AUV Technology and Application Basics

Section 4

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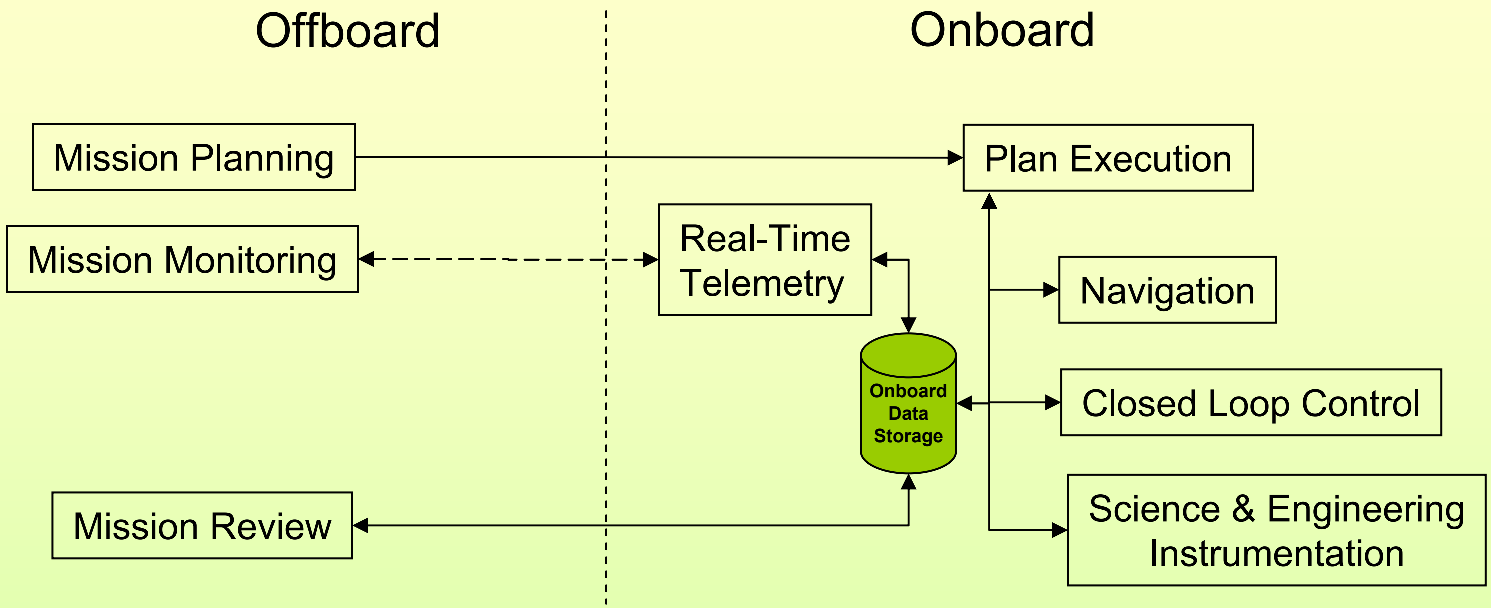
AUV Software



- Offboard software for mission planning, monitoring, post-mission data analysis
- On-board execution monitoring/decision making capability
- On-board integration of navigation, control & instrumentation data streams
  - Timestamping/sampling latency
  - Data sharing
- Some vehicles feature real-time subsurface telemetry & control function

Onboard Software

- A few general points
  - Large investment for most AUV's
  - Minimize impact of vehicle sensor/instrument reconfiguration
  - Extensible/maintainable in the field
- Structure
  - Concurrent/Multiple threads
  - Single threads
- Many different architectures, but they all provide…
  - Common framework upon which other software modules are built
  - Provides common interface to I/O, timing, logging, etc
  - Some way to sequence the AUV through different control modes/trajectories
- Existing architecutres you might see
  - Labview (used in Fetch! AUV)
  - MOOS (used by MIT AUV)
  - Framework (MBARI, BLUEFIN)

Mission Planning

- Goal – generate a trajectory through the water column that satisfies the science/technical goals of the survey
- Key Constraints
  - Science Objectives
  - Domain Constraints (Bathymetry, tides, hazards to navigation)
  - Vehicle Constraints (power, speed, navigation accuracy, safeguards)
  - Computer/GUI support tremendous help
- Simulation of plan to verify
  - nominal/off-nominal execution
  - Linear dynamics
- Plan execution tends to be non-deterministic; need robust way to express desired actions of vehicle
- Ways of expressing plan
  - Sequence of low level actions/control modes
  - Desired states which get decoded at run-time into actions
  - Behaviors (low level control modes) which get layered together at run-time to achieve desired states (layered control)

Typical Mission Sequence

```
behavior getgps {
duration = 300;
minHits = 120;
abortOnTimeout = True;
}
```

```
behavior setpoint {
duration = 30;
heading = 212;
speed = 1.5;
verticalMode = pitch;
pitch = 0;
}
```

```
behavior descend {
horizontalMode = heading;
horizontal = 212;
pitch = -15;
speed = 1.5;
maxDepth = 5;
duration = 60;
}
```

```
behavior waypoint_yoyo {
latitude = 36.89198;
longitude = -122.2268;
captureRadius = 10;
duration = 2400;
speed = 1.5;
minDepth = 3;
maxDepth = 100;
minAltitude = 7;
maxCycles = 1000;
}
```

```
behavior ascend {
duration = 1200;
horizontalMode = rudder;
horizontal = 10;
pitch = 20;
speed = 1.5;
endDepth = 2;
}
```

```
behavior getgps {
duration = 300;
minHits = 30;
abortOnTimeout = True;
}
```

Mission Planning Tools (Bluefin Robotics)

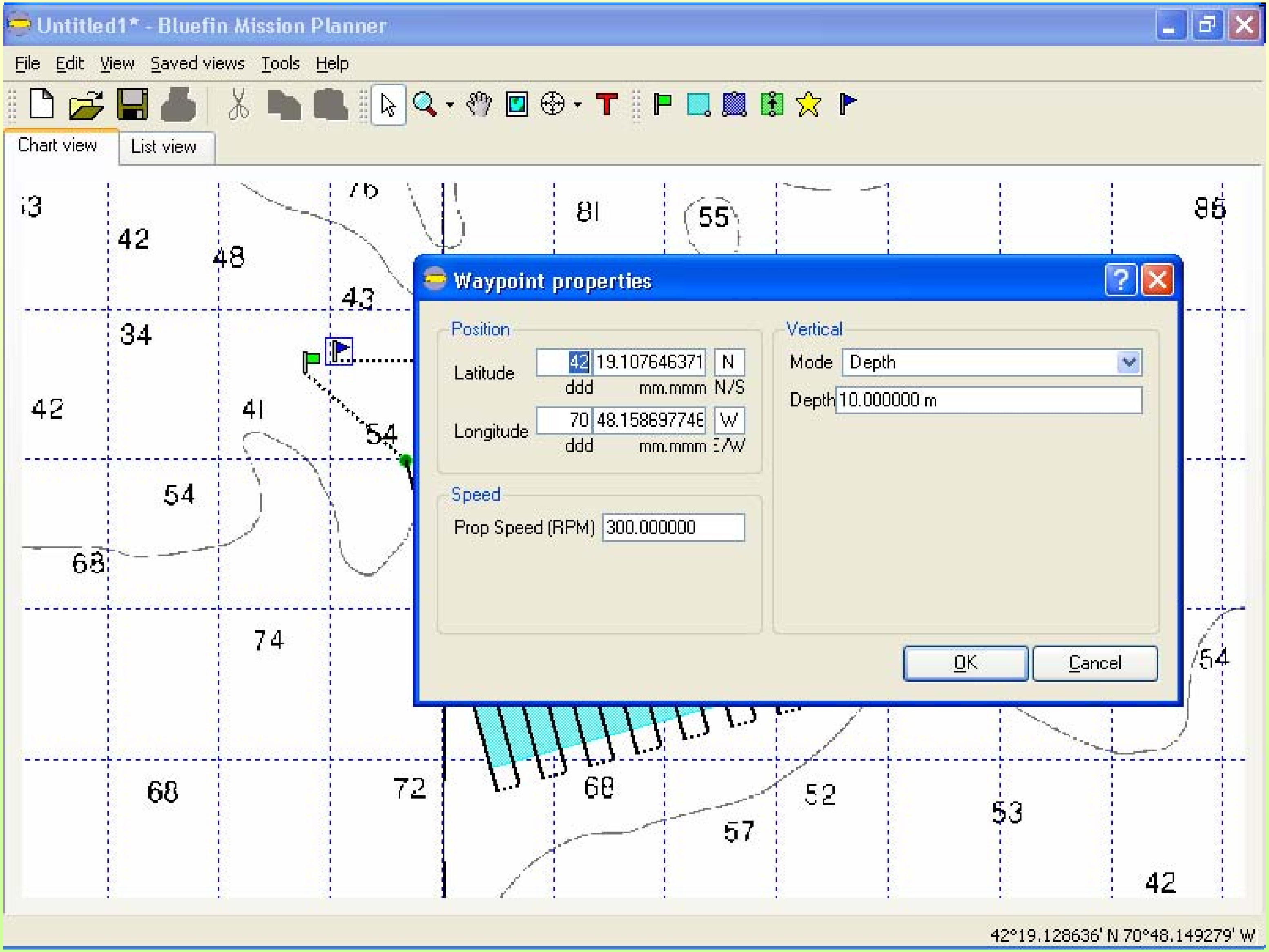


Image Credit: Bluefin Robotics

Mission Planning Tools (MIT/MOOS)

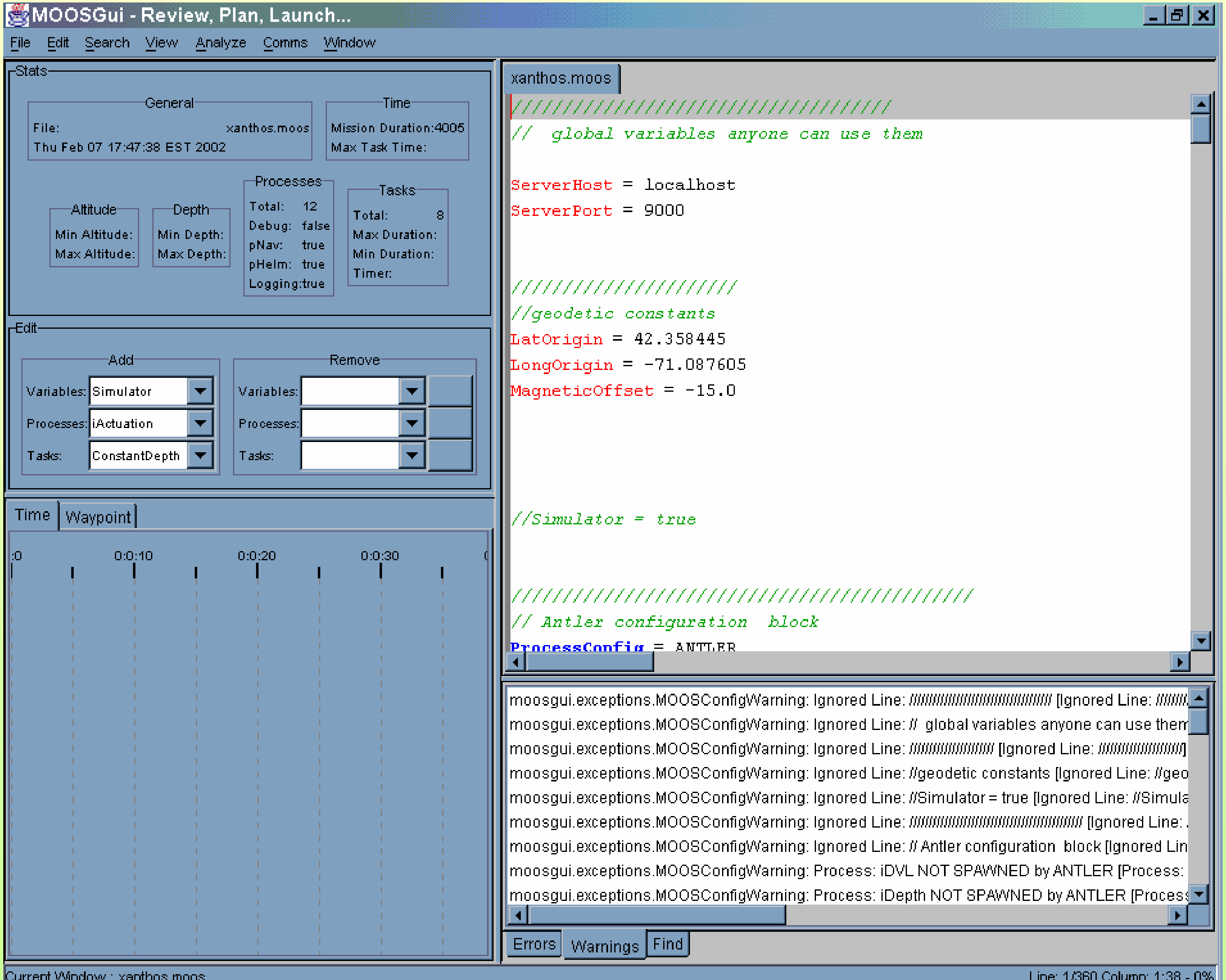
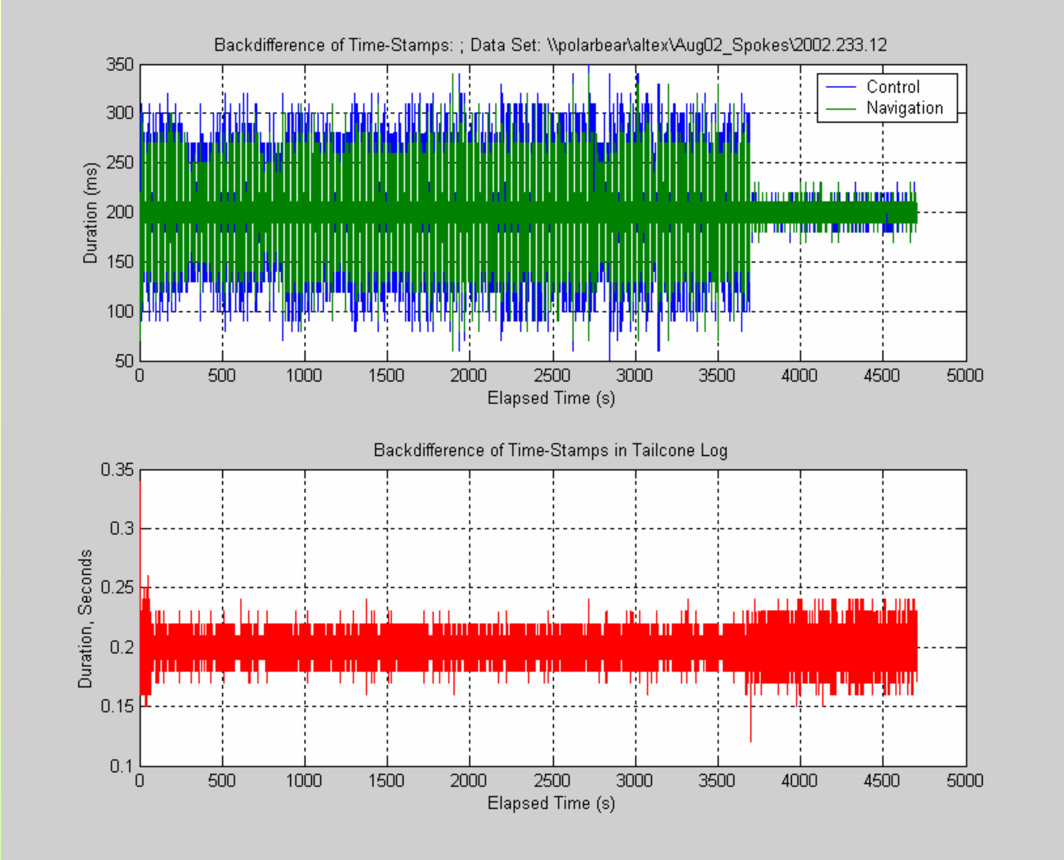


Image Credit: MIT Ocean Engineering

Mission Monitoring/Review

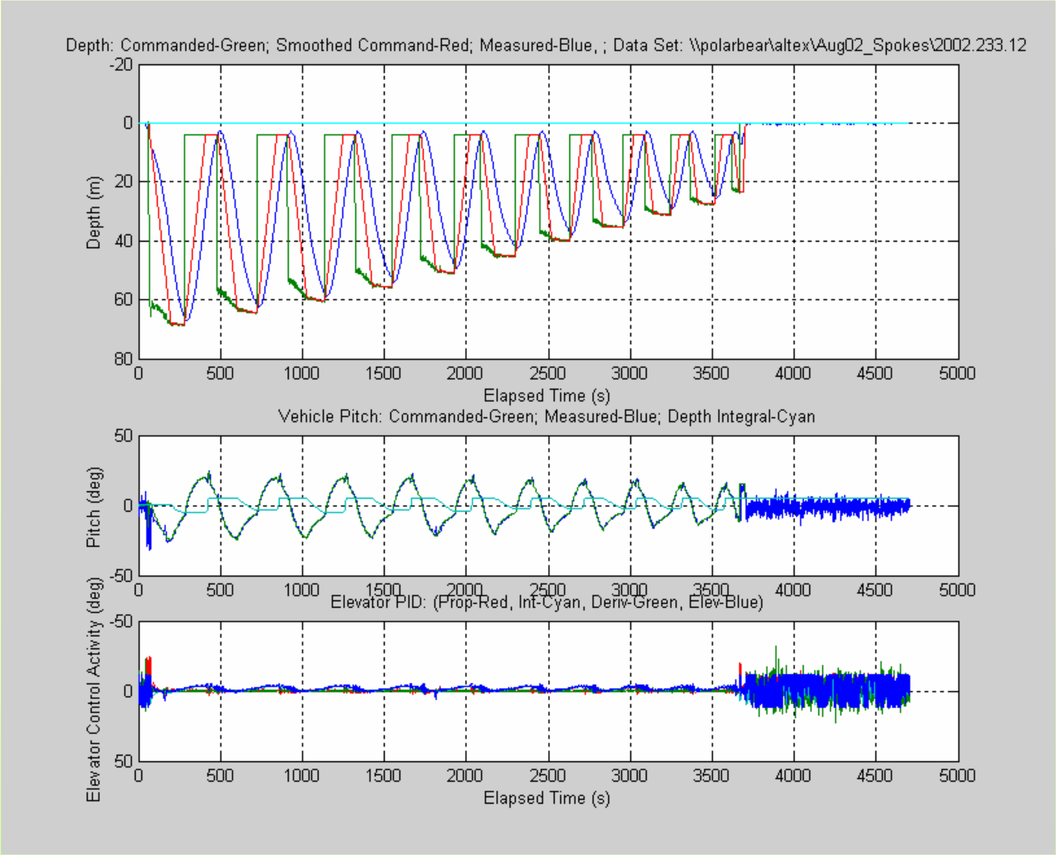
- Goal – look at the data (quicklook and post-cruise) and determine what was actually observed
- Requirements
  - Handle large data sets (12 hour mission means ~60-100MB of data)
  - Allow adjustment of common error sources
    - Navigation
    - Calibration error
    - Hysterisis
  - Maintain metadata
    - calibration coefficients, time, processing stages
  - Quickly plot relevant engineering & science variables
    - Determine mission quality in real-time
- Data formats
  - Netcdf, matlab (binary & ascii), CSV, …
- Processing/display tools
  - ODV, Matlab, IDL, ferret, …

Quick Look Plots – System Timing



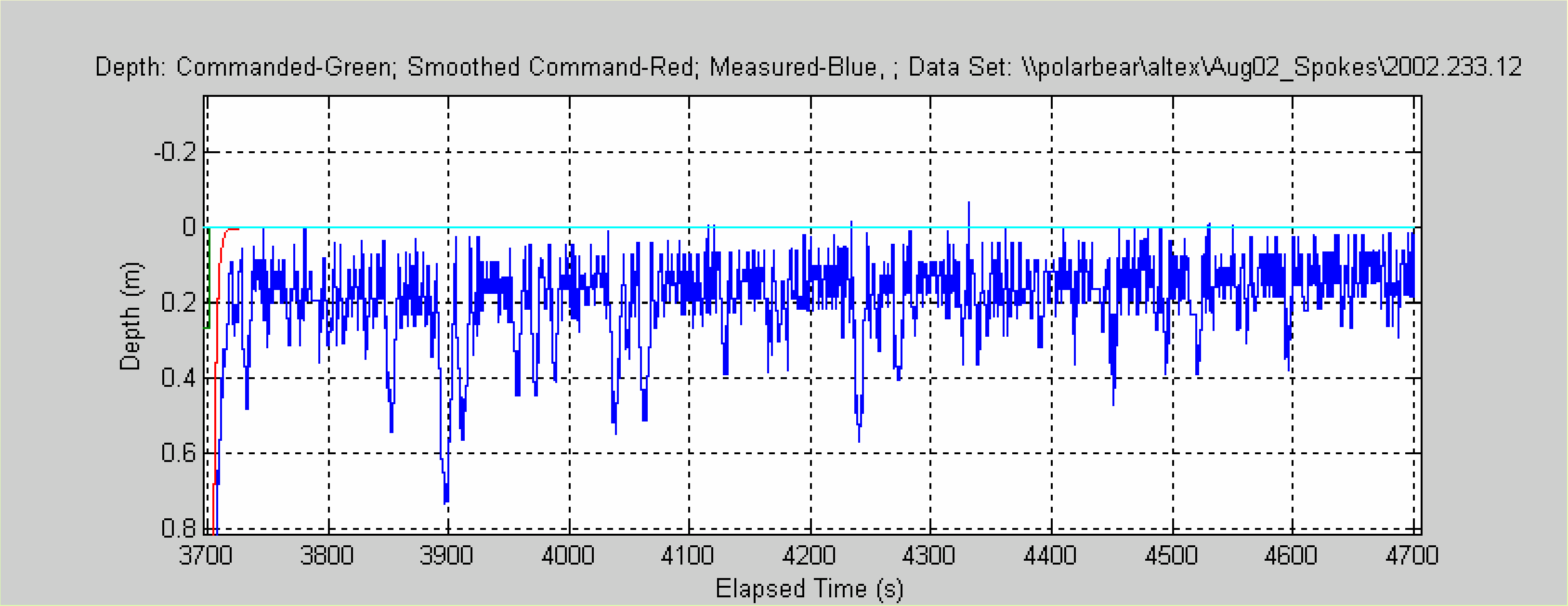
- Plots show cycle rates of critical control processes
- Useful in diagnosis of various software/hardware problems
  - Processor scheduling/overload
  - Serial data errors
  - Deadlocks

Quick Look Plots – Vertical Plane Control



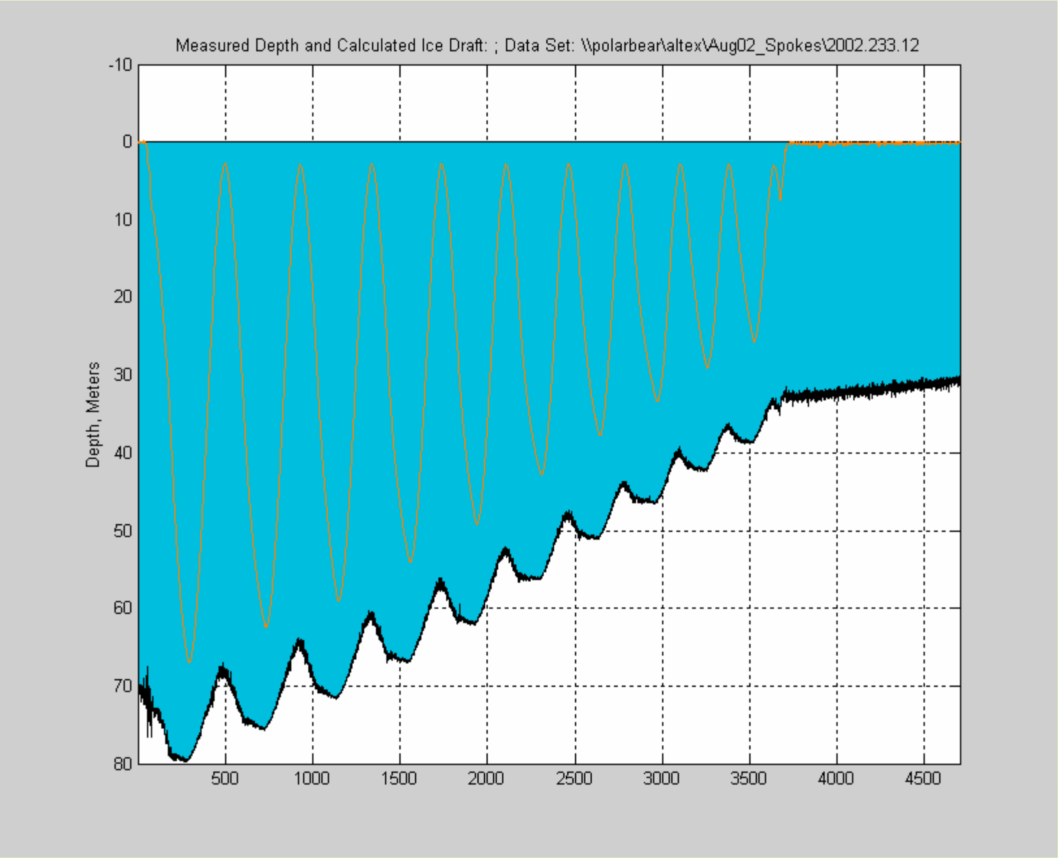
- Plots show commanded and measured vertical response of AUV
- Useful in diagnosis of various problems
  - Poor ballasting/broken elevator
  - Poor control gains
  - Pressure sensor performance

Quick Look Plots – Vertical Plane Control



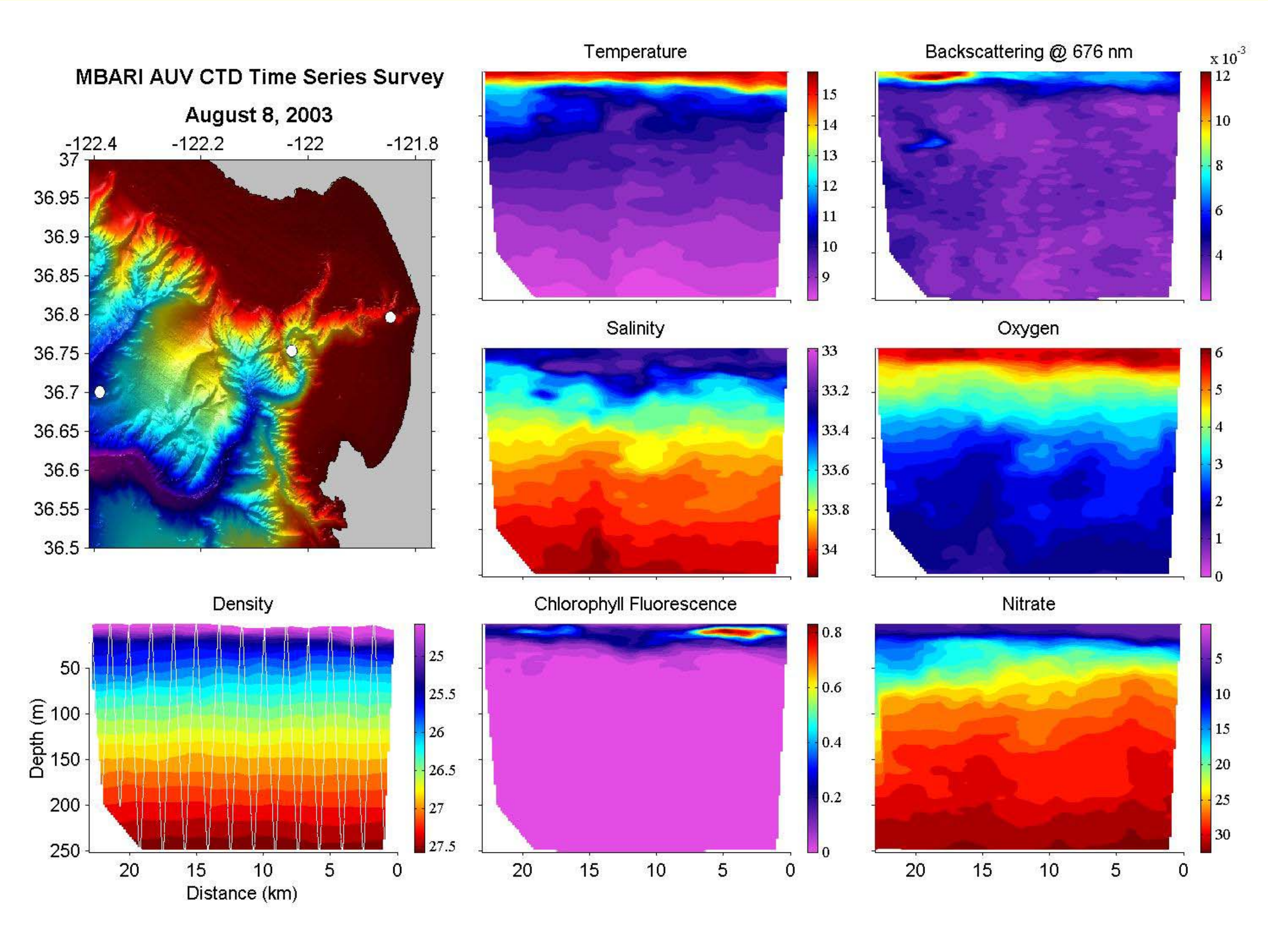
- Zoom in of depth during last part of mission
  - Note that vehicle never really surfaces at end of mission

Quick Look Plots - Altitude



- Altitude based on measured beam ranges from 300kHz DVL/ADCP
- “Rolling” bottom caused by lever arm between pressure sensor & ADCP
- Note altitude-terminated undulations

Post-Mission Plots



AUV Navigation Architectures

- Autonomous
  - Velocity log aided dead reckoning
  - Unaided & Aided inertial
  - Heading errors & Currents dominate error budget
- Surface Aided
  - Short & Ultra-Short Baseline (SBL & USBL)
  - Inverted Long Baseline
    - Places transponders on surface instead of bottom
  - Inverted USBL
    - Places transponder on ship, phased array receiver on AUV
  - Depending on solution, may require additional telemetry channel
- GPS
  - Availability of augmentation solutions (WAAS,SBAS, Commercial Correction Providers, etc) can provide worldwide differential accuracy
- Bottom Aided
  - Long baseline
    - Typically requires water depths > 4 x baseline length
  - Bottom Locked Doppler & Correlation Velocity Log
    - Subject to altitude restrictions

Navigation Architectures

System	Accuracy	Power	Constraint
GPS	150-1m	O(1 W)	Surface only
Doppler Velocity Log w/ Magnetic AHRS	~1% Dist. Travel	25 W	1m-500m Altitude
Correlation Velocity Log w/ Magnetic AHRS	~1% Dist Travel	25W	>500m
Long Baseline Acoustic Navigation	5 cm @ 100 m 3 m @ 10 km	O(5 W)	Calibration and deployment
USBL Acoustic Navigation	.1% to 10% of Slant Range	0(30 W)	Telemetry from Surface
Inertial Navigation System	1 nm/hr (RLG & Hi Perform. IFOG)	12-20 W	Initialization
INS/DVL	.05 to .1% Dist Travel	25-40 W	Initialization

Navigation – Magnetic Heading Reference

- Magnetoresistive Magnetometer
  - Based on principle of anositropic magnetoresistance, where resistance of ferrous metals changes based on incident magnetic field
  - Wheatstone bridge of four sensing elements creates self-compensating single axis magnetometer
  - Three-axis configuration w/ orientation sensing creates full up compass
  - Honeywell & other manufacturers produce surface mount IC's w/ multi-axis magnetometers, conditioning electronics, on-chip temperature compensation
  - Integrated packages w/ accelerometers offer 1^o to 2^o magnetic heading accuracy

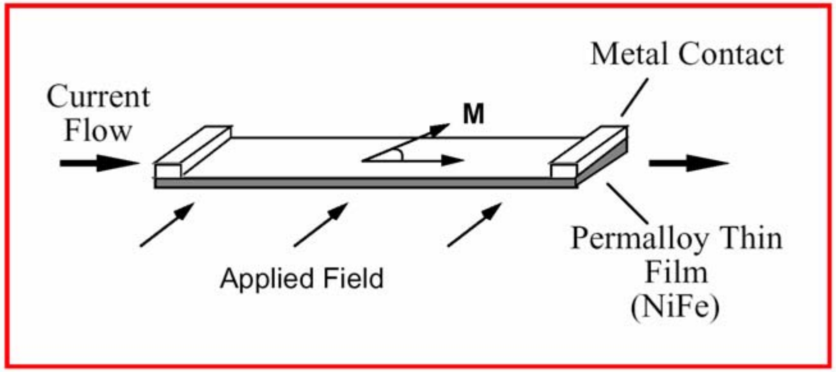


Figure 1. Principle of operation for MR sensors.

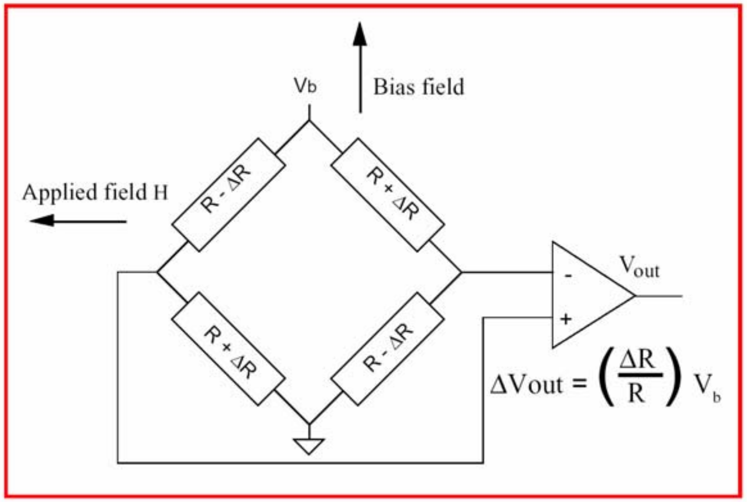


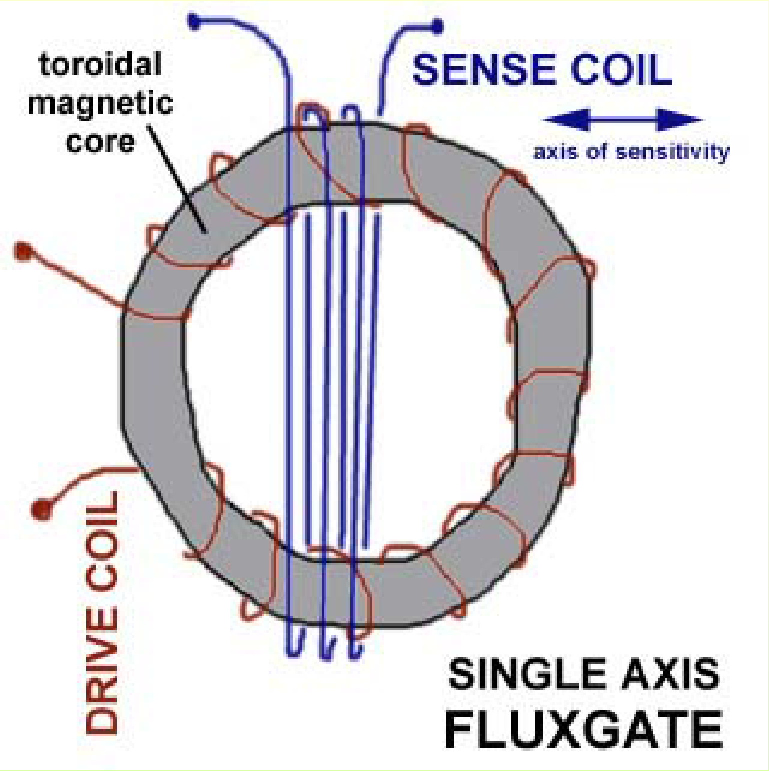
Figure 2. Magnetoresistive transducers.

Figures from http://www.ssec.honeywell.com/magnetic/datasheets/magsen.pdf

Navigation – Magnetic Heading Reference

- Flux Gate Magnetometer
  - Sense coil is inductively coupled to drive coil
  - Incident magnetic field drives core towards saturation, causing asymmetries in sense coil
  - Demodulation of sense coil signal by drive coil signal allows simple compensation and measurement of field
  - Instead of toroidal core shown, element can also be constructed using rod core w/ overlapping drive & sense coils
  - Complete system again includes three axis magnetometer, two-axis tilt sensor

Figure from http://beale.best.vwh.net/measure/fluxgate/



Navigation – Magnetic Heading Reference

- Hard Iron Distortions
  - Caused by local, static magnetic field(s) (nearby magnets, etc)
  - Must ensure these do not saturate detector
  - Modeled as vector (direction & magnitude) offset and subtracted from measured field
  - Automatically calibrate by rotating magnetometer through 360^{o} in yaw, practical range of pitch & roll (similar to spinning the compass in aircraft or ship)
  - Also calibrate by referencing optically to local landmarks, GPS, etc.
- Soft Iron Distortions
  - Caused by changes in magnetic field of nearby ferrous metals due to change in orientation with Earth's magnetic field
  - Harder to compensate
    - Usually requires several repeated spins & dips
- Commercial Vendors (note, not a paid endorsement)
  - Crossbow Technologies (www.xbow.com)
  - Precision Navigation Incorporated (www.precisionnav.com)
  - Honeywell (www.ssec.honeywell.com)
  - Leica Corporation
  - KVH

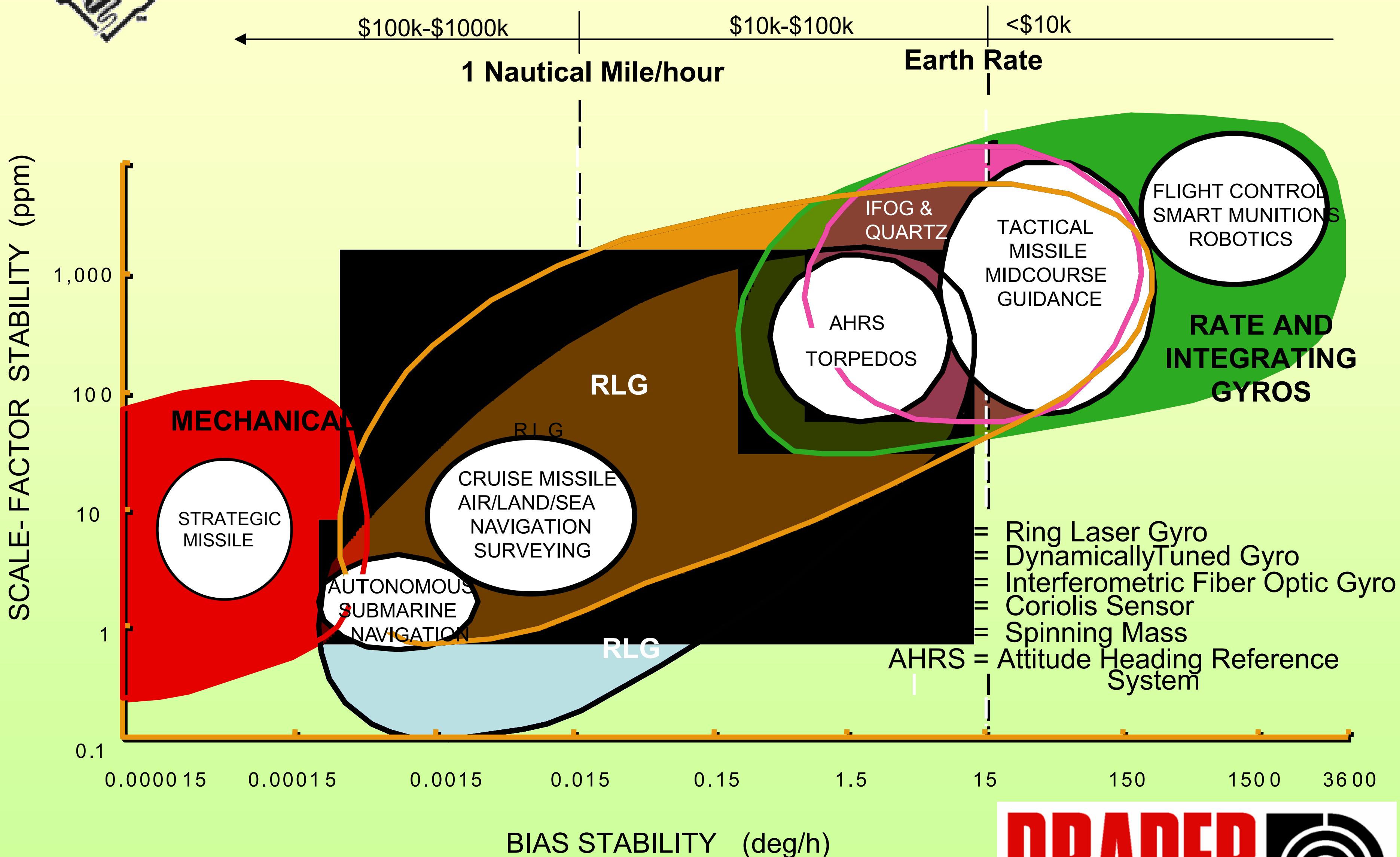
Navigation – Magnetic Heading Reference

- Integration w/ Tilt Sensors
  - Provide vertical reference to convert field measurements to heading
  - Electrolytic Tilt Sensors
    - Higher static accuracy, poor dynamic accuracy, limited range
  - Solid State Accelerometers
    - Higher dynamic accuracy, (typically) lower static accuracy, wide range
- Integration w/ Rate Sensors
  - Provides mechanism to
    - filter noise
    - detect dynamic field disturbances
  - Some vendors (Crossbow for example) integrate full-blown Kalman filters
    - provide higher output rates than possible with standalone magnetometer
  - Typical rate sensors are lower-end vibratory gyros
    - Drift rates typically .01^{o}/s to 1^{o}/s
    - Piezo-electric
    - Piezo-ceramic
    - MEMS

Navigation - Gyroscopes

- Angular rate measurement device
- Figures of Merit
  - Bias Stability (degrees/s)
    - Measures how stable rate bias of gyro is over operational range
  - Scale Factor Stability (PPM)
    - Measures how stable scaling factor between analog output and engineering units
  - Angular Random Walk ((degrees/hour)/root hertz)
    - Measures Gaussian noise of rate output
- System Configurations
  - Rate Systems
    - Gyro-compasses
    - Short-term heading reference
  - Integrating Systems
    - Inertial Navigators

Navigation - Gyro Heading Reference Performance

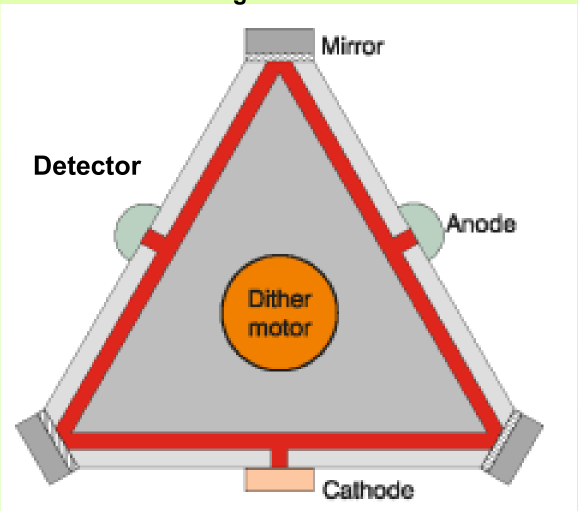


Graphic courtesy of Neil Barbour, Draper

Navigation – Ring Laser Gyro

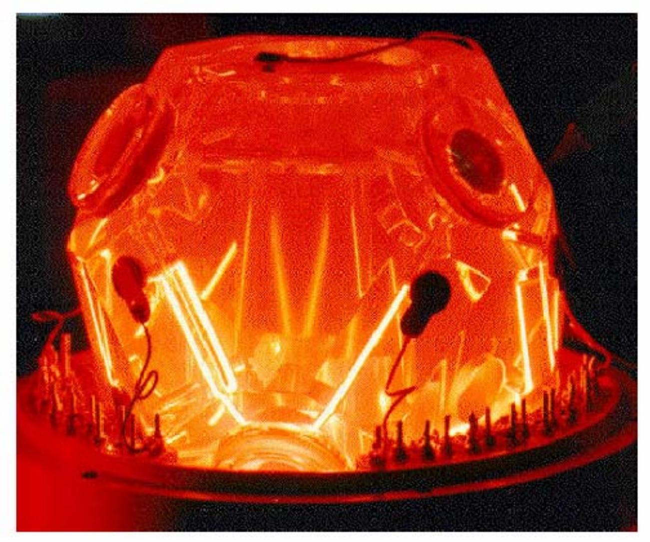
- Resonant laser cavity filled with He-Ne mixture
- High voltage (approximately 1kV) applied between anode and cathode to cause lasing to occur
- Laser propagates in both clockwise and counter-clockwise direction
- Optical detector measures output due to interference between two propagation paths
  - Rotation of gyro causes corresponding change in phase between CCW/CW beams
  - Referred to as Sagnac Effect
- Dithering motor vibrates gyro at high frequency, prevents two paths from falling into phase with each other
- DOD programs target cost at $636/three axis RLG!!!
- ~.00002^{o}/s drift (compared to .01^{o}/s to 1^{o}/s for quartz systems)

Single Axis RLG



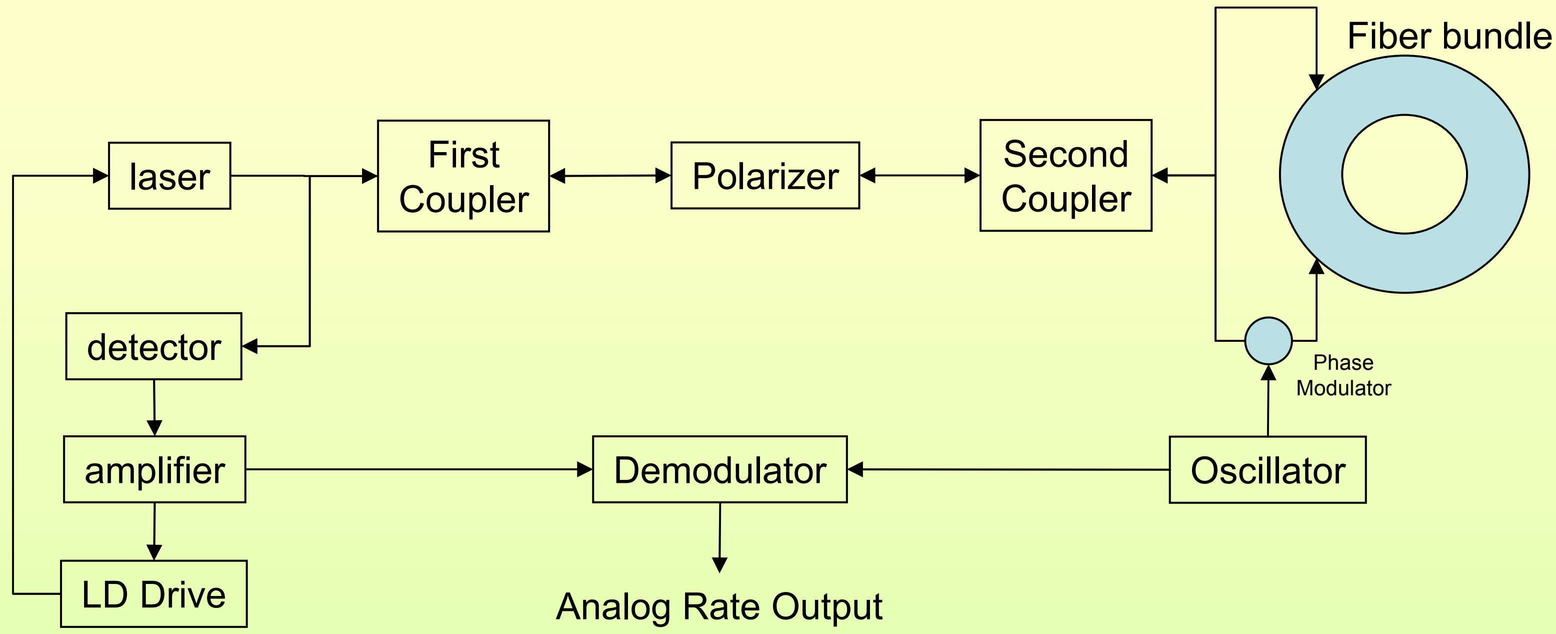
http://www.pakaviation.com/PVA/Library/Docs/inertial_navigation.html

Three Axis RLG



http://www.dodmantech.com/successes/Navy/04-08/MRLG.pdf

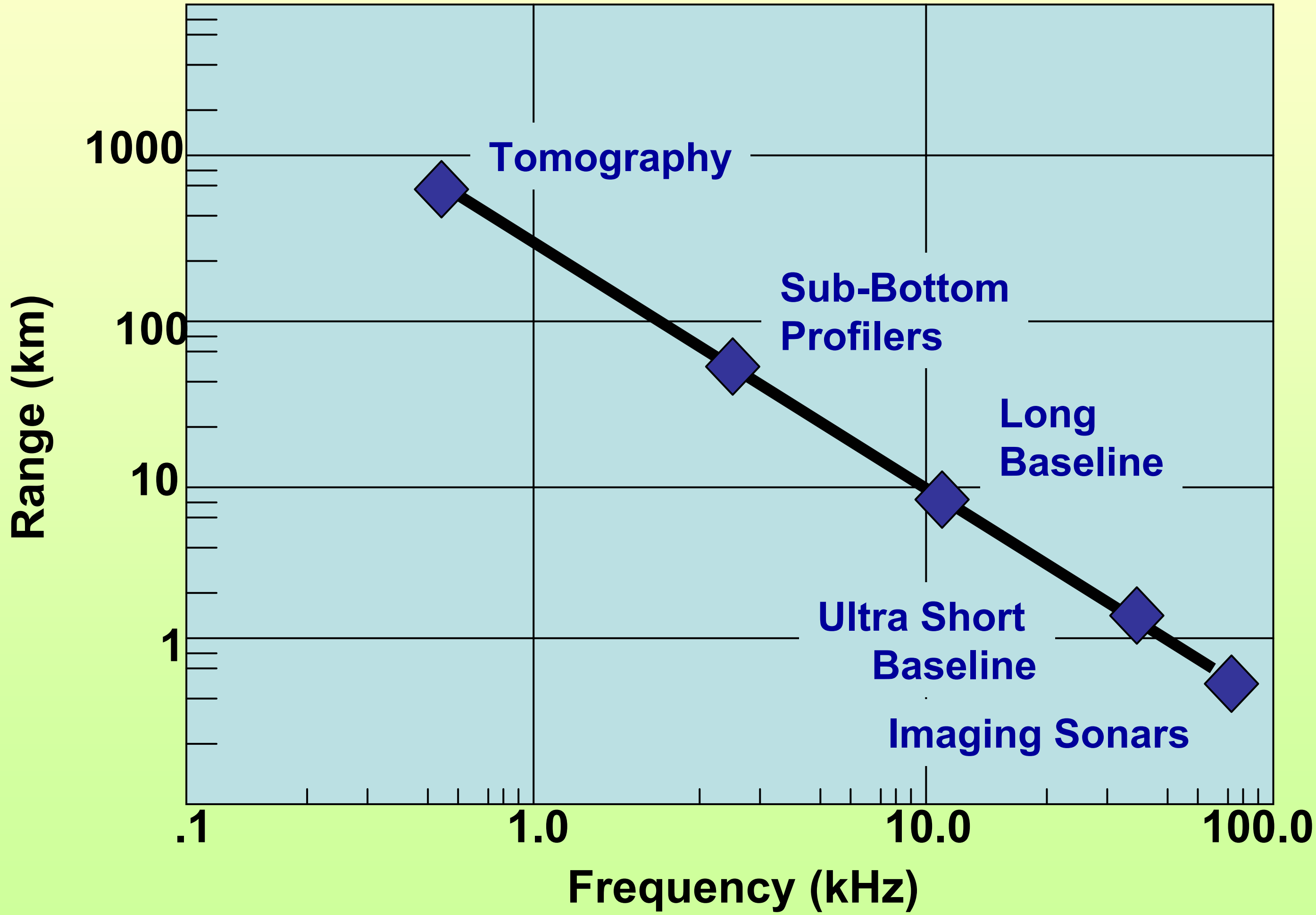
Navigation – Fiber Optic Gyro



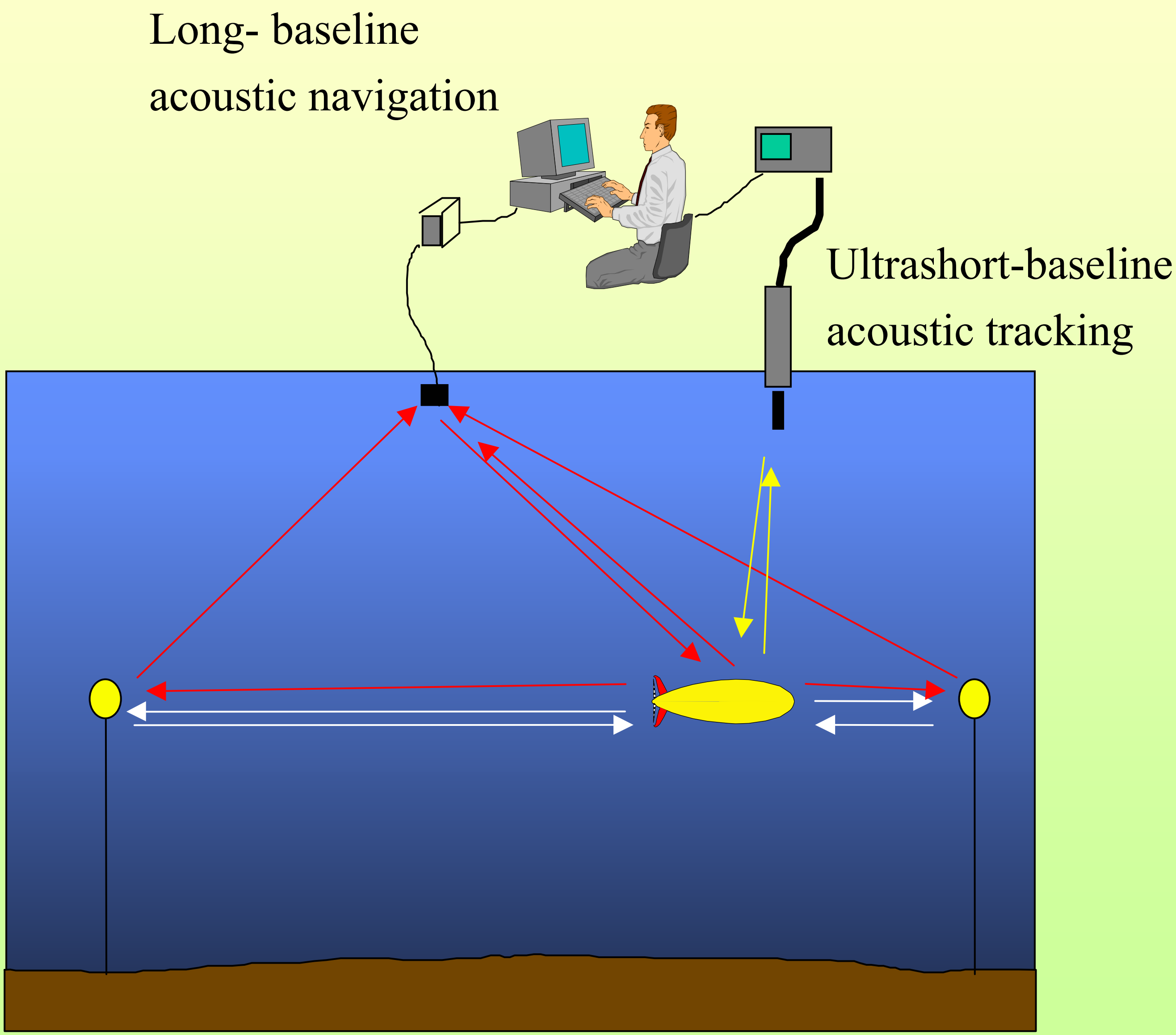
- Laser light enters first coupler, polarizer, second coupler
- Second coupler splits laser into CW and CCW beam which traverse fiber bundle
- Beam is modulated to prevent "lock-in"
- Returns CW and CCW beams return to detector
- Demodulator removes phase modulation, producing rate output

Navigation – Acoustics

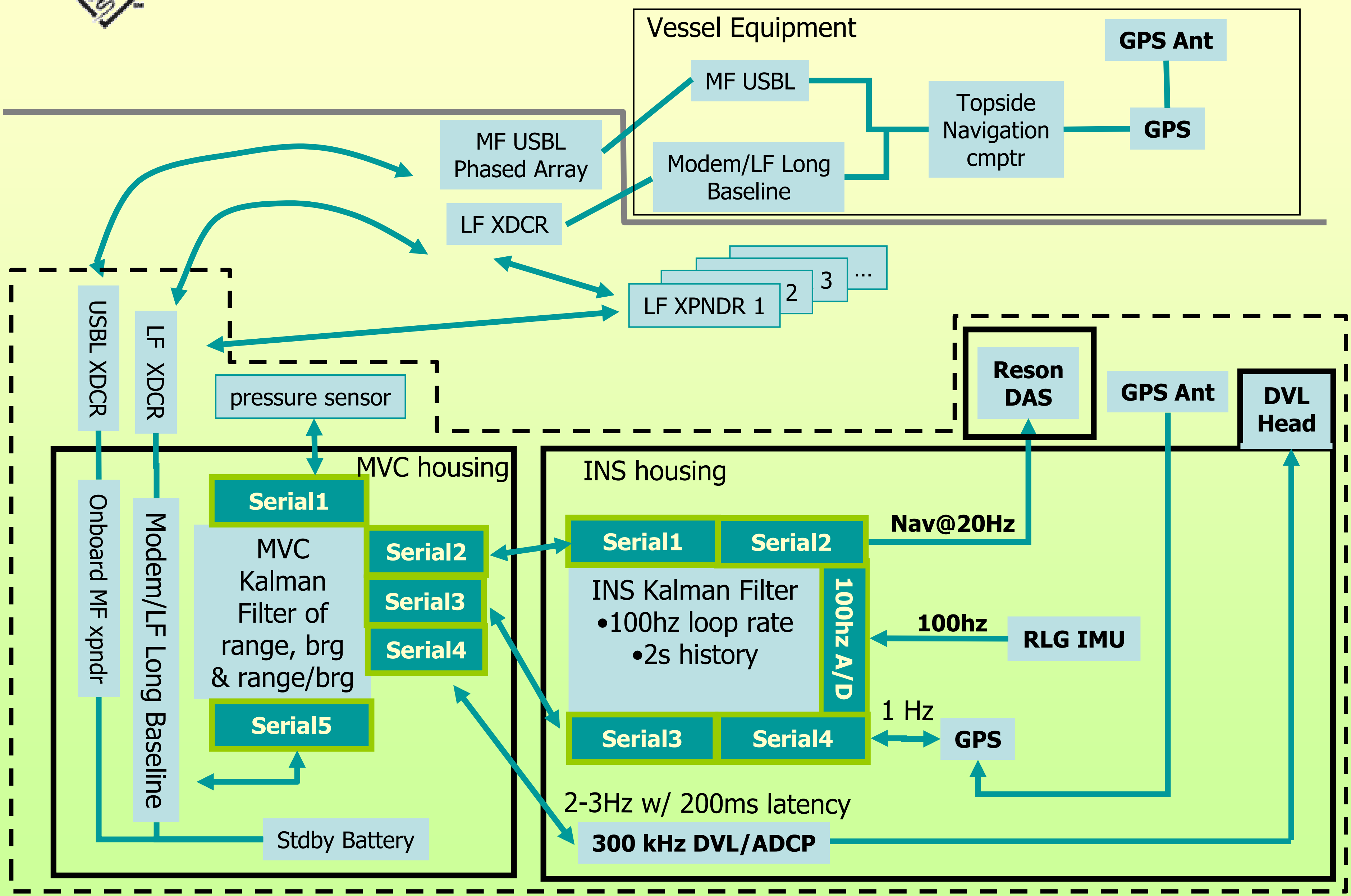
- **Range at which Absorption approximates 10 dB**



Navigation– Long Baseline/USBL Navigation



Navigation Design for Surface-Aided Acoustic Survey



Navigation - References

- http://www.pakaviation.com/PVA/Library/Docs/inertial_navigation.html
- http://www.dodmantech.com/successes/Navy/04-08/MRLG.pdf
- http://www.ixsea-oceano.com/images/products/Octans_highly_compact.pdf
- **"Modern Inertial and Satellite Navigation Systems",** Alonzo Kelly, CMU-RI-TR-94-15, available at http://www.frc.ri.cmu.edu/~alonzo/pubs/reports/pdf_files/nav.pdf
- "FIBER OPTIC RATE GYROS AS REPLACEMENTS FOR MECHANICAL GYROS",S. M. Bennett, R. Dyott, D. Allen, J. Brunner, R. Kidwell and R. Miller, Presented at the AIAA98 Conference (available at http://www.kvh.com/pdf/aiaa98.pdf"