angular)	+/-4G (1,700 degrees/second^2)
Maximum Shock to Interrupt Navigation	>4G >80 m seconds
Maximum Latitude	80°
Cable Length Accuracy	0.5 ft/1,000 ft (0.15 m/ 305 m) surveyed
Total Weight	412 lbs (187 kg)
Total Volume Displaced	1.33ft^3 (0.0377 m^3)

Accuracy: Under typical conditions of tool operations, the RIGS system will yield uncertainties of 1-2 ft/1,000 ft (0.305-0.61 m/305m) of hole surveyed, with a maximum of 2.6 ft/1,000 ft (0.905 m/305 m) at horizontal.



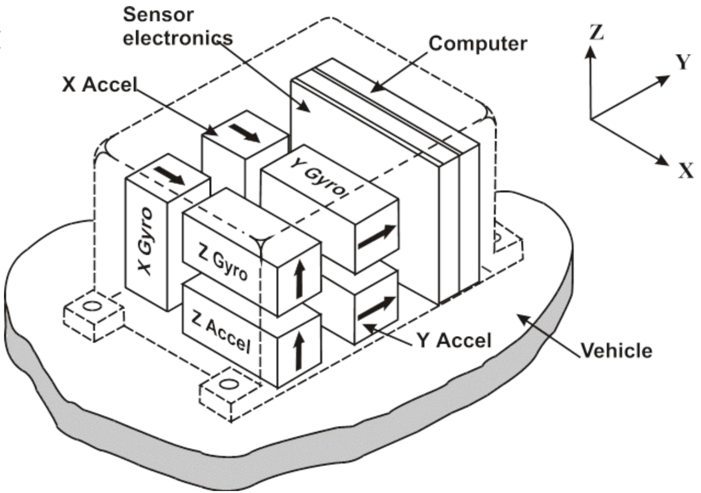
Also – way back when – "RIGS"

Strapdown inertial navigation systems are constructed with:

Three angular rate sensors or gyros

Three accelerometers

Sensor electronics and a processor

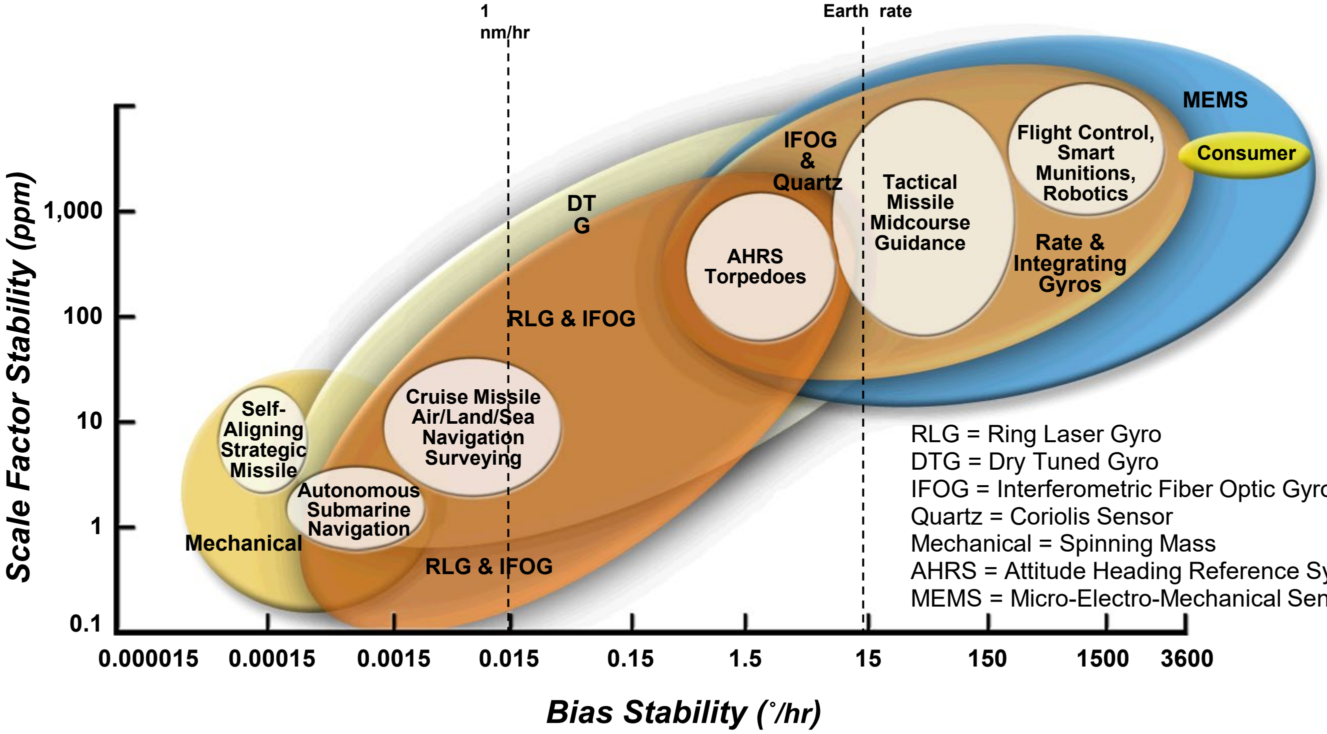


An IMU is an Inertial Measurement Unit – outputs raw rate and acceleration

An INS is an Inertial Navigation System – outputs position, attitude, velocity

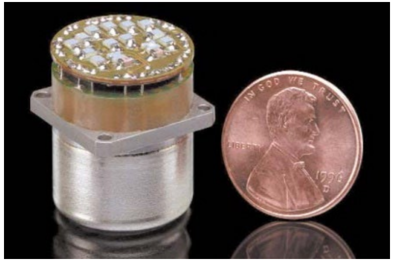
An INS is an IMU with more signal conditioning and processing

A Basic Strapdown Inertial Navigator



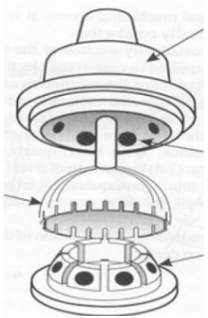
RLG = Ring Laser Gyro
DTG = Dry Tuned Gyro
IFOG = Interferometric Fiber Optic Gyro
Quartz = Coriolis Sensor
Mechanical = Spinning Mass
AHRS = Attitude Heading Reference System
MEMS = Micro-Electro-Mechanical Sensors

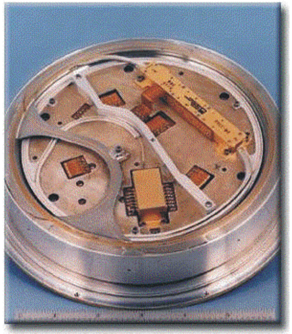
Courtesy of Draper Labs

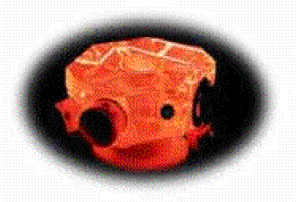


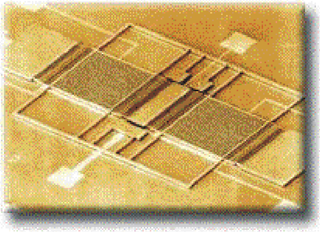
Mechanical, spinning mass or "rotor" gyro (DTG)
Commonly used in well bore survey
(Northrop, Honeywell, Kearfott, UTC Aerospace, Gyrodata and many others)

Vibratory/Resonant (HRG)
(Systron Donner, SAFRAN Sagem, Murata, Northrop, UTC Aerospace)









Optical – Ring Laser Gyro (RLG) and Fiber Optic Gyro (FOG)
(Honeywell, Northrop, Kearfott, iXsea, Sagem, etc.)

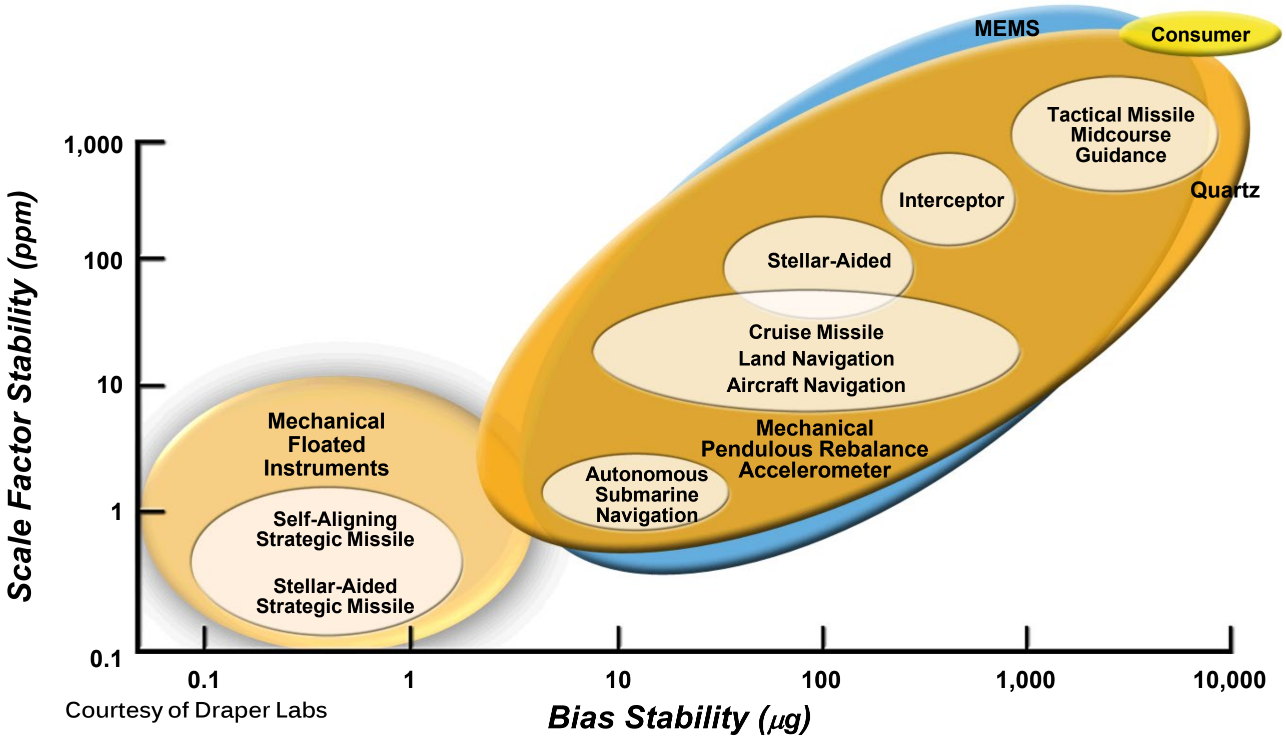
Pros Rapid reaction and turn on(<1s)
Ideally suited for strapdown operation
No moving parts - very rugged

Cons Performance increases with baseline
RLG is a high voltage device
FOG can be temperature sensitive

Micro Electro Mech. Sensors (MEMS)
(Draper/Honeywell, Northrop, JPL, BAe, AD, Bosch, etc. etc. etc.)

Pros Very small
No moving parts
Very low cost

Cons Higher precision still under development
Limited performance range (only for a while)
Bias stability – very difficult to model all errors across temp range.



Courtesy of Draper Labs

Force Rebalance Accels - Honeywell Q-Flex, Northrop Grumman A4, Kearfott Mod

Pros
- Highly reliable - relatively low cost
- Wide bandwidth
- Low bias error

Cons
- Analog output
- self heating under changing acceleration
- Power consumption

Pendulous Rebalance Accels. – Draper design made by Honeywell and Northrop

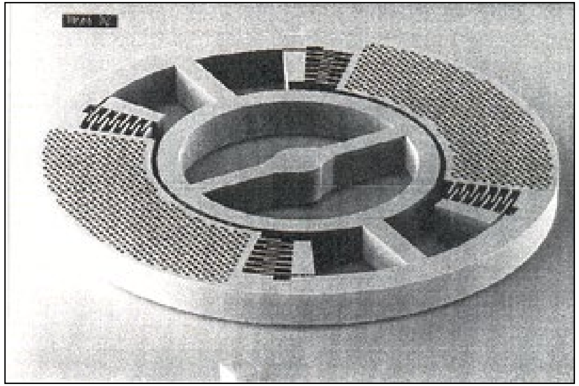
Pros
- Reliable, rugged, small
- Well understood error model
- Pendulous Integrating Gyro Accel. (PIGA) as good as it gets used for ICBM and general missile guidance

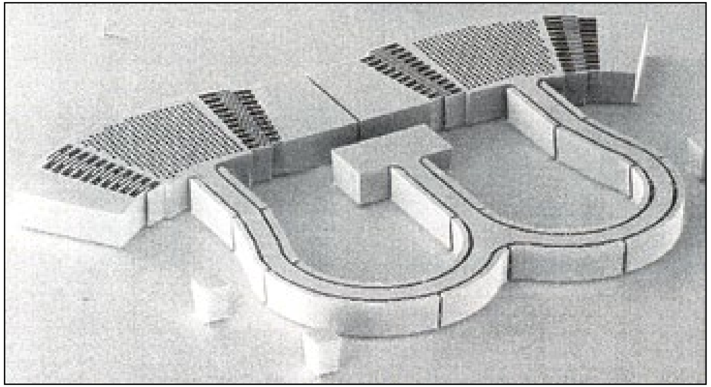
Cons
- PIGA – Cost

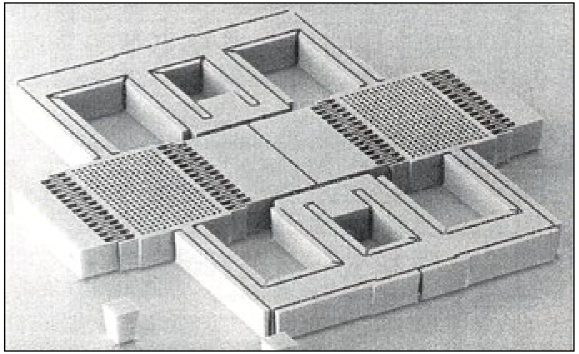
Resonant Element Accel. Sundstrand, Allied Signal, Adkem

Pros
- Digital output
- Low power

Cons
- Not good in high shock environment
- Detailed calibration required







Critical photolithographic manufacturing process in silicon wafers.
Noise is the challenge.
Adding very high-speed DSP processing around the core sensor is allowing significant improvements

MEMS Technologies

The performance of an INS is usually rated in terms of its position error growth rate once the INS is navigating in *free inertial* mode (no aiding).

The USAF defines INS in the following manner*:

INS Classification	Position Error Growth Rate	Heading Errors	Inclination Errors
Low (Tactical)	> 2nm/hr	>0.2°	>0.1°
Medium (Navigation)	0.5 to 2nm/hr	0.05 ° to 0.2 °	0.02 ° to 0.1 °
Precision (Strategic)	<0.5nm/hr	<0.05 °	<0.01 °

Several vendors offer 1nm/day INS – these can be difficult to export

*Following a standard ground alignment at 50 ° or lower latitude – USAF SNU84-1

INS Terminology

The W-PINS project was developed in two phases:

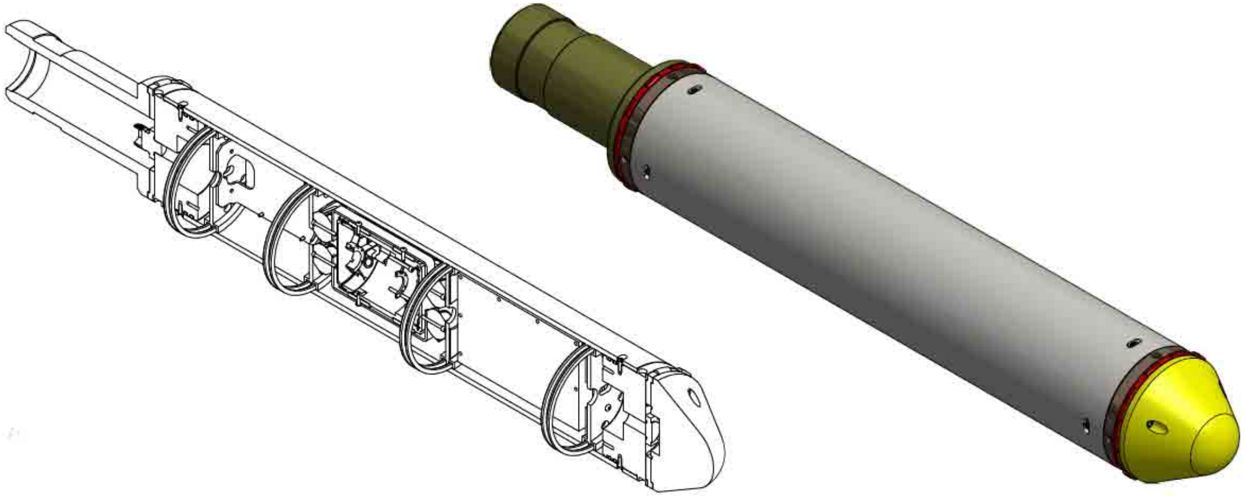
Phase 1 was concept testing:
The conclusion after testing in Phase 1 was that we could reliably meet the target set to position the "toe" of a SAG-D well to within a tolerance of +/- 2m (R_{95}) in the horizontal and within +/- 2m (2 Sigma) in the vertical.

The largest error seen in our horizontal data over a 2.6km round trip was 0.64m (R_{95})

The largest error in the vertical data over a 5km round trip was 1.365m (2σ).

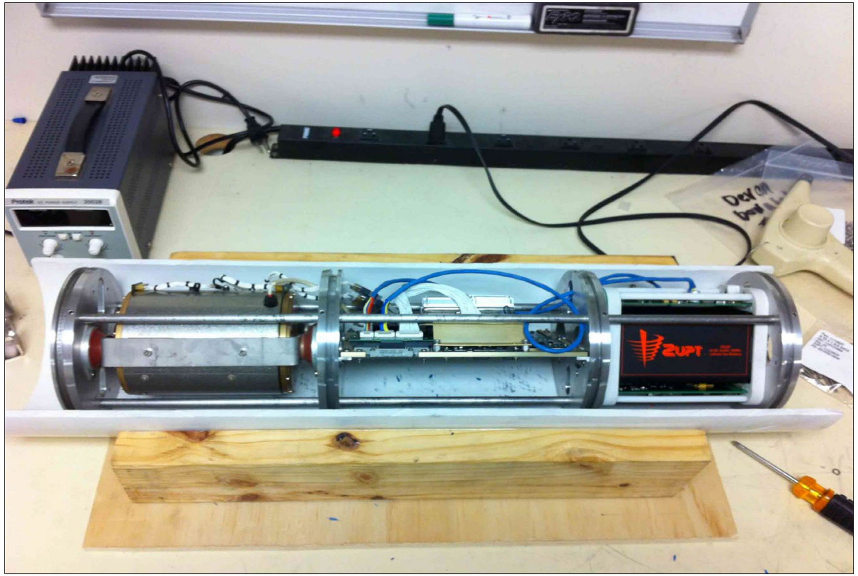
W-PINS - Development

Control for Phase 1



The concept was a core tube assembly containing all components, battery powered for 16 hours continuous operations with data logging for multiple operations. Housing was manufactured from DOM 4340. The end caps, nose cone and fishing neck were manufactured from 4340 bar stock.

W-PINS Phase 2 Tests



The core of W-PINS contains an IMU compartment, an IMU signal processing PCB and a processor, battery, storage compartment.

The width of the IMU signal processing PCB is what limited the ID, hence OD of this system build. We were going to build a 30mm smaller version and development funding dried up!

W-PINS Phase 2 Tests

Align at a known control point, anywhere near to the wellhead (+/- 500m) – tumble to ensure system is fully aligned.

Keep unit powered

Update (horizontal and vertical) at well site. This location can be dimensionally controlled by conventional survey techniques.

This should be the well center. If the rotary is well know this will work. If not we will have to provide a static sampled, post processed GNSS control position for the rotary (+/- 3cm Absolute, 1 sigma in x,y,z).

Disconnect monitoring software from tool.

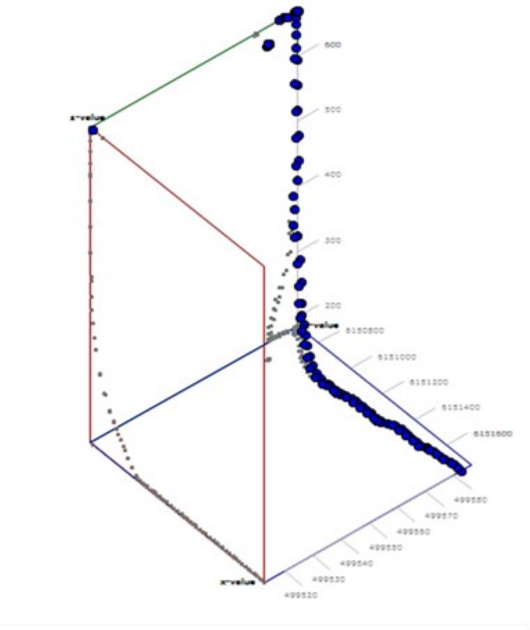
Run into, run out of the hole – motion 2mins, zupt 30s. Stay awake while this is happening and learn how well bore tractors do not do what they are told. Can also run on coiled tubing.

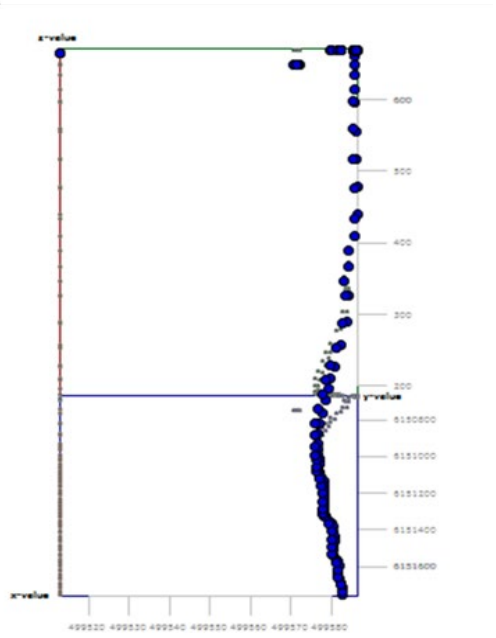
Recover to rotary, download data, process data.

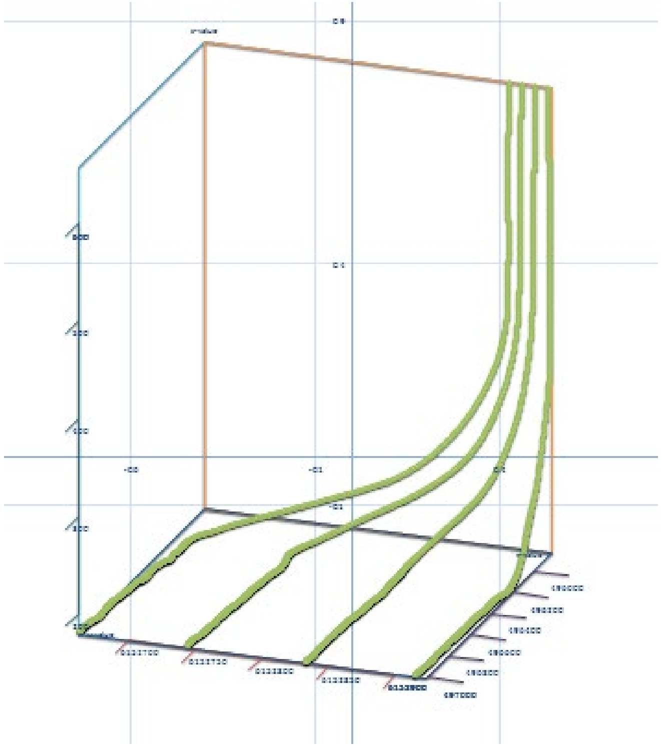
W-PINS Operational Procedure

		Northing	Easting	Orth Height
Run 1	Alignment	6150671.633	499582.411	669.824
	Prior to update	6150670.910	499582.570	669.02
	Misclosure	0.723	-0.159	0.804
	Half	0.362	-0.079	0.402
Run 2	Alignment	6150671.639	499582.411	669.824
	Prior to update	6150672.441	499581.723	670.070
	Misclosure	-0.802	0.688	-0.246
	Half	-0.401	0.344	-0.123
Run 1 Toe	Unprocessed	6151756.664	499582.737	186.84
	Compensated	6151757.026	499582.658	187.242
Run 2 Toe	Unprocessed	6151757.005	499581.369	187.27
	Compensated	6151756.604	499581.713	187.147
Difference	Uncompensated	-0.341	1.368	-0.430
Difference	Compensated	0.421	0.945	0.095

W-PINS Sample Data From Field Use







W-PINS Data Plotted

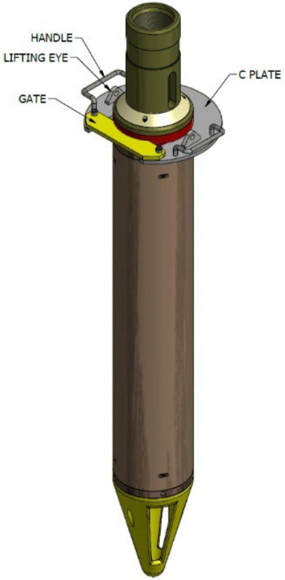
The original tool had no easy access to allow for communications while on the well. The modified tool fishing neck does. But still 7" OD.

Centralizers - needed above and below the tool. Modified the nose cone to allow for a centralizer to be installed below the tool.

Tool handling was an issue. Had to modify handling interfaces, c-plates, etc.

Wireline tractors used – with issues.

Coiled tubing was much more reliable in the SAG-D wells



Modifications Made For Production Work

We learned a lot from our operational periods in the field. Project ended due to slowdown in SAG-D, loss of contracted work. Some of the improvements we contemplated, but never completed:

Improvements to post processing software

Wireline real time communications

Wireline power

Reduce the diameter – maximum reduction with this quality IMU ~ 30mm in the OD (to 5.9”?).

Extend the temp spec a little (maybe 90°C) – BUT

Conclusions – Improvements Still to be Made

Re-statement of the "Shortcomings" of FINDS – exactly the same for W-PINS

No downhole communications

Battery powered

Temperature limited

The system only delivers an absolute location of the well bore

Classic metrics the industry uses "along hole depth", "inclination" and "azimuth" have to be back-calculated using a method which may introduce uncertainties.

BUT - We think the industry actually wants an absolute location not Inc, Az, Depth

Conclusions – Back to the FINDS system of 1980's

What are the benefits of "navigating" the wellbore with an INS – versus conventional gyro tools?

Absolute coordinates provided for the full well bore – in a local coordinate reference frame

Precise quality metric delivered by closing the traverse – you know how good it is!

No local or regional magnetic declination issues – navigates without any impact

No error propagated through the full wellbore due one bad reading

Centralizer not critical – we are navigating the center of the IMU – not mimicking the wellbore inclination with the tool.

The “***Holy grail***” for such a tool:

<2” dia - including a 20,000psi housing

Fully operational to 275°C

~ 1,000:1 accuracy

Survive or work in high shock, BHA environment

Why this tool does not exist:

Baseline length is everything – 0.005°/hr single axis is

~>1,000m FOG, >~20cm RLG, 3”?? dia DTG, *1.5”dia HRG – maybe a linear IMU

Smallest navigation grade (0.005°/hr) inertial components we are aware of define our future potential ID are close to 3.5”. For a 20,000psi pressure housing. This would then need a flask/Dewar or heat shield. With this heat protection we will not be much smaller than we are today to be able to survive high-pressure high temp.

No MEMS or Cold Atom sensors exist anywhere close to this specification today!

Does a Market Exist?

Some markets may exist again?

SAG-D

High Latitude, East/West wells, multiple wells in close proximity, large well bore casing to TD

Top hole prior to kick off

Congested well planning, close approach drilling?

Relief well assistance

For the foreseeable future we believe that a 5" to 6" OD 20,000psi, 100°C tool is as good as it gets for inertial navigation for well bore surveys – but even this needs investment.

But the work has to be continuous or regular to make the investment needed worthwhile.

Does a Market Exist?

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Thank You!