Best Practices for Data Acquisition and Instrumentation

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Who are you, and why should I listen to you?

- BS in Physics, Colorado School of Mines
    - Electromagnetic specialty
- MS in Electrical Engineering, Colorado School of Mines
    - Instrumentation, Communications and Controls
- 13 Years at the US Geological Survey, Geomagnetism
    - Led Instrumentation Development, Calibration and Data Acquisition
- Development of analog/digital circuits, PCB, FPGA, uControllers systems

1. Course Goals

- ➔ **Study the Application**
  Asking the right questions is important
- ➔ **Senors**
  How do they work, how do their strengths and weakness impact your study
- ➔ **Fundamentals of Measurement**
  Understanding the principles, making good measurements
- ➔ **Data Acquisition**
  You've got the sensors signals, now what
- ➔ **Data Storage**
  Storing data, compression

Understanding your application is your first task.

Ask why, why why

And….

WHY?

Tip

Don't stop asking questions until you understand, and more importantly road map the project evolution.

Often, people know they want to do something, but don't know what they want to do.

Tip

Don't assume scientists will understand an application from an instrumentation and data acquisition perspective.

OUR minds function differently.

Identify the experts, and open dialogue. **The most painful lesson of my career!** Be willing to learn and you'll discover the true power of the geomag community.

Different groups have different personalities and different expertise.

1. Canada - electronic experts.
2. BGS - All around expertise
3. Jurgen Matzka - great bridge between science and instrumentation

Getting Started

You know why, and you've talked to the experts to understand their approach. Now own it!

- ➔ **Overwhelmed?**
  Refine and revert to your road map, just start checking things off the list. Open source solutions can help.

- ➔ **Caution!**
  Don't be completely dependent on someone else's solution. Take the time to understand not only **HOW** but **WHY**

Instrumentation and Signals

1. We can measure time (frequency) more accurately and stable than any other signal. **WHY?** Because we have been doing it forever.
2. Voltage, when you can't use frequency or time. **Analog or Digital?** What is the difference.
3. **Current.** Okay for short term applications where stability is NOT important.
4. What type of **Signal** does my instrument produce?
5. Is it **Vector or Scalar?**

Scalar Instruments

1. Proton precession mags (before even my day)
2. Overhauser magnetometers (present observatory standard)
3. Optically pumped magnetometers, based on helium, cesium, potassium and rubidium (modern electronics are driving down costs and increasing usability).
4. SQUID (superconducting quantum interface), cryogenically cooled, ultra sensitive. Not practical for observatory applications, unless you have a tunnel…

All technologies have been around since the 1960s

Overhauser vs. Optically Pumped

How do they work?

Overhauser:

- A fluid enriched with “free radicals” and protons. A small radio frequency (RF) is applied to polarize the spin of the free radicals which bond with protons. The RF is removed and the protons freely vibrate with a frequency proportional to the external magnetic field.

PROs: Stable and reliable technology. Absolute accuracy tied to atomic standards. Little/no heading error, little/no temperature coefficients

CONs: Slow sampling relative to OPMs and fluxgates. Low sensitivity, and large sensors.

Tip

It is often difficult for manufacturers to accurately evaluate all the important parameters.

Observatory work is not the norm for these sensors.

Overhauser vs. Optically Pumped

How do they work?

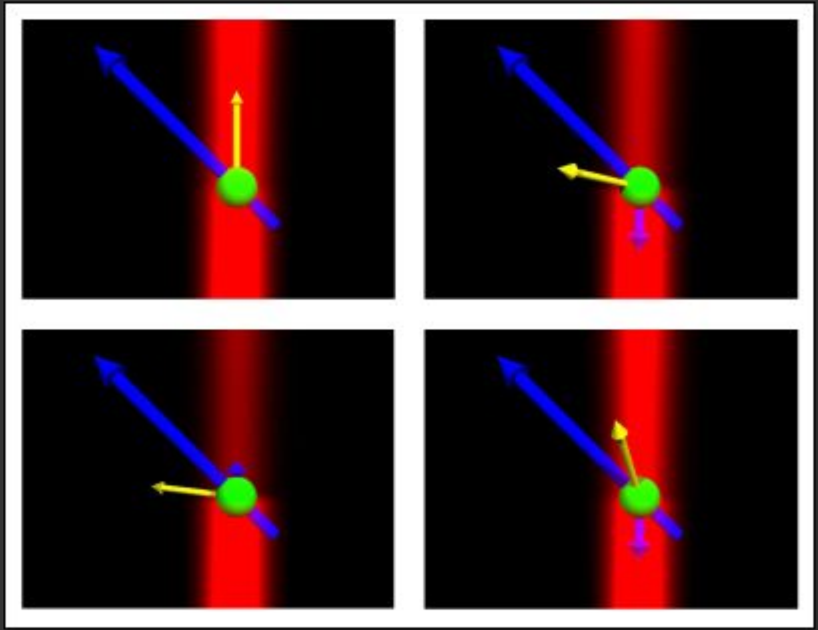
OPM (helium, cesium, potassium and rubidium):

- Light is passed through an ionized alkali (or Helium) vapor gas to pump atoms into higher energy states. Light absorption is related to the external magnetic field.

Element	Pros	Cons
He	Small, Very Accurate, Long legacy in Space	Limited Availability, Expensive
Cs	Larger sensor, very accurate	Deadzone, heading error, short runtime due to lamp
K	Larger sensor, very accurate	Deadzone, heading error, short runtime due to lamp
Rb	Very Small, Accurate, low power, laser not lamp	Deadzone, heading error, much less expensive

Tip

Heading errors and dead zones won't impact traditional observatory work. However, care must be taken if using these sensors for a survey or calibration.



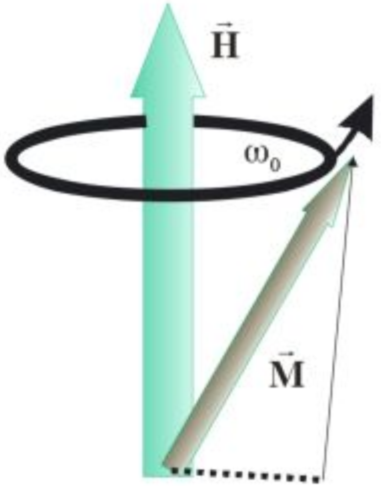
$$\frac{d\vec{\mathbf{A}}}{dt} = \vec{\mathbf{T}}$$

$$\vec{\mathbf{T}} = \vec{\mathbf{M}} \times \vec{\mathbf{H}}$$

$$\vec{\mathbf{M}} = \gamma\, \vec{\mathbf{A}}$$

$$\frac{d\vec{\mathbf{M}}}{dt} = \gamma \left[\vec{\mathbf{M}} \times \vec{\mathbf{H}}\right]$$

$$\omega_0 = \gamma H_0$$



- Courtesy of Geometerics, http://mfam.geometrics.com/atomicmagnetomet.html

Our friend, the Fluxgate.

Robust, reliable, sensitive but NOT stable or accurate.

Single, double and triaxial configurations. Signal consists of a DC offset (digital output) and an analog signal (remainder about zero).

1. Single Axis: Declination and Inclination magnetometer (DIM).
2. Dual Axis: Coupled with an Overhauser to yield triaxial measurements
3. Triaxial: Most common real-time observatory instrument.

Fluxgate

What are the used for?

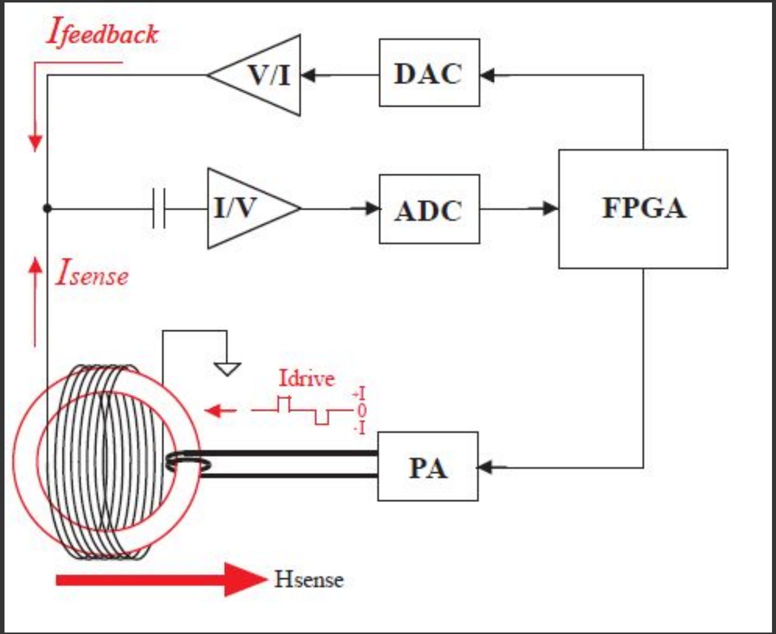
- Most magnetic applications. Navigation, geophysical, military, surveying, directional drilling, space.

How do they work?

- A wond low-noise core of various geometry (toroidal, race-track…).
- Winding provides and excitation signal which is high frequency (15-30 kHz).
- Excitation signal is usually shared across all three axes.
- A sense winding, generates the DC offset to "null the field" and used to measure the residual magnetic field.
- Typically output Analog and Digital signals, or purely digital signals.

Tip

Alway be mindful of the temperature coefficient. As temperatures change, the geometry of the sensor changes, thus the signal accuracy is altered. The best observatories, have stable temperatures, or high levels of temperature compensation.



* A radiation hardened digital fluxgate magnetometer, D. M. Miles et al.

The Hybrids

- Leveraging absolute accuracy to produce vector measurements
    - Many methods, and experiments
    - Build underwater observatory
- DI Flux
    - Robotic absolutes
- dIdD
    - A scalar sensor in a set of orthogonalized coils
    - Derived from law of cosines
- PVM
    - Double the ambient field in a direction, subtract half the current
    - Remnant magnitude is the uncompensated vector component
- Many solutions developed by German instrumentation teams
    - Known sensor rotations to back out sensor calibrations

Calibration

What characteristics are we looking at?

- Scale values, digital bias values, orthogonality, linearity

Methods

- Calibration using coil systems
  - Tri-axial set of coils, driven by programmable power supplies
  - Coil constants and orthogonality of coils must be measured
  - Traceable back to Overhauser, other atomic standard, and DIM measurement
- Calibration using scalar and known orientation changes
  - Rotation of sensor in Earth's field in known increments
  - Traceable to atomic standard, and confidence in increments
- Inter-calibration
  - Placement of calibrated reference sensor in close proximity
  - Accuracy can be quite high, depending on the reference sensor

Tip

Many great papers have been published for satellite magnetometer calibration. These serve as a great guide.

- The small coils at NASA Goddard

Geoelectric and magnetotelluric.

Increasingly important to the geomagnetic community. Used for ground induced current monitoring, prediction and simulations.

Long Term and Short term systems.

1. Two-three induction coils sensors.
    a. Single access sensors
    b. Great for higher frequency magnetic measurements
    c. 10 Hz - 1 kHz
    d. Large, and should be buried to add stability.
    e. Placed X, Y and Z
2. 1-3 pairs of Electrodes
    a. Varying separation
    b. Varying chemistry Cu-Cu, Pb-Pb....
    c. Requires lightning protection!
    d. REQUIRES lightning protection!
    e. Placed in X and Y orientation

2. Recap

- ➔ **Study the Application**
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Fundamentals of Measurement

Frequency if possible, then voltage and lastly current

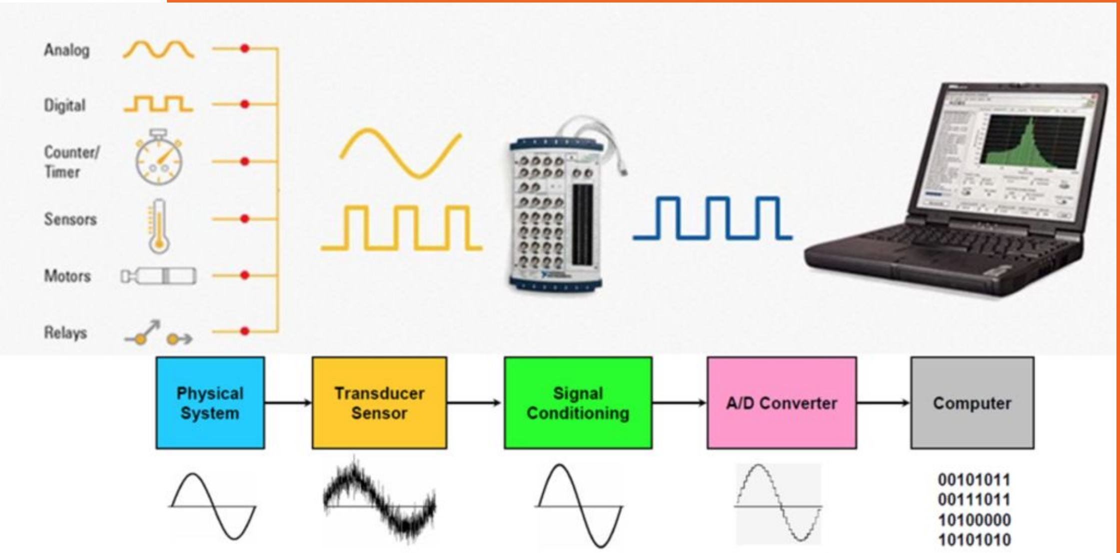
- Time measurements are accurate stable and atomically traceable
- Voltage, it's all about the bits and oversampling
- Current, dependent on a reference resistance

Timestamping and Timing

- Critical for coordination
- GPS, local oscillators, networked
- Identify the sources of time shift

Filtering

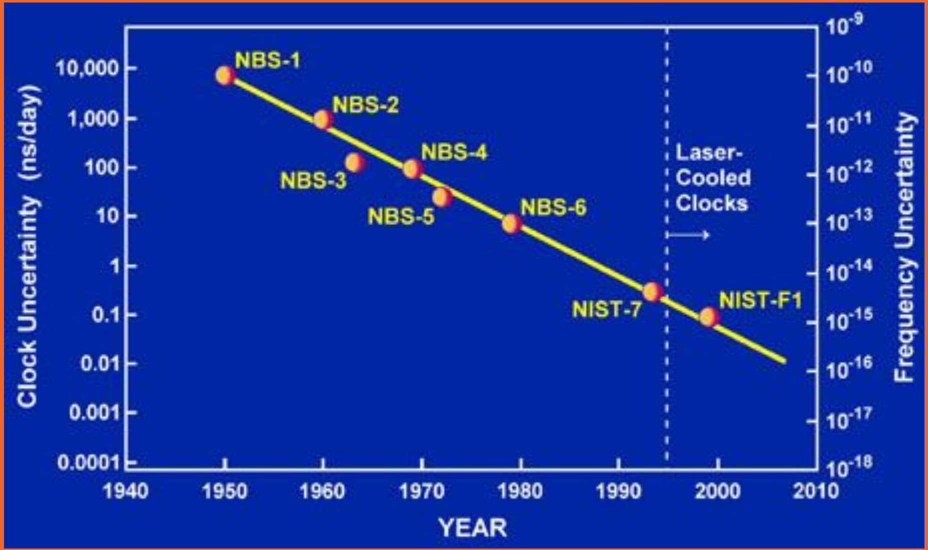
- Analog and Digital techniques
- Know what you are trying to filter, but also know what you need to keep
- There is no "one-size fits all" filter
- Your application may require a series of filters Analog and Digital



~ https://medium.com/daqifi-data-acquisition/types-of-data-acquisition-systems-6ce3d997a2ce

Frequency and Time

- Based on atomic standards
  - Vibration of alkali metals, (cesium)
  - Long term stability
  - OCXO, TCXO, Rb, Cs….
  - Laser cooled
  - Optical Transitions, in dev
- Measurement technique
  - A reference clock is used
  - Signal Edges are counted



https://youtu.be/9ikbD7UGzoI

The ADC

Conversion of Real-World analog signals to digital signal

- Sampling speed, resolution, effective resolution
- Many different types
  - Sigma-Delta (very common)
  - Successive Approximation
  - Integrating

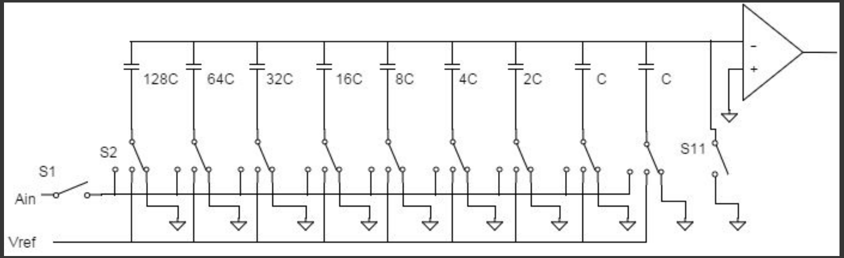
How do they work?

- SA, compares input signal to defined voltage references, reads the levels triggered.
  - Fast, but lower resolution

- ςΔ, reduces the dependence on analog components, 75% digital
  - Uses a modulator, decimator and filter to achieve higher resolution
  - Oversampling: Quadruple the sample rate, add 1 bit of resolution
  - Slow, but higher resolution

Tip

Understand not all 24-bit resolution is created equal. Understanding the role of sampling technique is very important to understanding the Effective Resolution.



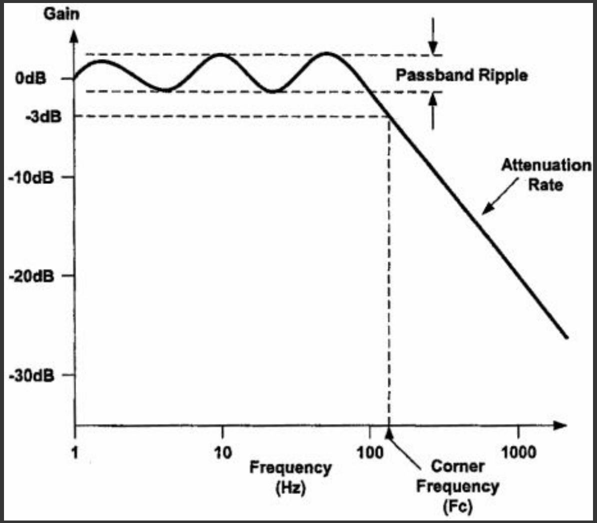
ADC type	Resolution (bits)	Max. speed	Advantages	Disadvantages	Applications
SAR	8-18	10 M	• Fastest • Low power • Inexpensive • Can use a multiplexer	• Less resolution • Greater noise	• Data acquisition • Industrial control • Battery-powered
Δ-Σ	8-32	1 M (192 ksamples/s, typical)	• Lowest noise • Highest resolution • No S/H amplifier needed	• Slowest • Moderate cost and power consumption	• Instrumentation • Audio • Medical

*allaboutcircuits.com

Filtering and Decimation

Analog, Digital (real-time and post processing)

- Analog
  - Low Pass, High Pass, Notch, Band Pass
  - Butterworth, Chebyshev (common for instruments)
  - Important Parameters: Corner Frequency, #poles,
  - Magnitude response
    - -3 dB point, pass band ripple, Attenuation Rate
  - Phase response
    - Phase response, phase lag
- Usually developed by manufacturer, but can often be reconfigured
- Require high precision and stable resistors and capacitors
- Filters can be cascaded to alter the response at various frequency



Tip

Initial research is critical to designing proper filtering technique. Analog is very hard, even impossible to undo.

Digital Filtering and Decimation

- Again, understanding the project is critical!
  - What are the signals of interests?
  - Why are they interesting?
  - What are the other potentially important signals
- Two main classifications of digital filter IIR, FIR
  - IIR filters: Less computationally intensive, more complicated to design
  - FIR filters: Easy to design, but require more computation. No phase shift across the frequency band.
- Filtering types similar to analog Low Pass, High Pass, Notch and Pass Band
- Windowing functions within these classifications can be used to decimate data, eg, 10Hz to 1Hz.
- Why decimation?
  - Data storage is limited
  - Telemitry is limited