Oregon State University

College of Earth, Ocean, and Atmospheric Sciences

Faster, Lighter, Cheaper: Developing new instrumentation to broaden access to MT

Adam Schultz[1], Brady Fry[1,2], Taylor Viti[1]

National Geoelectromagnetic Facility
College of Earth, Ocean and Atmospheric Sciences, Oregon State University

[2]Chaytus Research and Engineering, LLC, Corvallis, Oregon

16 February 2022 15:00 UT, 07:00 Pacific

Today’s Menu

1. Evolution of MT instrumentation and technique – a brief personal history
2. Large array EM/MT surveys for regional/continental scale investigations, 3-D/4-D target discrimination and resource/reservoir monitoring
3. Barriers to more widescale adoption of MT/EM methods
4. IoMT – the Internet of MT

OK Boomer…

1. In my experience, ageing is inevitable, if you are lucky, but it doesn’t have too many advantages…
2. Having said that, sometimes you get in at or close enough the beginning of things to make life interesting…

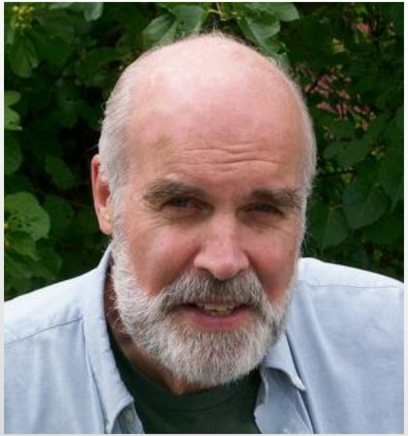
High School Years

1. NSF summer research experience for high school students – City University of New York (1974) - built cosmic ray telescope with scintillation detectors and coincidence counters to examine impact of micrometeoroids on secondary cosmic ray production, learned Fortran IV/WATFOR using paper tape/teletype and IBM 029 card punch; ground a Newtonian telescope mirror
2. Discovered it’s fun to be a nerd! Expensive toys…

College Years

1. Went to Brown University to be an astrophysicist in 1975. Too stupid. At night worked as an Assistant Operator of IBM 360/67 mainframe computer (1 MB of hand-wound core memory and the world's first virtual machine!)
2. Tried to get accepted into planetary geology program, but told there were no jobs since Apollo Program was winding down and no one cared about space anymore, though got to play with Viking Mars lander!
3. Happened to see a student job posted on the bulletin board in the Dept. of Geological Sciences – something called "Geophysical Technician" and New Mexico was mentioned. I'm in!

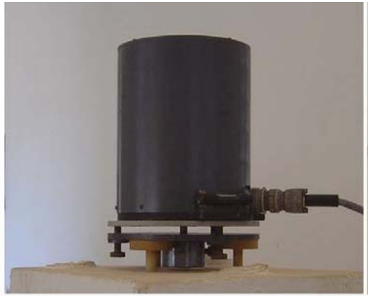
Jack Hermance



(Ask me by what nickname was John Francis Hermance known to his crew?)

1. In 1977 I was hired to help build a wideband MT system and an analog computer for processing, to maintain and deploy long-period MT systems that recorded on strip charts, and to code and operate a frequency-domain MT analysis system written in BASIC on a Tektronix 4051 storage-screen computer with 8-bit 1-Mhz Motorola 6800 CPU, 32 KB of RAM, and a 300 kB cartridge tape drive
2. …and to join with Jens Pedersen, Rick Ehrenbard and Jacques Lord on a massive transect through Northern New Mexico and the Valles Caldera/Hot Dry Rock Project

Mid-1970’s Long-Period MT instruments



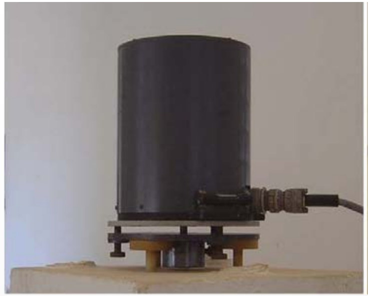
Long-period E,B field analog lines went into camper where racks of ink/paper strip chart recorders generated squiggles. One vehicle also held the analog computer for wideband MT.

Electrodes were primitive Coors© porous ceramic filter pots (used for beer production), with copper rods inserted into aqueous $CuSO_4$ solution. These had to be visited and topped up with solution several times a day.

EDA fluxgate magnetometers for long-period, with noise levels of ~1 nT/√ Hz @ 1 Hz (modern fluxgates can be sub 3-7 pT/√Hz @ 1 Hz).

Strip chart records were manually digitized into 10, 30 or 60 s sample rate intervals and then keyed manually into Tektronix 4051 processing computer

Mid-1970’s wideband MT instruments



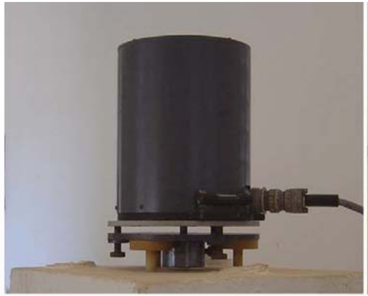
Another camper for wideband!

SQUID magnetometers were being experimented with, but required liquid hydrogen, so impractical for extended remote area fieldwork

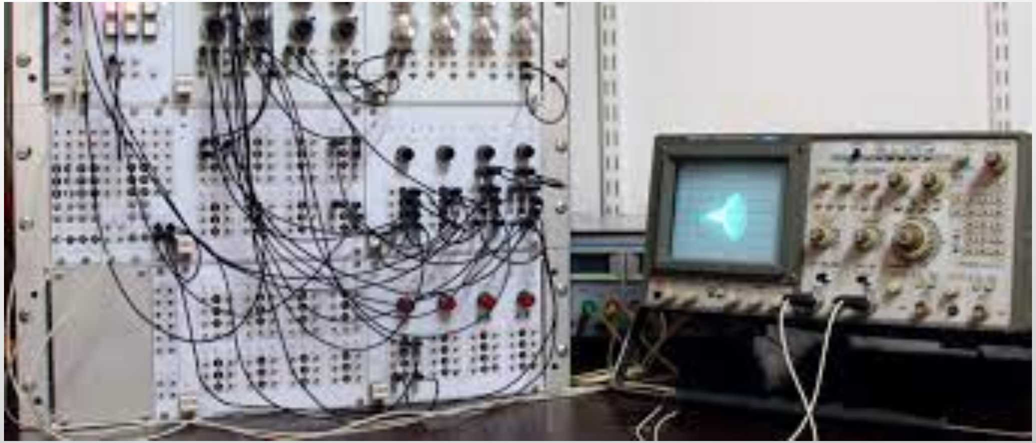
We hand laminated strips of magnetically permeable material that we annealed by boiling in liquid hydrogen and then hand wound coils around the cores to create our own induction coils

While 10- and 12-bit digitizers were becoming known, they were neither precise nor fast enough for wideband MT

Mid-1970's wideband MT instruments

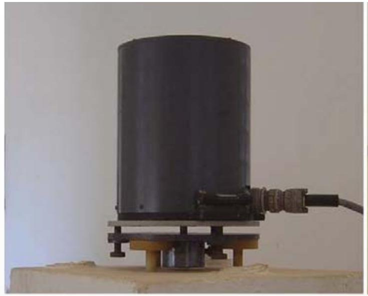


Analog computer! (An example, not the actual one)



Yes, that camper again! We had a couple. And a van. We destroyed. Hertz wasn't pleased. Sorry. We were young.

Stop for a breath…



What is the point of this trip down memory lane?

Simple. Back in the day, the price of admission to the ”MT Club” was high. Incredibly high. You had to know how to do more or less… everything. And generally there wasn’t a manual to guide you.

OK, let’s move along and wrap up this travelogue with a few more slides.

The Inter-College Break

1. Wanted to get into marine CSEM – thought it would be the next big thing.
2. Southern California! Not bad in 1979! Made a big impression.
3. At Scripps Institution of Oceanography, in what is now the Walter Munk Building at IGPP, I worked for Charles S. (Chip) Cox (photo inset above) in 1979 where I coded the marine CSEM analysis software (Fortran 77, PRIMEOS operating system) ahead of his first cruise to the East Pacific Rise.
4. (I attempted a cruise there with him in 1978 on the brand new but defective "New Horizon" but we were defeated by weather – could have drowned actually)…
5. A major lesson learned from Chip – "remember to turn the thing on before you throw it over the side of the ship!"
6. Got accepted to the Ph.D. program in Seattle so moved the the great North! (or to Canadians, the South!)

Gradual School in Seattle

1. I started in the PhD program at the Graduate Program in Geophysics at the University of Washington (advisor: Jimmy Larsen, Committee Chair: John Booker) in 1979. Dug a lot of holes for seismometers since Stew Smith (seismologist) was supporting my first year and tried to turn me into another seismologist.

2. Didn’t much like seismology. Kind of boring. Hah! But I like it better now, just glad I’m not one of them. Too crowded a field. Good thing no one understands EM. We have magical powers and can say whatever we want!

3. Mount Saint Helens 1980 – all hell broke loose – glad I didn’t get killed – MT there using digital(!) 12-bit SeaData cassette tape recorders, EDA fluxgates, crummy electrodes with John Booker.

4. First lake-bottom MT installation using USGS MT gear borrowed from Jim Towle (as above) in Seattle/Lake Washington for ultra-long period MT to examine upper mantle – loooong dipoles, Ag-AgCl2 electrodes

More grad school (1979 – 1985)

1. Did my thesis research – global mantle electrical conductivity study using magnetic observatory data – showed that no global 1-D model was consistent with the data, and that models could be formally grouped into distinct tectonic regimes
2. Started a software company that developed FasterRaster™ - the first high-level graphics library for the IBM PC. Advisor got tired of me making money, so gave me an ultimatum to get rich or get a PhD. Made a bad choice always regretted – money is great! Wish I had more…

More grad school (1979 – 1985)

1. Took a year off from grad school because of a funding gap. Did a job with a cathodic protection survey company in the North Sea where I deployed large arrays of E-field sensor dipoles and (strip chart recorders again) to measure E-fields to compensate for telluric currents in their measurements. Job was hell. Lived on a gas recompression platform for months in Frigg Field between Aberdeen and Stavanger. Nearly killed a crew in a submarine. Analyzed the data in Houston, TX in the summer. Houston in the summer is even worse hell.
2. Then took a job using MT for geothermal exploration at Coso Hot Springs, California and in Philippines with UNOCAL in Brea, California with college buddy Jens Pedersen. Amdahl mainframe with color terminals!

The Postdoc Years (1985-1986)

1. Cecile and Ida Green Scholar at IGPP, SIO, Univ. California San Diego

2. Worked in developing obscure algorithms for analysis/inversion of global EM data
    1. One day the great man himself, Cecil Green, walked into my office (which I was then sharing with Jason Phipps-Morgan) and asked me what I was working on. I told him. He replied – "well as long as YOU think that's interesting" and then walked out. I got paid anyway.

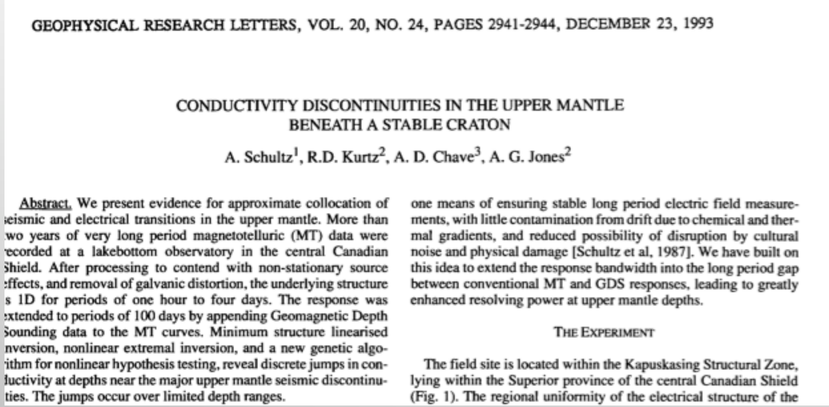
The Postdoc Years (1985-1986)

1. Played around in the lab with people like Spahr Webb, Steve Constable, Pascal Tarits. Developed some new, weird and possibly still interesting Ag-$AgCl_2$ electrodes for marine EM.

2. Went to sea on EMSLAB deployment and recovery cruise with Jean Filloux, Laurie Law etc. Technically was postdoc with Alan Chave, but he'd moved to Bell Labs, so winged it… Marveled at Filloux's suspended torsion wire magnetometer with optical nulling and his separate marine E-field sensor with mechanical solenoid chopper amplifier! They were enormous! Later I built my own small chopper, but then proposed to NSF to build a chopperless marine CSEM/MT system with induction coils – but Steve beat me to it!

Assistant Professor (1986-1991)

1. At University of Washington School of Oceanography
2. Developed my first embedded systems for marine hydrothermal research, using C and assembly language
3. Developed and co-operated ocean bottom seismometers for Office of Naval Research
4. Lots of diving in research submersibles to mid-ocean ridge vent fields, marine deployments
5. Built my first 16-bit long-period MT system for lakebottom/lakeside deployment in northern Ontario, Narod magnetometer, home-built E-field amps



GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 24, PAGES 2941-2944, DECEMBER 23, 1993

CONDUCTIVITY DISCONTINUITIES IN THE UPPER MANTLE BENEATH A STABLE CRATON

A. Schultz[1], R.D. Kurtz[2], A. D. Chave[3], A. G. Jones[2]

Abstract. We present evidence for approximate collocation of eismic and electrical transitions in the upper mantle. More than wo years of very long period magnetotelluric (MT) data were ecorded at a lakebottom observatory in the central Canadian Shield. After processing to contend with non-stationary source ffects, and removal of galvanic distortion, the underlying structure s 1D for periods of one hour to four days. The response was xtended to periods of 100 days by appending Geomagnetic Depth Sounding data to the MT curves. Minimum structure linearised nversion, nonlinear extremal inversion, and a new genetic algoithm for nonlinear hypothesis testing, reveal discrete jumps in conluctivity at depths near the major upper mantle seismic discontinuties. The jumps occur over limited depth ranges.

one means of ensuring stable long period electric field measurements, with little contamination from drift due to chemical and thermal gradients, and reduced possibility of disruption by cultural noise and physical damage [Schultz et al, 1987]. We have built on this idea to extend the response bandwidth into the long period gap between conventional MT and GDS responses, leading to greatly enhanced resolving power at upper mantle depths.

THE EXPERIMENT

The field site is located within the Kapuskasing Structural Zone, lying within the Superior province of the central Canadian Shield (Fig. 1). The regional uniformity of the electrical structure of the

Then Cambridge, Cardiff, Oregon State

1. At Cambridge/Cardiff I built more advanced hydrothermal gear and finally my first marine MT system then developed more marine hydrothermal sensors and samplers for operation in extreme environments (in the UK)
2. 1993 carried out MT experiment in Zimbabwe with Kathy Whaler using MT equipment pool in Edinburgh's equipment – circuit boards hand-built by… Alan Jones! Barely worked at all! Gear got smoked in Africa – nearly total write-off but great experience.
3. Started and directed Earth-Ocean Systems, Ltd in England and developed instrumentation for extreme environments
4. In 2003 returned to the US to take up present position at Oregon State University where gradually transitioned from marine hydrothermal and EM work to continental work, eventually becoming the lead for the EarthScope MT program and director of the National Geoelectromagnetic Facility – a large MT instrument pool

So, what's the take-home message?

1. Being an ageing Boomer, I got to use computers when they were hand-built, coded on paper and using switch panels, and when the MT experimentalist had to design the experiment, design and build the instruments, deploy and retrieve them under terrible conditions, wade through horrendous noise, create new algorithms to analyze the data when the statistics were not well established (the pre-dawn of robust methods), and…

   … other words – to own the ENTIRE process of the creative cycle, and to be solely and totally responsible for the outcomes. Oh, yeah, and get the funding too…

That circumstance is a rare privilege few going into MT can experience today. We try to maintain that spirit in my lab even now, but it isn't easy to keep the lights on and only a select few labs can offer that sort of immersion in "Edisonian invention and discovery" (hi Steve!)

Where do we go from here?

1. I just described a process that represents an enormously high price of admission. You can't expect *everyone* going into MT to go through all of that! While our equipment has become more sophisticated, there are a number of commercial MT equipment suppliers with some very capable and expensive instruments, but our *workflow* remains deeply rooted in the mid-20*th* century
2. Data just comes from the internet, doesn't it?
3. Well, perhaps it should!
4. How do we lower the price of admission and widen the take-up of MT and related methods?
5. What problems do we address? What are the bottlenecks?
6. We think that the answer may lie in the…

IoMT - The Internet of MT

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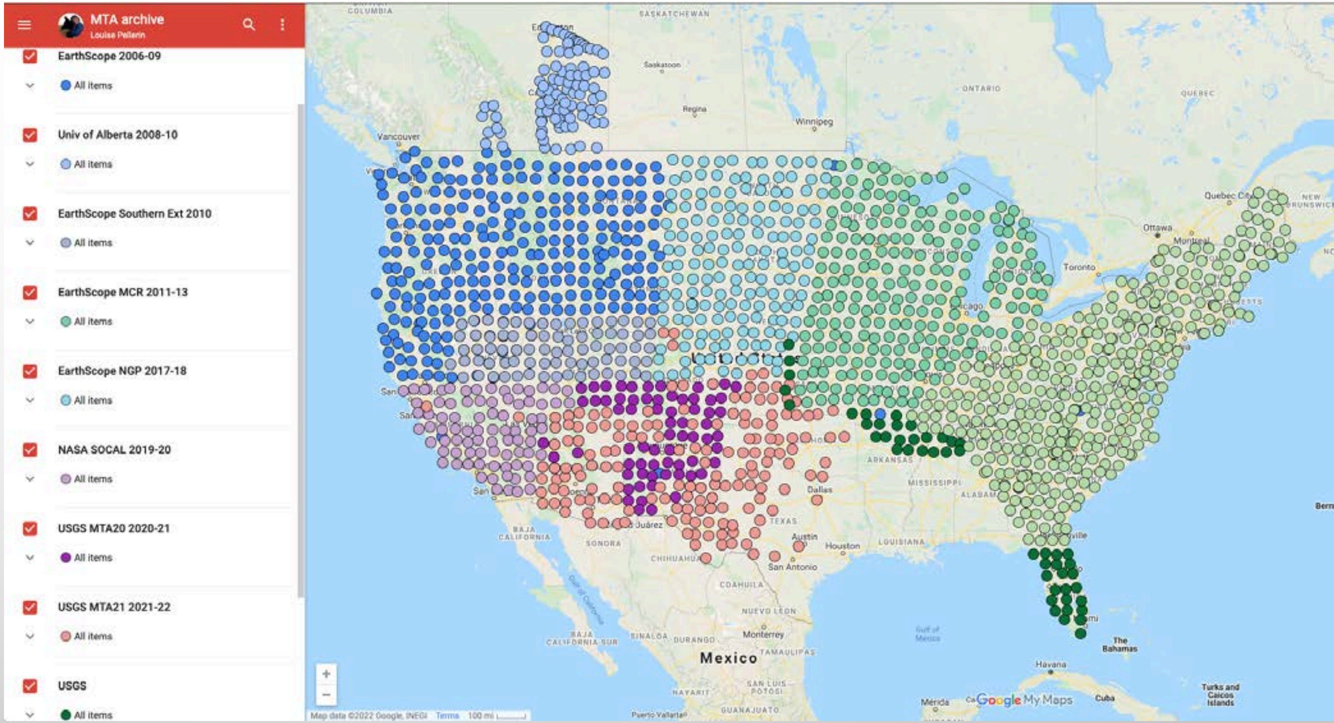
The Magnetotelluric (MT) Array – temporary electric and magnetic field monitoring stations

Installed by Oregon State University and contractors (funded by NSF (2006-2018), NASA (2019-2020), USGS (2020-Present)

Starting in 2005, we deployed 7 long-term MT “Backbone Stations” distributed across the conterminous US (CONUS) and then started temporary deployments of long-period MT stations on a 70-km grid of points spanning the continent.

We plan to complete the MT Array in mid-2024 with >1900 stations

We use Narod NIMS MT systems, OSU electrodes and have developed a large MT instrument pool to support the effort



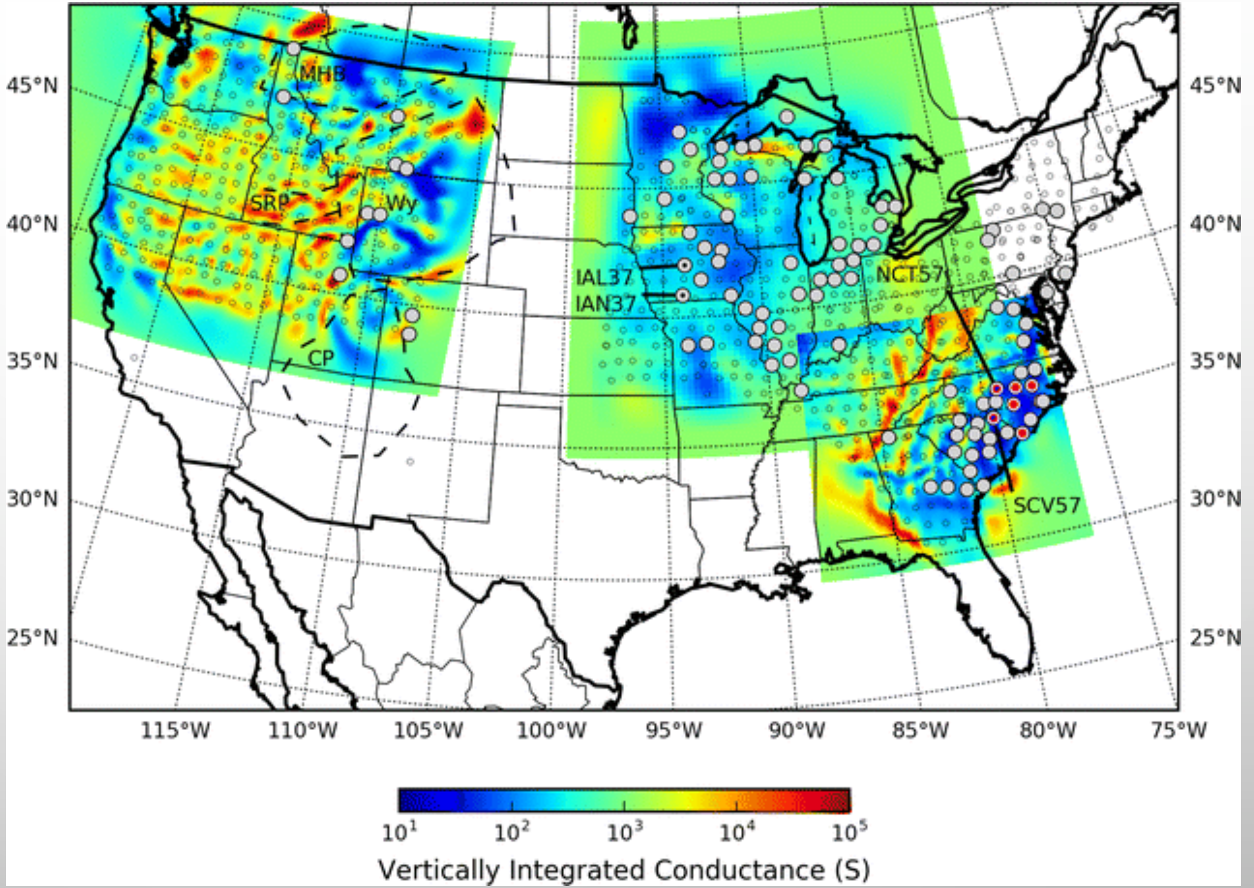
3-4 orders-of-magnitude heterogeneity at all depths

3-D conductivity structure

Vertically integrated Earth conductance (from 15–150 km) calculated from the 3-D MT inverse solutions of Meqbel et al. (2014) (northwestern USA), Yang et al. (2015) (north-central USA), and Murphy and Egbert (2017) (southeastern USA).

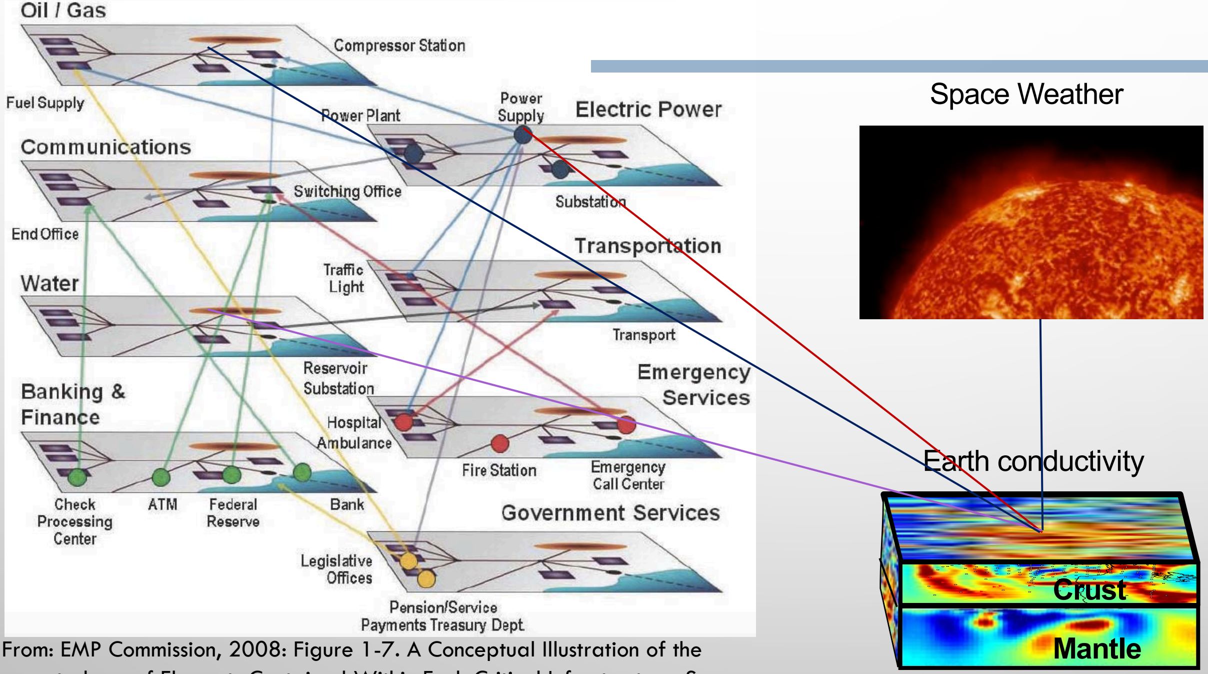
[From: Murphy & Egbert, 2018]

So – sure – really useful for fundamental geosciences. But also for so much more…



GICs due to Space Weather

Interconnections: Critical infrastructure/Electromagnetic environment

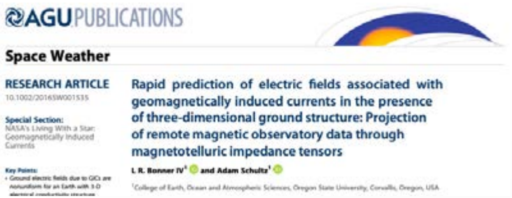


(left) From: EMP Commission, 2008: Figure 1-7. A Conceptual Illustration of the Interconnectedness of Elements Contained Within Each Critical Infrastructure. Some connections are not shown (diagram provided courtesy of Sandia National Laboratory).

"In practice, understanding the interdependence may be a difficult task because subject area experts are not necessarily attuned to coupling mechanisms that span the boundary between their respective discipline and another, and because an accurate representation of the interdependence requires a familiarity with transdisciplinary phenomena." –

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack – Critical National Infrastructures, 2008.

OSU 3-D model calculated voltage at substations due to 1989 GMD, 3/13/1989 09:00-15:00UT (peak GMD)


AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE
10.1002/2016SW001535

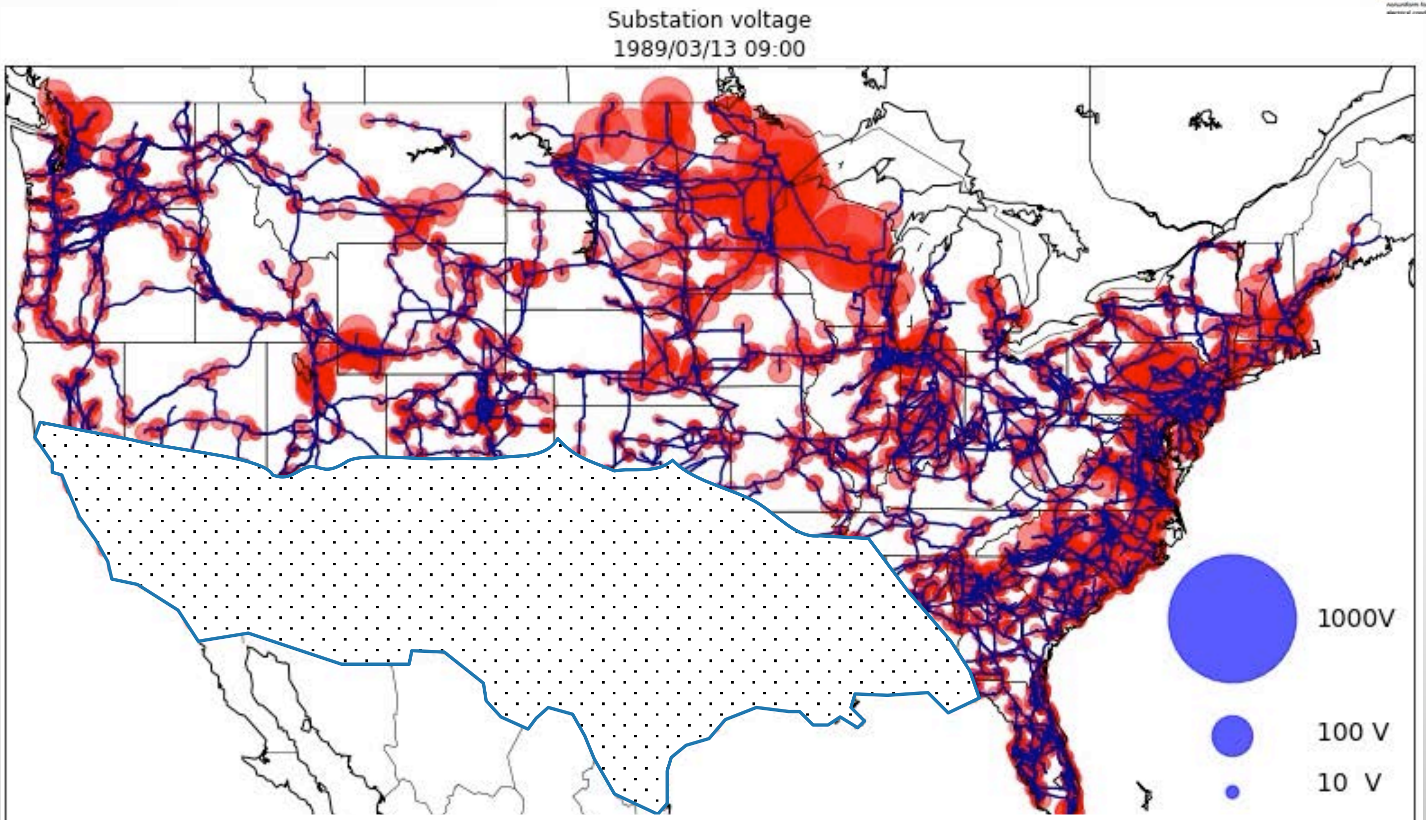
Special Section:
NASA's Living With a Star: Geomagnetically Induced Currents

Key Points:
• Ground electric fields due to GICs are nonuniform for an Earth with 3-D electrical conductivity structure

Rapid prediction of electric fields associated with geomagnetically induced currents in the presence of three-dimensional ground structure: Projection of remote magnetic observatory data through magnetotelluric impedance tensors

L. R. Bonner IV[1] and Adam Schultz[1]

[1]College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA



Note – large GMD induced bus voltages in the South as well as in the North – impact of 3-D ground conductivity

Ground-level electric fields integrated along the path of the high-voltage transmission lines. Voltage is shown relative to ground at one Ohio substation. Algorithm by Bonner & Schultz, Space Weather, factoring in 3-D crust/mantle conductivity.

Note – true voltage state calculation requires integration with power flow model.

(Path integration and mapping using BEZPy by G. Lucas, USGS)

What started as fundamental Geoscience through NSF EarthScope support became an issue of protecting critical infrastructure through NASA and USGS funding

- 3D crust and upper mantle structure, when factored in the power flowing through the electric transmission network, fundamentally changes the risk to the power grid from space weather – this was a collaborative effort by OSU (A. Schultz) and USGS (J. Love, A. Kelbert) plus support by NASA (A. Pulkkinen, J. Spann), with IRIS working with NASA to provide 2-years bridging support while we were working on longer-term funding stream, followed by…
- …several years of efforts through SWORM, OSTP to elevate the issue to gain White House support…
- …ended up with a Presidential Executive Order requiring that we complete the MT Array in the conterminous US plus various regulatory requirements about data availability

Taking a break at Vice President Pence's office in the EEOB after an interesting day presenting information on MT, space weather and critical infrastructure to people in the Situation Room… One of them is me. Another is a Major General looking like a civilian, and the other is my guest, our VP for Research. Later went to the US Senate to get some funding…

Political/Regulatory

GMD/GIC Risk Assessment and Mitigation – requirements and regulatory framework

- The National Space Weather Action Plan and NSWA Strategy [NSTC, 2015; update 2019]
- Executive Order 13744 [Obama, 2016]
- Federal Energy Regulatory Commission (FERC) Orders 779 [2013], 851
- North American Electric Reliability Corporation (NERC) TPL 007-1,2/3

Risk assessments must factor in ground conductivity; mandate transmission system sensor and magnetic field data to be collected

EMP

- Executive Order 13865 [Trump, March 26, 2019]; line item in federal FY2020 budget
- Game on! Let's keep mapping the continent! Today, America, tomorrow, somewhere else!

Sect'y Interior directed to:

1) **Support the research, development, deployment, and operation of capabilities that enhance understanding of variations of Earth's magnetic field associated with [natural and human-made electro-magnetic pulses] EMPs,** and
2) **Within 4 years of the date of this order, the Secretary of the Interior shall complete a magnetotelluric survey of the contiguous United States to help critical infrastructure owners and operators conduct EMP vulnerability assessments.**

NATIONAL GEOELECTROMAGNETIC FACILITY AT OSU

(Note – observatory quality triaxial fluxgate magnetometers used for long-period MT; specialized induction coil magnetic field sensors for wideband MT)

By mid-2019:

98 MT systems

- 60 long-period
- 28 wideband
- 10 RFMT
- Mixed ownership – OSU, NSF, U. Manitoba

Now implementing real-time Cloud sync telemetry to long-period systems

Building out first 24 OSU extended band MT systems (DARTs) with requirements for 100 more next year

NATIONAL GEOELECTROMAGNETIC FACILITY AT OSU

Dedicated Electrodics lab – currently producing OSU Series-4 dual chamber Petiau electrodes

NGF Electrodics and electronics personnel (Brady Fry, Taylor Viti, Jacob Lovio, Leandra Weydt) produce and test hundreds of MT electrodes per year and work on calibration and field testing of equipment.

Controlled temperature facility for testing 80 electrodes at a time; controlled magnetic field facility inside Faraday shield for calibrating magnetometers. Field test site 20 km from lab suitable for long-period MT tests

Narod NIMS MT system with Narod triaxial ring-core fluxgate sensor and OSU Series-2 Pb-PbCl2 dual-chamber gel electrodes

(left) Narod NIMS transportable configuration

(right) Narod NIMS underground vault observatory with 3G telemetry

Zonge ZEN Rx6 wideband MT system co-developed with OSU under NSF funding; our NIMS instrument pool

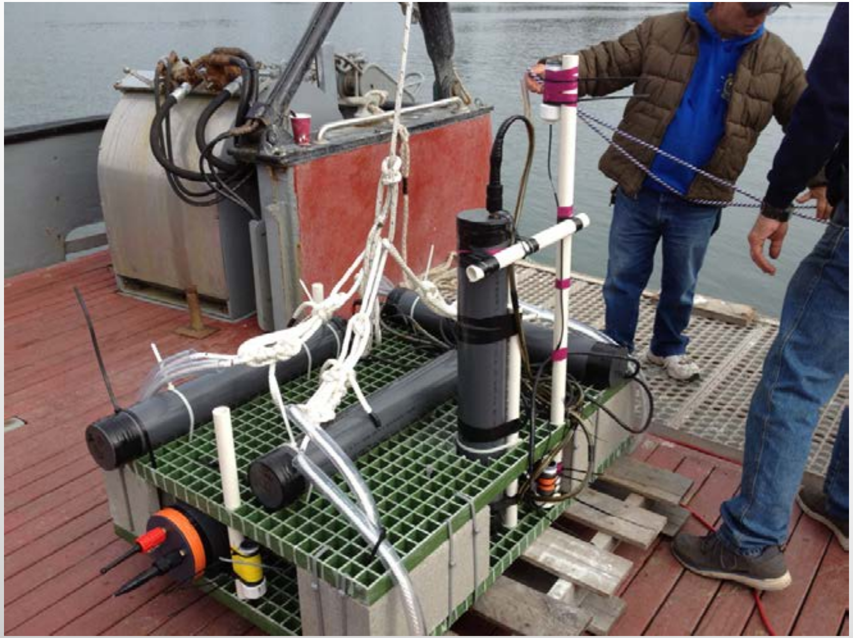
Ultra wide-band EM receivers configurable for dc, micro-Hz-to-MHz operations, and related support equipment.

The NGF currently operates

- 16 Zonge ZEN Rx6 (ultra)wideband EM receivers,
- 10 custom Zonge ZEN Rx6 radiofrequency MT receivers
- 18 Zonge/Geotell ANT/4 induction coils
- 30 Zonge/Geotell ANT/6 induction coils
- 27 Zonge/Geotell ANT/7 induction coils
- a number of Zonge/Geotell ANT/2 and 2m induction coils, and
- 10 LEMI 031 fluxgate magnetometers.

5-6 channel, 32-bit digitizer (27 noise-free bits @ 1 Hz), ZIGBEE mesh network, OSU series 2 electrodes.

Early oregon coastal test of a marine configuration, 9-channel ZEN with Zonge/Geotell Ant-2 induction coils, Ag-$CgCl_2$ electrodes, optional 3-ch seismometer, chip-scale atomic clock



(left) prototype version of 3 E, 3 B sensor marine sled. (right) custom molded, self-buoyant, trawl-resistant outer housing for 9-ch integrated 32-bit mt/seismic sensor system; acoustic telemetry

Initial puck system design – integrated MT receiver, LiPo batteries and fluxgate

(left) In this conceptual design prototype we considered an all-in-one package that could be deployed quickly and self orient using MEMS-based positional sensors. A number of down-sides became evident when considering different deployment scenarios.

(right) Early version of OSU Series-4 electrodes.

OSU-Zonge ZEN Rx6 long-term geothermal monitoring deployment at Newberry Volcano, Oregon powered by solar and by methanol fuel cell systems

This was one of several systems monitoring an enhanced geothermal systems stimulation project carried out under US Dept. of Energy support by AltaRock Energy.

Joint deployment of OSU Zonge ZEN and Phoenix Geophysics MTU5 systems at Mount Saint Helens, Washington in October, 2018

(left) Approaching the crater, site installation. (right) Subaerial configuration of ZEN/ANT-4 coils developed by OSU for MT installation without ground disturbance. Makes permitting easy!

The Magnetotelluric (MT) Array – temporary electric and magnetic field monitoring stations

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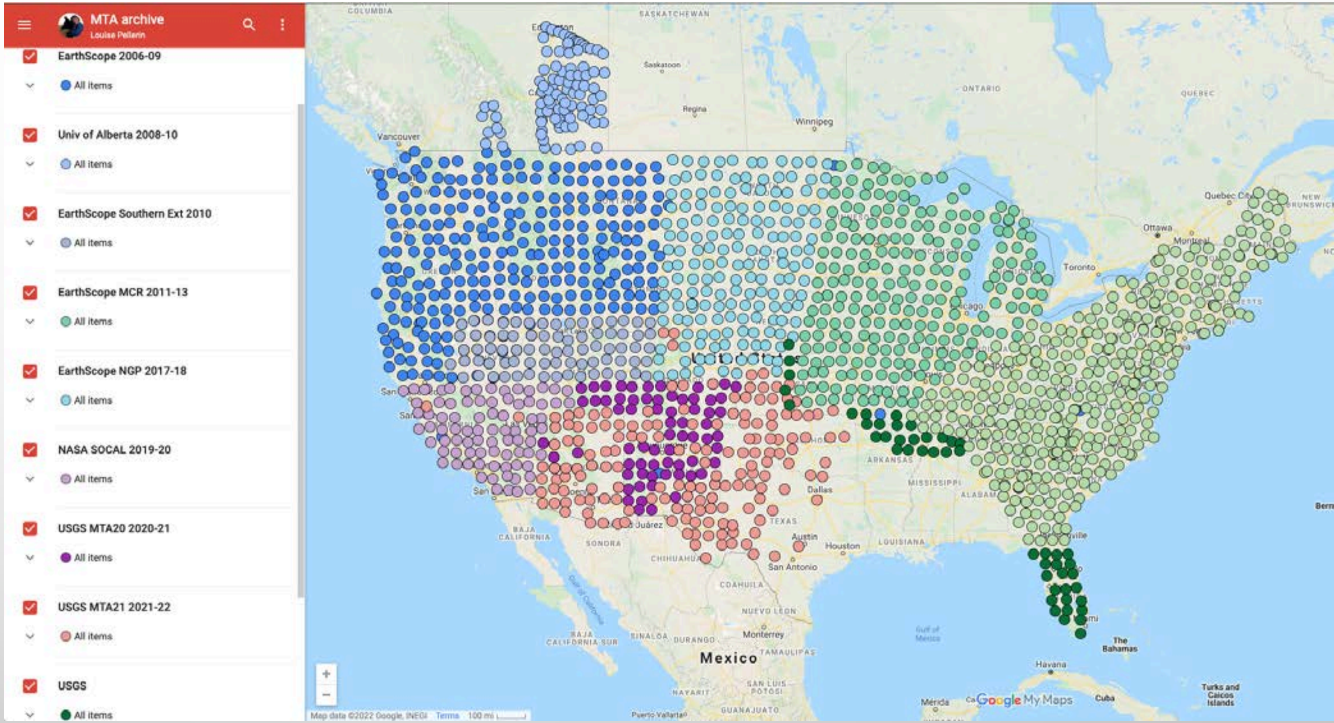
Logistics, logistics, logistics!

How do we do this efficiently?

A rolling temporary array spanning thousands of km with multiple field crews?

What causes delays, bottlenecks, drives up costs and leads to missed targets?

-> Strong technical support, fast repairs, tight communications and above all…
… Situational Awareness is essential!



OK – so that's all about MT equipment and present-day capabilities…

How do we lower the price of admission to the MT club?

How do we lower the cost of obtaining, processing and interpreting MT data?

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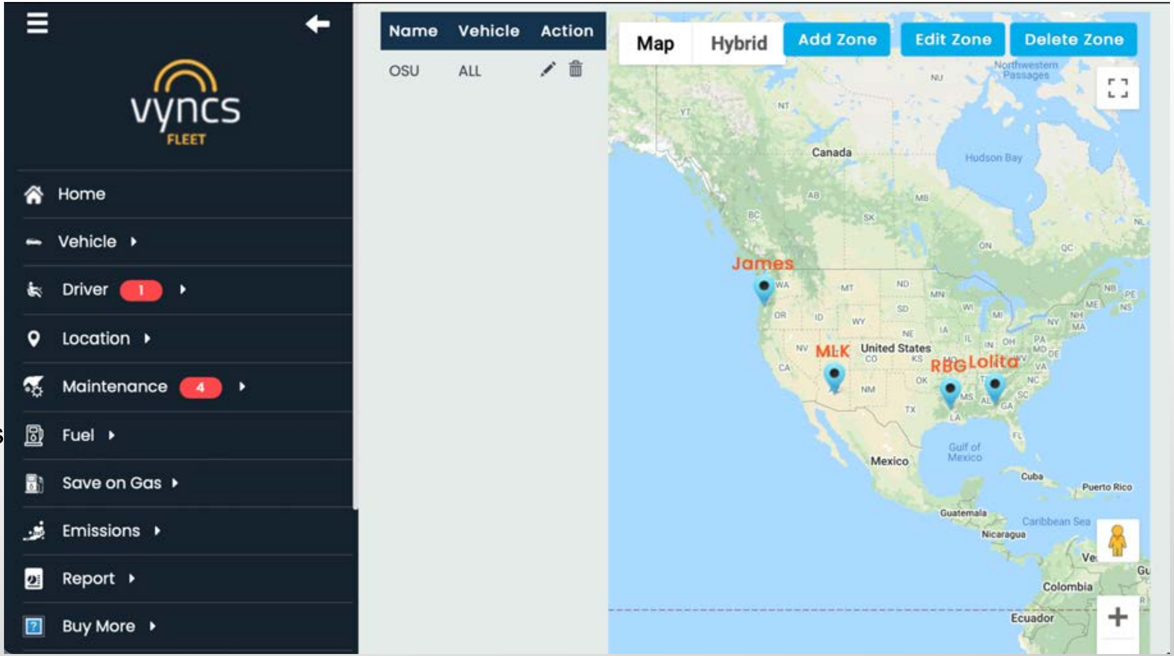
Situational Awareness increases efficiency of operations

We need to know where our crews are at all times, and what they are doing

- Real-time fleet tracking
- Semi-automated daily site visit and production reports using established forms and metadata
- Instrument problems reports
- Slack workspaces and channels
- Auto cloud synchronization of data from the field to multiple cloud services
- Rapid in-field data processing for QC
- Rapid RR processing and archival/distribution
- Weekly web meetings for permitting, data quality, planning, with weekly reporting



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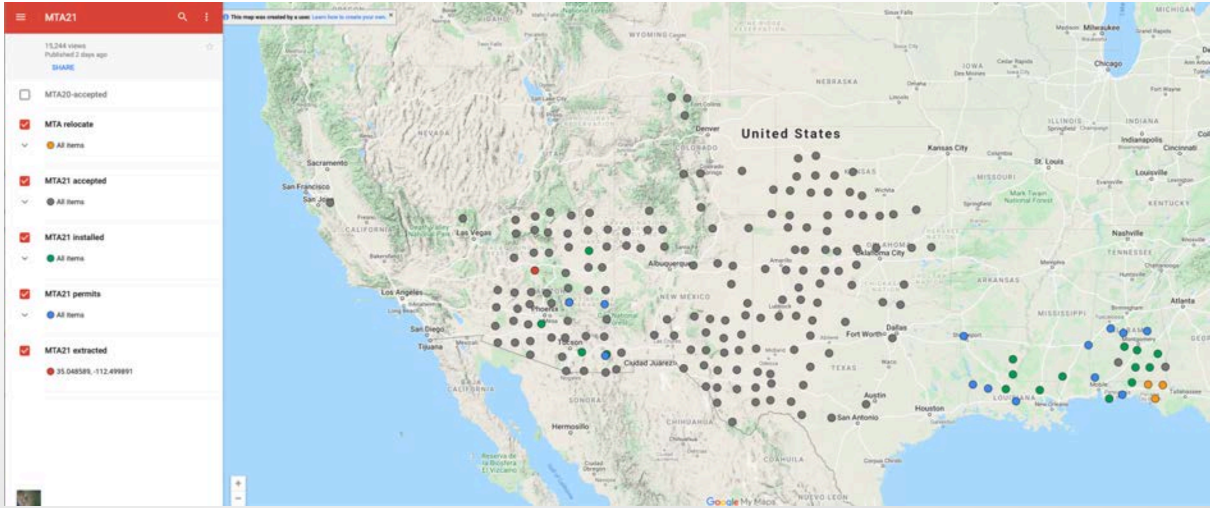


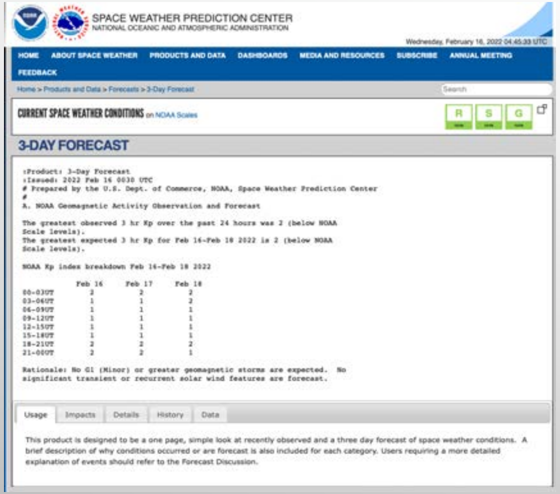
Continuously updated field operations status maps (provided by Green Geophysics)

Situational Awareness increases efficiency of operations

Safety, safety safety… and efficiency!

Awareness of *field conditions* through

- Nightly updates from field crews (emails, Slack) including field data processing reports



SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Wednesday, February 16, 2022 04:45:33 UTC

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Home > Products and Data > Forecasts > 3-Day Forecast

CURRENT SPACE WEATHER CONDITIONS on NOAA Scales — R S G

3-DAY FORECAST

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:Product: 3-Day Forecast
:Issued: 2022 Feb 16 0030 UTC
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
#
A. NOAA Geomagnetic Activity Observation and Forecast

The greatest observed 3 hr Kp over the past 24 hours was 2 (below NOAA
Scale levels).
The greatest expected 3 hr Kp for Feb 16-Feb 18 2022 is 2 (below NOAA
Scale levels).

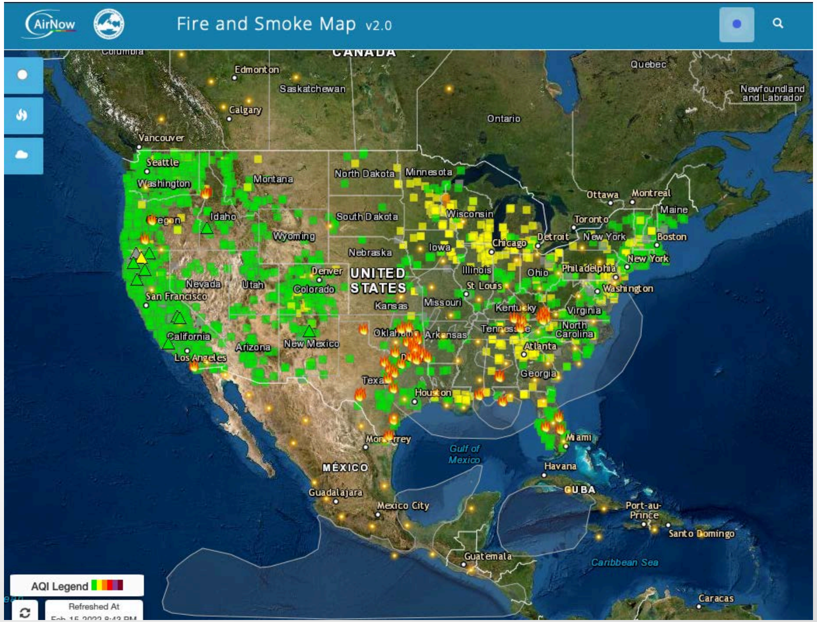
NOAA Kp index breakdown Feb 16-Feb 18 2022

             Feb 16     Feb 17     Feb 18
00-03UT        2          2          2
03-06UT        1          1          2
06-09UT        1          1          1
09-12UT        1          1          1
12-15UT        1          1          1
15-18UT        1          1          1
18-21UT        2          2          2
21-00UT        2          2          1

Rationale: No G1 (Minor) or greater geomagnetic storms are expected.  No
significant transient or recurrent solar wind features are forecast.
```

Usage | Impacts | Details | History | Data

This product is designed to be a one page, simple look at recently observed and a three day forecast of space weather conditions. A brief description of why conditions occurred or are forecast is also included for each category. Users requiring a more detailed explanation of events should refer to the Forecast Discussion.



National and regional fire and smoke maps – climate change is impacting our operations!

Emphasizing additional deployments when geomagnetic disturbance levels are favorable

Situational Awareness increases efficiency of operations

Daily production and site visit reports via cloud synched shared folders, emails and Slack workspace channels

Each 2-person crew (one ¾ ton 4x4 pickup truck with lockable canopy, 11 NIMS instruments and support equipment) reports each evening.

NIMS MT instrument user interface NIMSpy requires crew to populate metadata accurately and then assists with semi-automated reporting

2022-02-15_LAB43c.txt

```
Date:                        2022-02-15

Software:                    NIMSpy v0.11.2

Crew:                        Lena Tokmakoff & Britt Bommer

Run ID:           LAB43c
Site Name:                   Dismal Swamp, LA, USA

Status:           Check
------------------------------------------------------------
NIMS ID:                     2501-19
Mag ID:           2611-06
Electrodes ID:    N          42PB2106073
                  S          42PB2106044
                  E          42PB2106091
                  W          42PB210607E
                  G          Cu
------------------------------------------------------------
NS Length: 100, Azimuth: 0
EW Length: 100, Azimuth: 90
------------------------------------------------------------
Electrode Parameters, prior to installation:

Resistance (ohms):
(N+ to S-) =
(N- to S+) =
(E+ to E-) =
(E- to W+) =

Voltage (mV):
(N+ to S-) DCV =
(E+ to W-) DCV =
------------------------------------------------------------
Electrode Parameters, at Check:

Resistance (ohms):
(N+ to S-) =                 760
(N- to S+) =                 817
(E+ to W-) =                 1253
(E- to W+) =                 1247
(N+ to G-) =                 -5.325 M
(N- to G+) =                 11.35 M

Voltage (mV):
(N+ to S-) DCV =             6.8
(E+ to W-) DCV =             -0.2
(N+ to G-) DCV =             535.6

(N+ to S-) ACV =             7.4
(E+ to W-) ACV =             3.6
(N+ to G-) ACV =             536.1
------------------------------------------------------------
Gain =                       LL
(GPS+ to Ex Gain-) =         OL
(GPS+ to Ey Gain-) =         OL
------------------------------------------------------------
Last time stamp for previous run =       15/02/22 18:48:36
First time stamp for run =               15/02/22 19:48:23

Lat =                        31.262241 N
Long =                       91.764407 W
Altitude =                   33.1 M
Declination =
------------------------------------------------------------
Battery (V) =                13.3 V
------------------------------------------------------------
Comments:

Site undisturbed upon arrival - much drier than install. Battery dead at 12.36v.  219 hours of data (10
days).  All trode resistances under 1200ohms.  Hy: 270.  Releveled mag and swapped out batteries - 13.02v
upon departure.

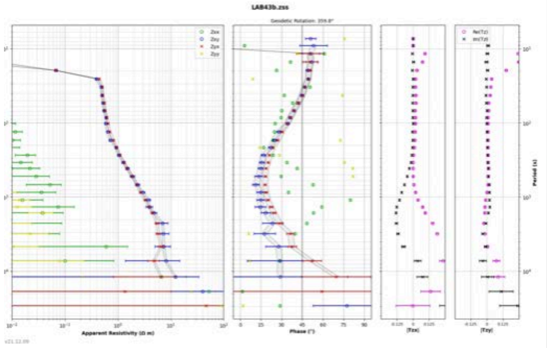
[Previous Comments]: X array at 0 deg rot.  Site located in supersaturated clay based marsh.  Warm overcast
day.  Small WMA road 300m N.  Some puddles and water seeping nearby.  Shallow NIMs hole to avoid water
table.  Russian buckets installed.  Mag cable NMC3A.  Battery upon departure: 12.94v.
```

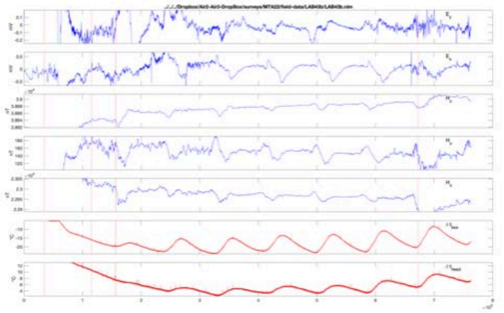
Today Lena and I serviced LAB43. This site we had quite a bit of trouble upon install with water filling our holes as soon as we dug them. This site had the NIMS above ground and the Mag installed with 2 bags around it, both methods kept the equipment dry and protected from any water. The electrodes had low resistances when measured E/W roughly 1.2k and N/S roughly 700. We believe the water table is near or at the surface of the location we installed in and that that might be the reason the E channels were less than optimal. We changed the batteries and leveled the Mag again before setting it for its c run.

Tomorrow we plan on servicing LAA43.

Cheers,
Britt

2022-02-15_LAB43c.txt





Situational Awareness increases efficiency of operations

Situational awareness is improved through…

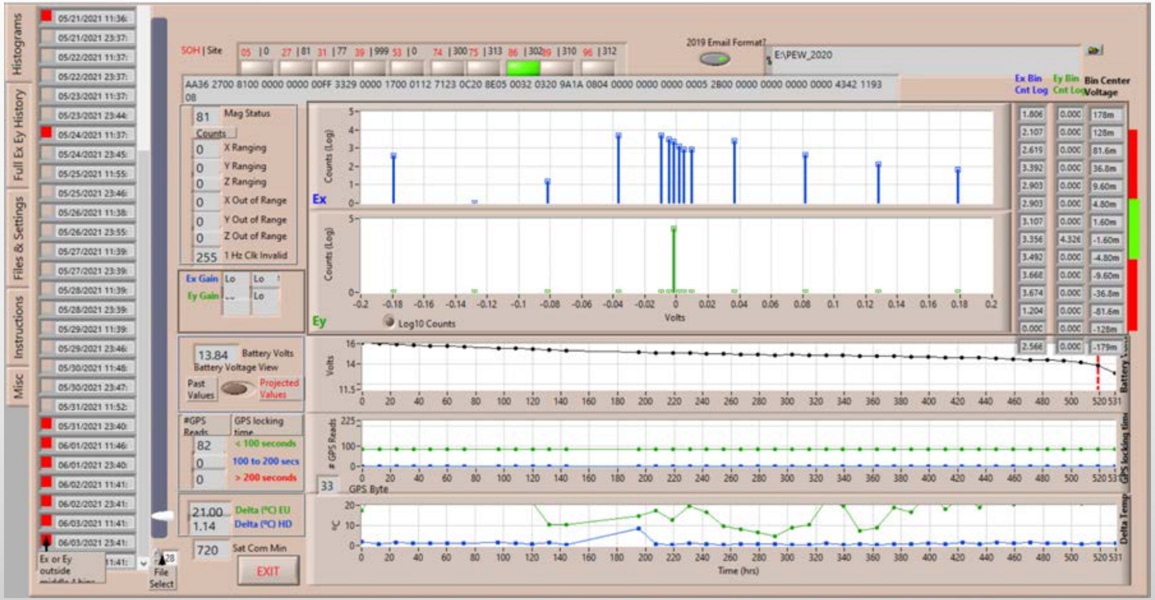
- Telemetry of State of Health (SoH) of your MT equipment
    - We've implemented USGS SoH satellite telemtry (Paul Bedrosian) on a number of our systems (next slide)

- The gold standard however is moving from manual data retrieval and cloud synchronization upon connection of field computers to the internet (what we have been doing for years), plus SoH, to real-time telemetry of all data direct from the field (what we are implementing this year) and then finally

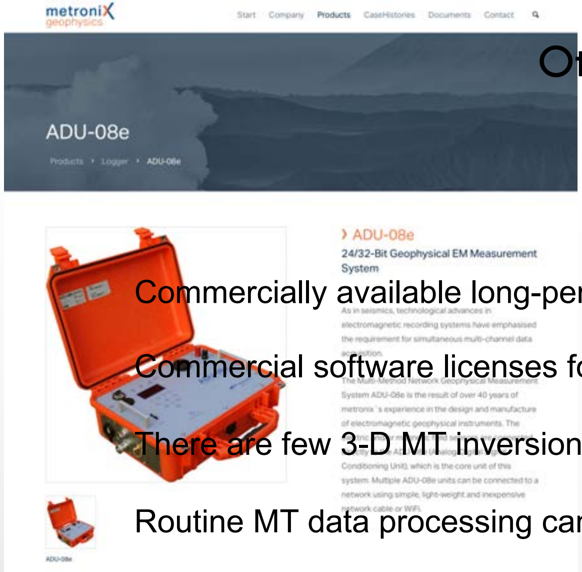
- Building automatic cloud sync/telemetry/remote command and control into all future hardware

Situational Awareness increases efficiency of operations

USGS SoH system (implemented on 6 OSU NIMS)



Other barriers to wide-scale adoption of MT

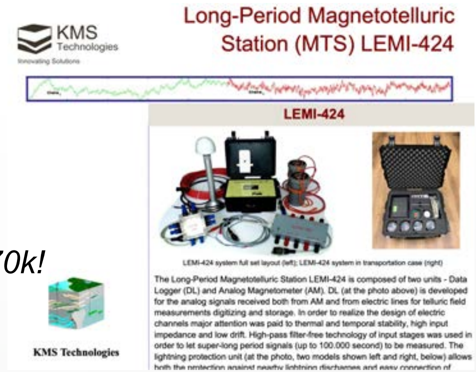


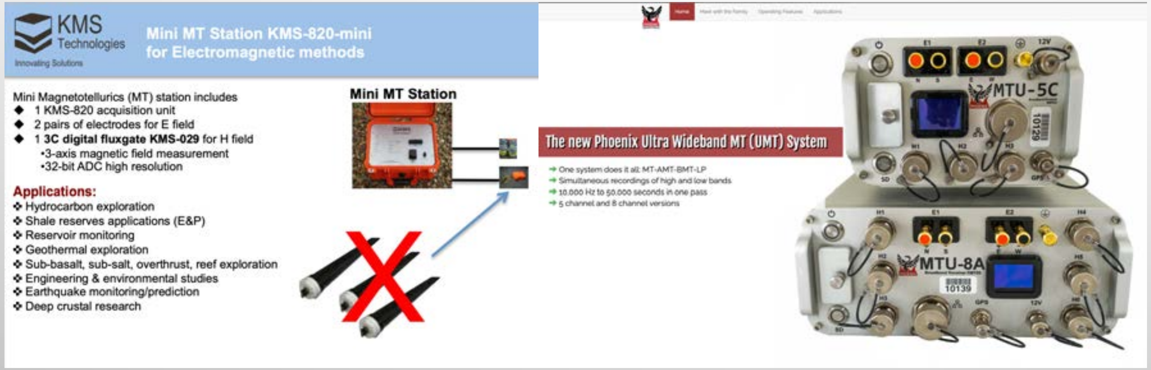
Commercially available long-period and wide-band MT equipment is *expensive. Even $60-70k!*

Commercial software licenses for MT data processing are expensive.

There are few 3-D MT inversion codes available, and these are expensive for commercial use.

Routine MT data processing can be time consuming and require some knowledge of coding to use.





Today’s Menu

1. Evolution of MT instrumentation and technique – a brief personal history
2. Large array EM/MT surveys for regional/continental scale investigations, 3-D/4-D target discrimination and resource/reservoir monitoring
3. Barriers to more widescale adoption of MT/EM methods
4. IoMT – the Internet of MT

IoMT

Data acquisition Devices

- Low cost
- Long- and extended-period and planned wide-band
- Integrated electronics and fluxgate magnetometer in latest design
- Integration with external induction coil sensors planned

Cloud-based server and software stack

- LTE data transmission
- Layers of service to meet customers need
- Secure, high-reliability web interface to validate, archive, and process data

IoMT

Data acquisition Device Design Concept Evolution (2017-Present)

- In 2017 we started on a small side-project (in our own spare time such as it is) to develop a next generation, low-cost MT data acquisition system
- Original concept was the “puck” – with a form-factor resembling a hockey puck as a dongle attached to an inexpensive ($50 USD) Android smartphone
- The smartphone provided large local data storage, sophisticated LTE and WiFi/Bluetooth for telemetry as well as a reasonably open software architecture and accessible app store to support software distribution
- After some experimentation we concluded it was better and more flexible to develop our own platform because of limitations/restrictions inherent to Android

IoMT Candidate Platforms

BeagleBoard

Raspberry Pi

Arduino

Micropython

IoMT Candidate Platforms

BeagleBoard
-High Power

Raspberry Pi
-High Power

Arduino
-Low Power

Micropython
-Low Power

IoMT Candidate Platforms

BeagleBoard
-High Power

Raspberry Pi
-High Power

Arduino
-Low Power
-Low Cost

Micropython
-Low Power
-Low Cost

IoMT Candidate Platforms

BeagleBoard
- -High Power

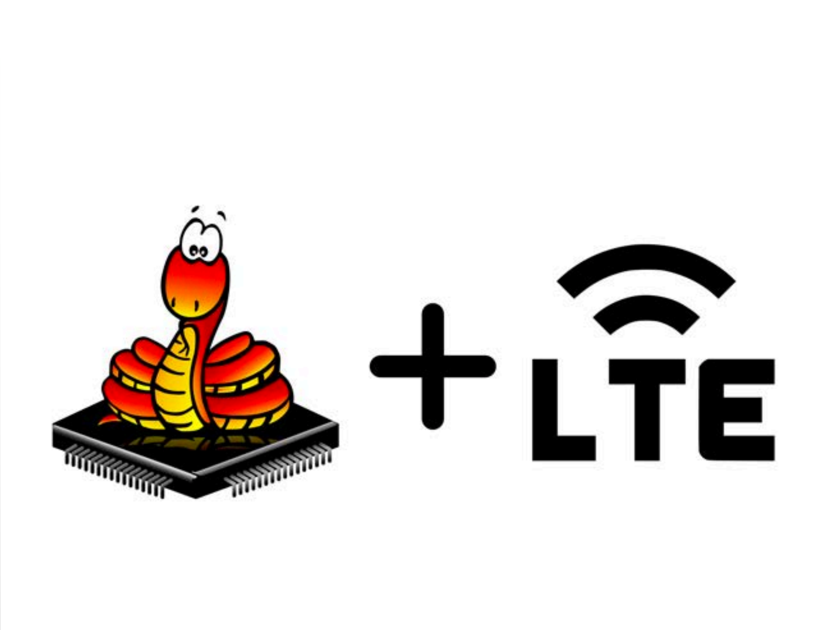
Raspberry Pi
- -High Power

Arduino
- -Low Power
- -Low Cost
- -C/C++ Based

Micropython
- -Low Power
- -Low Cost
- -Python Based

IoMT V1.0 Complete Baseline Functionality

- ARM capable 1 Hz system
- LTE timing delays
  - ADC servicing constraints

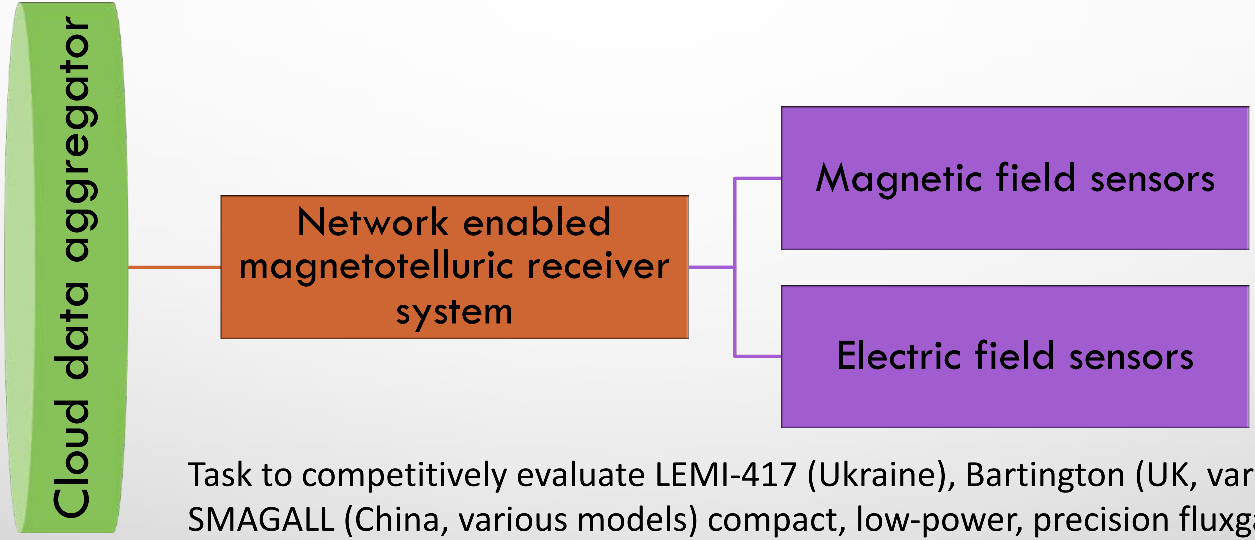


IoMT V1.0 Complete Baseline Functionality

- ARM capable 1 Hz system
- LTE timing delays
  - ADC servicing constraints
- FPGA
  - Service timing critical ADCs
  - Increased complexity
  - Sampling rate extendibility

IoMT

Puck Concept - Network-enabled MT sensor array system circa Feb 2017

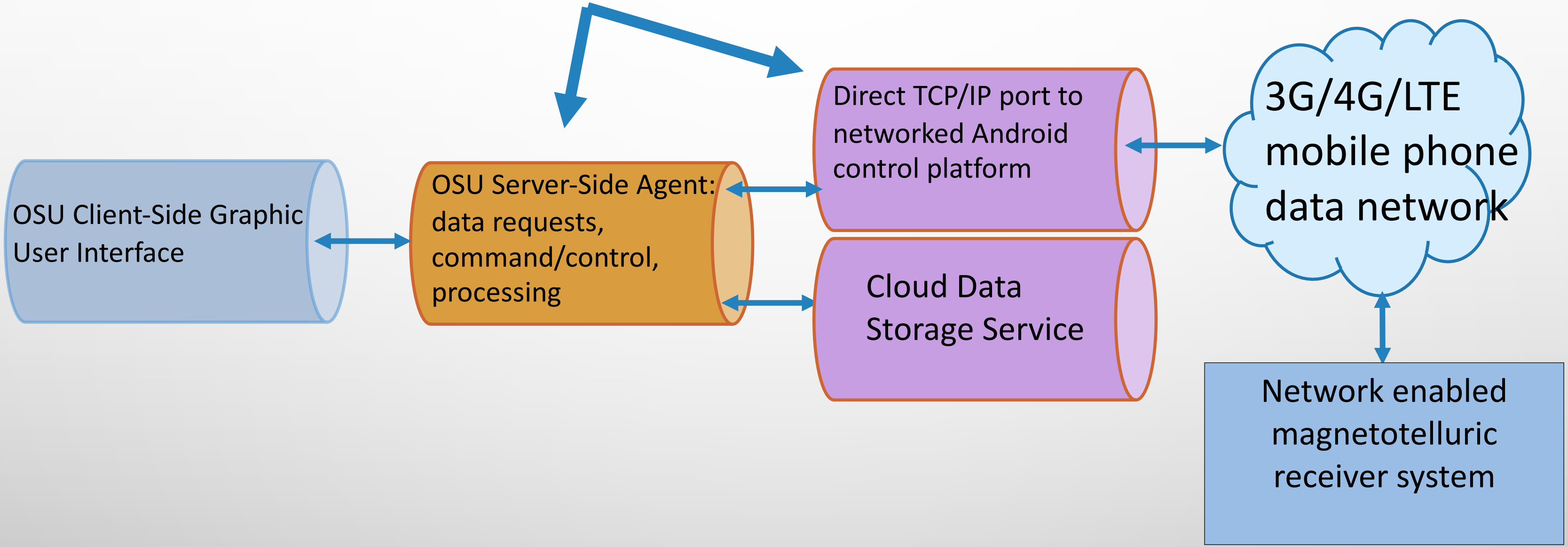


Task to competitively evaluate LEMI-417 (Ukraine), Bartington (UK, various models), SMAGALL (China, various models) compact, low-power, precision fluxgate sensors begins in March 2019, including lab and field testing of noise levels, performance and ease of integration into target platform design. This continued off-and-on until 2021. Initial order for 24 units issued.

IoMT

Puck Concept – Initial cloud data aggregator design concept circa Feb 2017

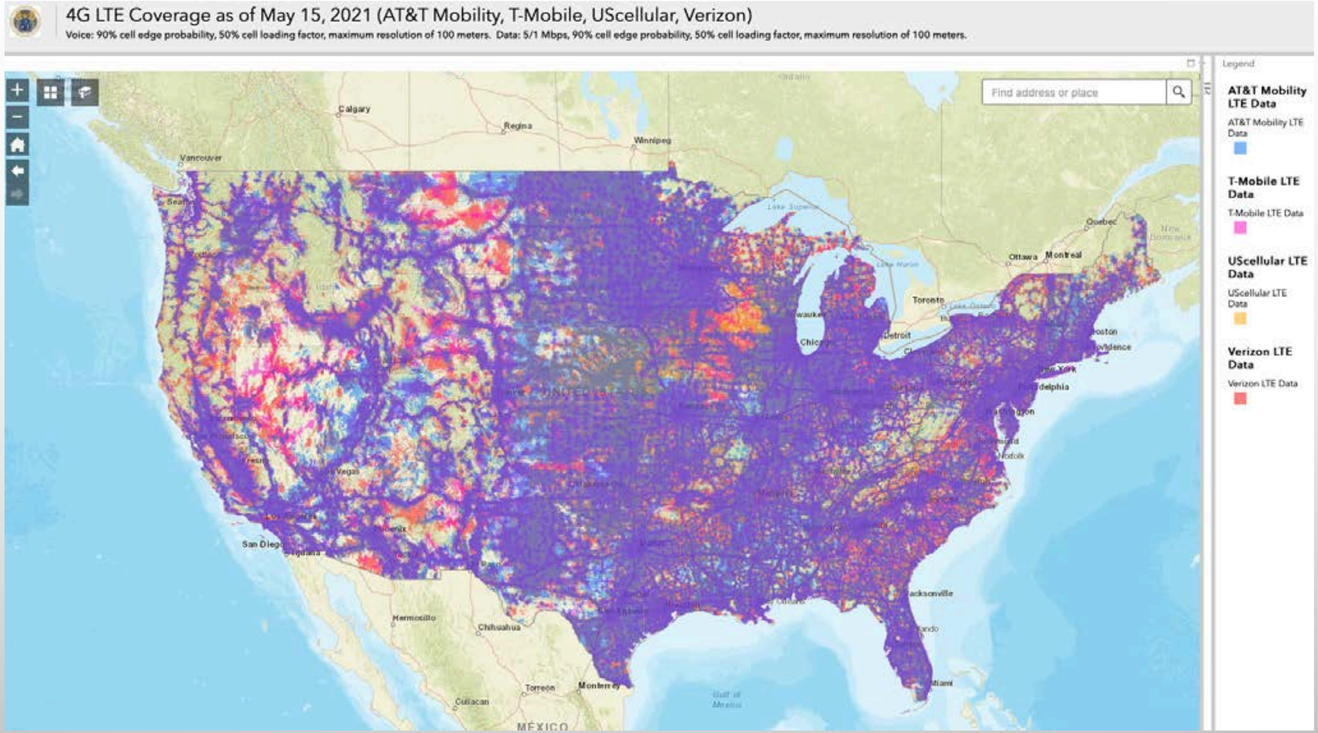
These aspects have evolved considerably through 2020-2021 (more later)



IoMT

Puck Concept – Why use 4G/LTE network (future 5G) for telemetry backhaul?

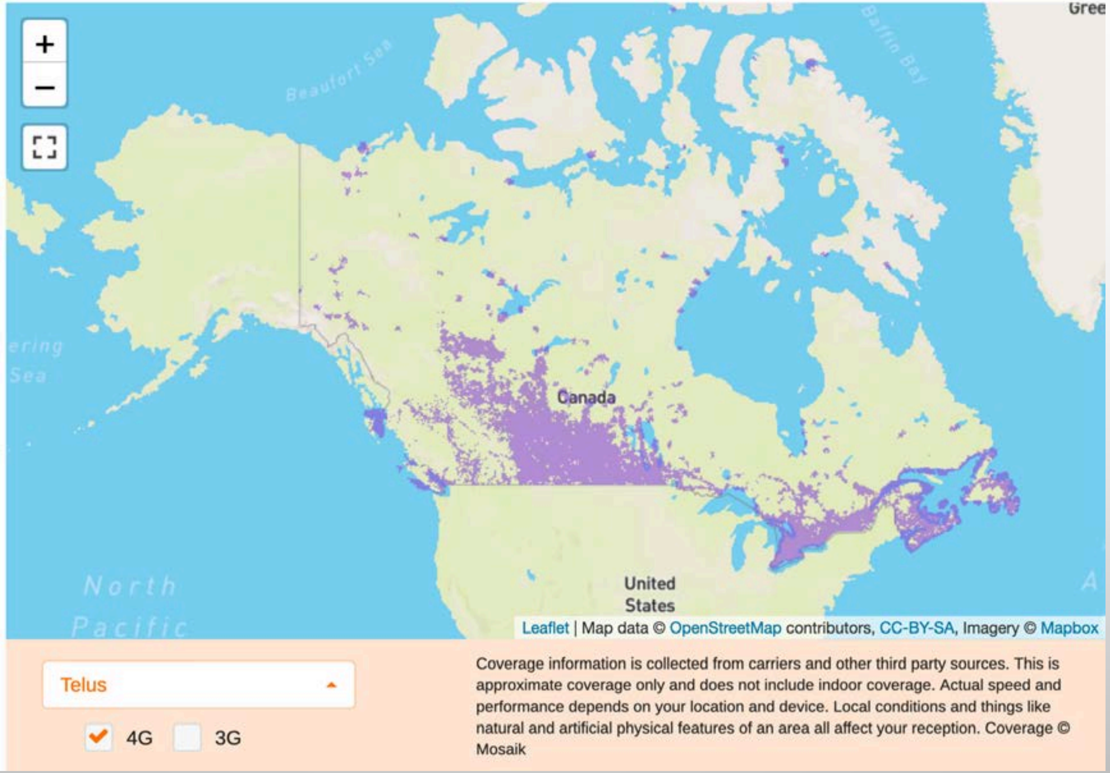
- Ubiquitous, high-speed, extremely low cost (<$15 USD/GB/month in US)



IoMT

Puck Concept – Why use 4G/LTE network (future 5G) for telemetry backhaul?

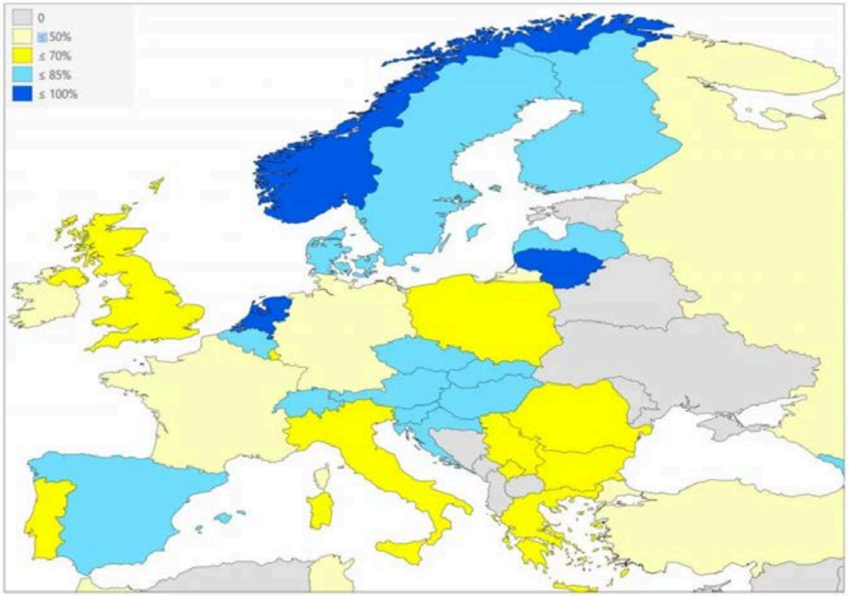
- Ubiquitous, high-speed, extremely low cost (<$14 CAD/0.55 GB/mo in Canada)



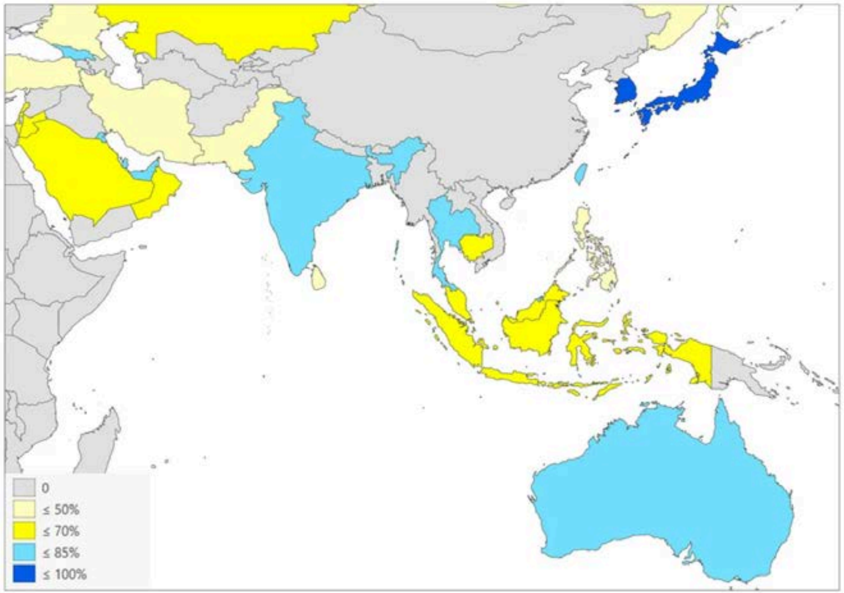
IoMT

Puck Concept – Why use 4G/LTE network (future 5G) for telemetry backhaul?

- Ubiquitous, high-speed, extremely low-cost in Europe, much of (Austral)/Asia



LTE Coverage in Europe

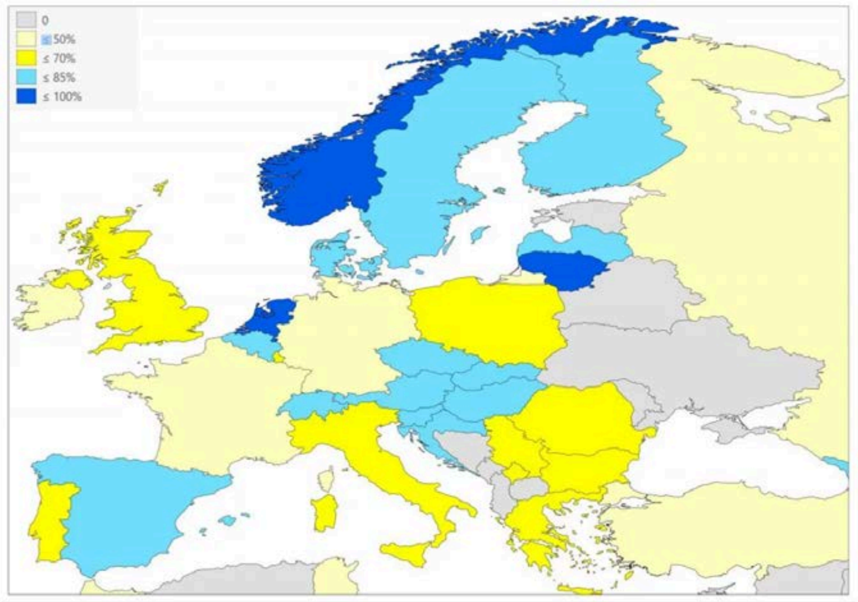


LTE Coverage in Asia

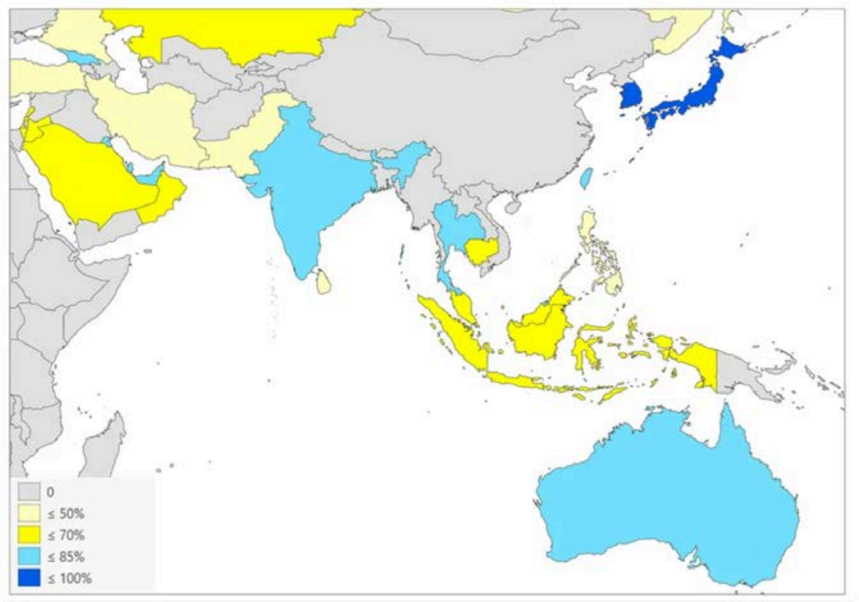
IoMT

Puck Concept – Why use 4G/LTE network (future 5G) for telemetry backhaul?

- Ubiquitous, high-speed, extremely low-cost in Europe, much of (Austral)/Asia



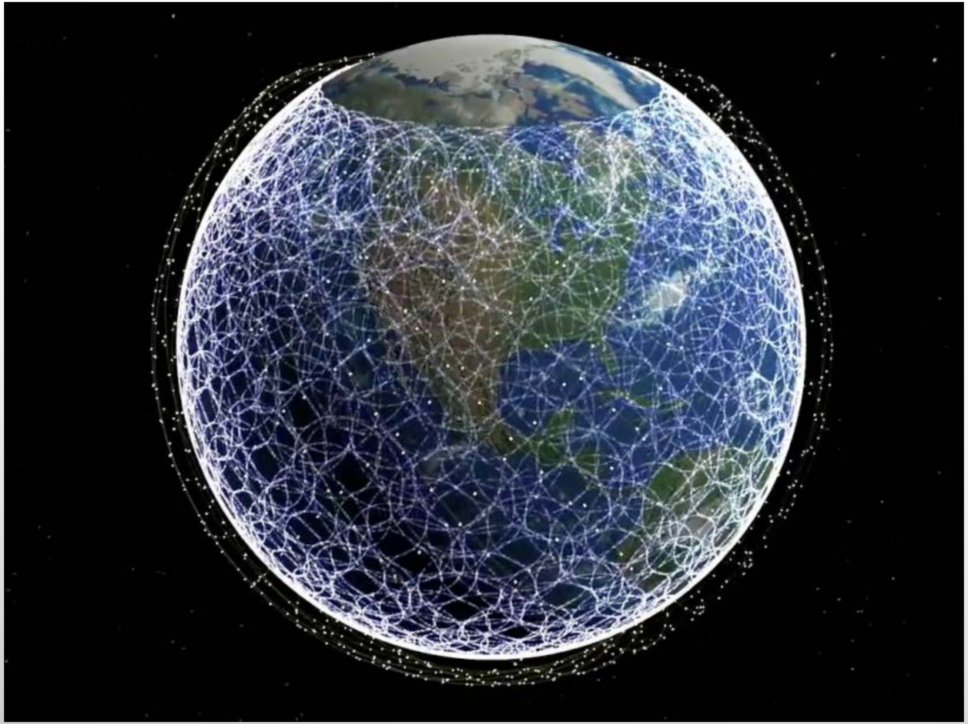
LTE Coverage in Europe



LTE Coverage in Asia

IoMT

But… satellite internet!



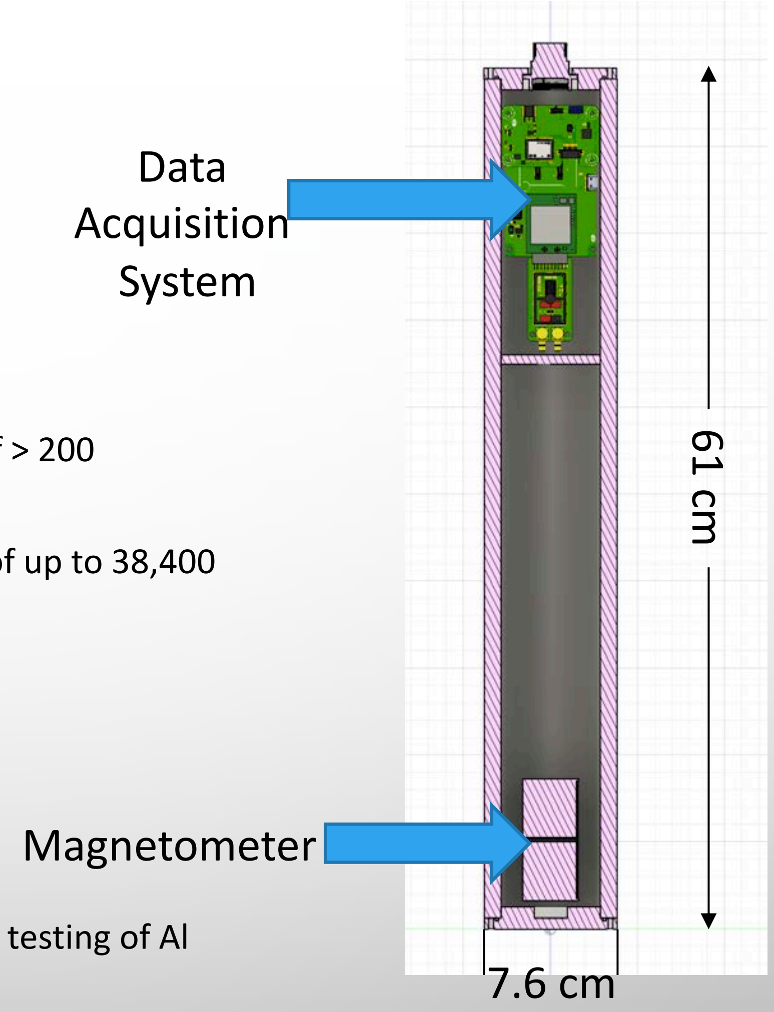
- Where ground-based LTE is unavailable, LTE satellite steps in – (StarLink satellite map on left)
- Pros – high data rates (up to 100 Mbps down/up) nearly global coverage
- Cons – higher cost – approx $500 USD for fixed ground station antenna and wifi router; currently works only within each country – licenses don’t extend across national borders. High power consumption (~100 W)
- Some service gaps and susceptibility to space weather (loss of 40 Starlink satellites last week from space weather)

IoMT Dart (2022)

- Data Acquisition with Rapid Telemetry
  - First in a family of devices
  - Low cost
  - Integrated magnetometer
  - GNSS timing and positioning
  - WIFI communication and control
  - LTE based telemetry
  - Fast installation – auger small diam hole 60 cm down into ground, insert liner then DART and quick orientation and level

DART V1.0 SPECS

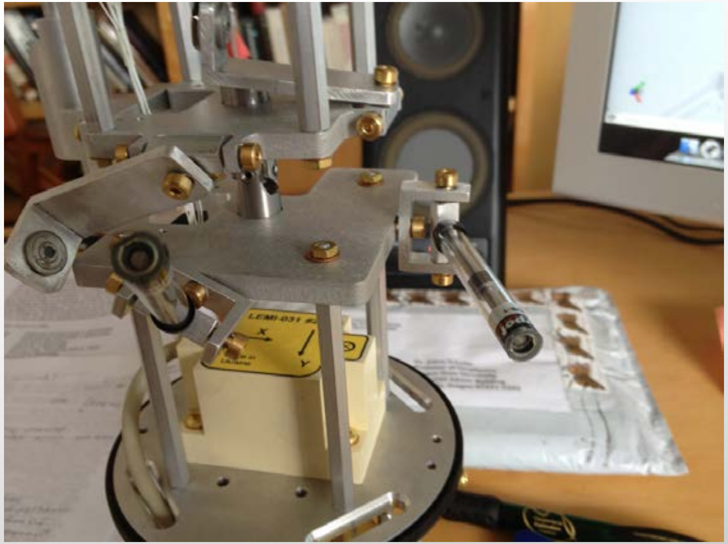
- Low power:
    - < 1 W without telemetry
    - < 2 W with telemetry
- 5 independent 32-bit ADCs
- 1 Hz base sampling rate (long-period), sustained rates of > 200 sps/channel (extended band)
- Platform architecture can support future development of up to 38,400 sps/channel (wideband)
- GNSS for timing and positioning
- WiFi
- Low power BT
- Carrier hopping LTE
- IP67 Aluminum housing, PVC alternate housing option – testing of Al alloy impacts on H-field in process



IoMT

Original Puck Concept - Network-enabled MT sensor array system circa Nov 2019

After initial acceptance testing, final valuation of orthogonality claims of certain manufacturers involved forensic investigation of fluxgate construction methods using x-ray microtomography. This assisted in the down-selection process ahead of selecting a vendor. More on that later.



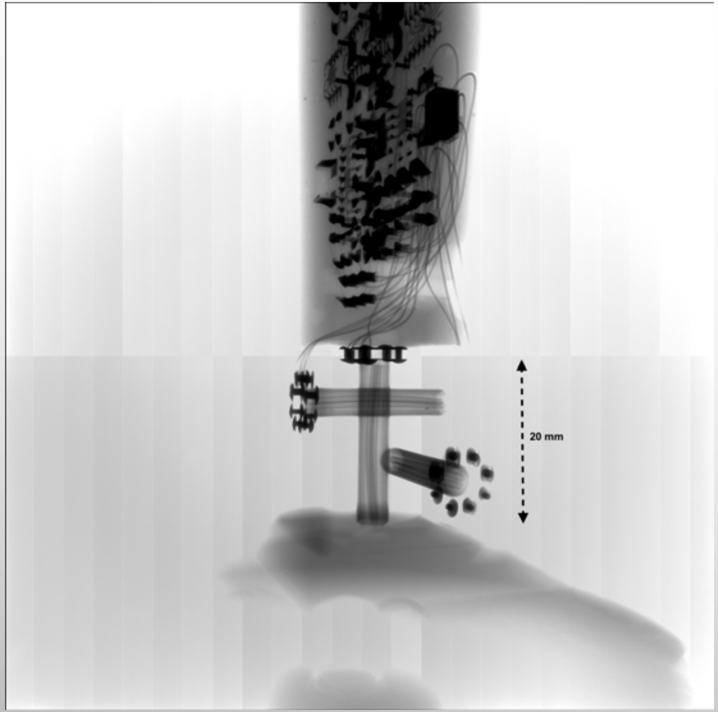
(left) One SMAGALL and two Bartington fluxgates

(right) Custom OSU spec LEMI-417 (one of ten)

IoMT

Original Puck Concept - Network-enabled MT sensor array system circa Nov 2019

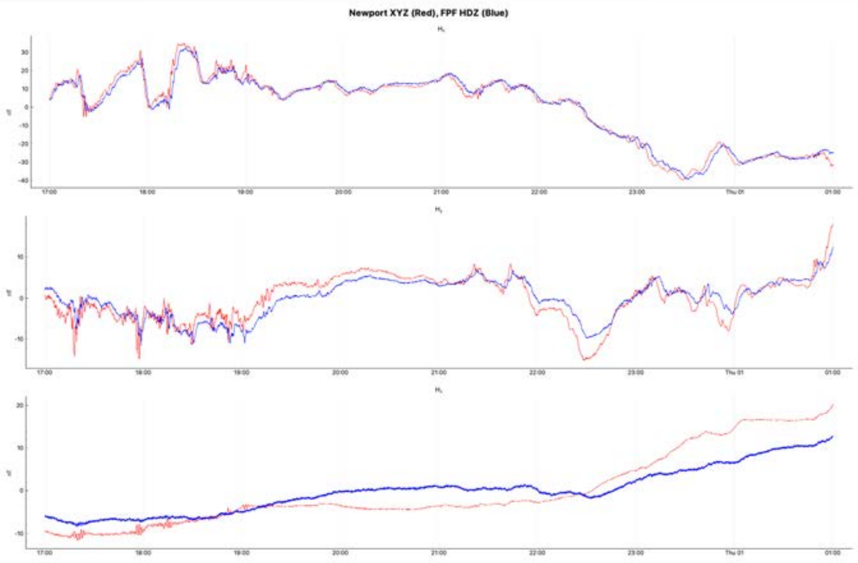
After initial acceptance testing, final valuation of orthogonality claims of certain manufacturers involved forensic investigation of fluxgate construction methods using x-ray microtomography. This assisted in the down-selection process ahead of selecting a vendor. More on that later.

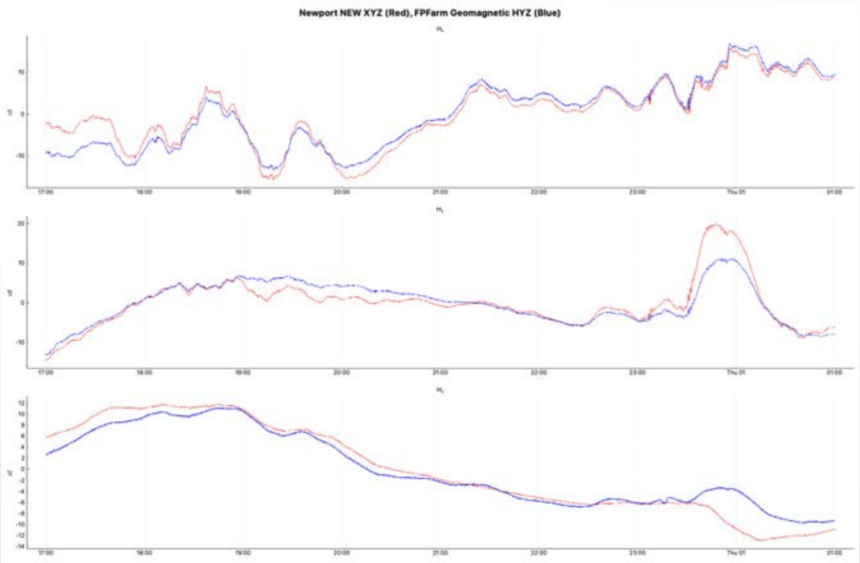


Bartington MAG649 Candidate Sensor

- While the Bartington MAG10 has seen adoption for MT, we are looking for lower cost, lower power options.
- We identified the MAG649 triaxial fluxgate magnetometer as best candidate for long-period MT (10,000 s – 1-10 s)
  - Low noise: <10pTrms/√Hz at 1Hz
  - Range: ±60µT or ±100µT
  - Bandwidth: 1 kHz
  - Acceptable DC offset and signal output range compatible with our ADC section design
  - IP67 housing as addt'l layer of protection against water ingress for only marginal additional cost compared to bare sensor

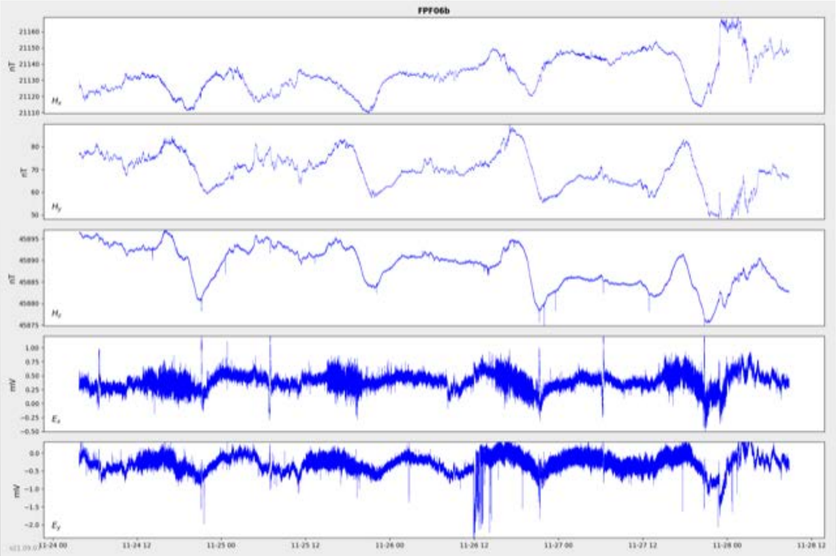
Data from field deployment of Bartington MAG649 and NAROD NIMS, November 2021 (left), exurban Benton County, Oregon (decl 14^{o} 53E’) compared with data from Newport Geophysical Observatory – NEW - (decl 14^{o} 29’E), Washington approximately 700 km to the northeast

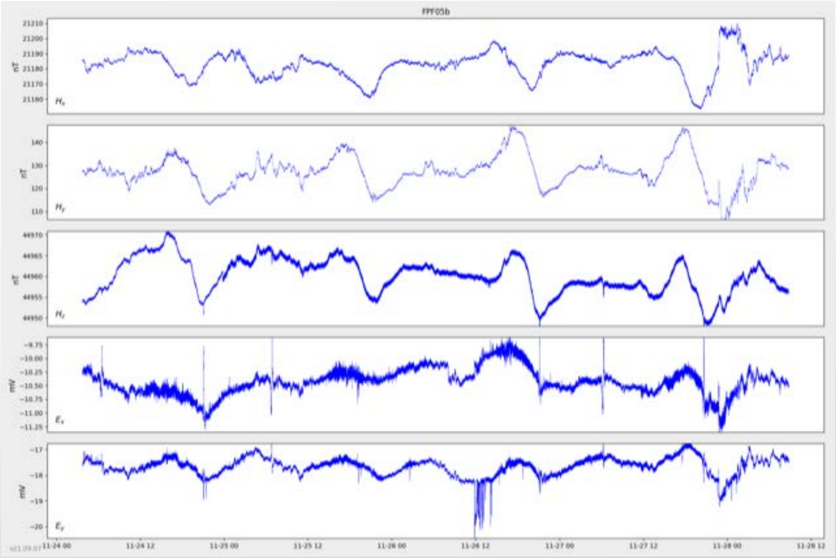




(left) Data from NEW and uPuck, (right) NEW and NIMS. (red) NEW Geomagnetic Observatory – geodetic coords, (blue) µPuck with Bartington MAG649 – geomagnetic coords – relative rotation 14^{o} 53’

Field deployment of Narod NIMS MT time series compared with µPuck (prototype) and Bartington MAG649, December 2021, exurban Benton County, Oregon

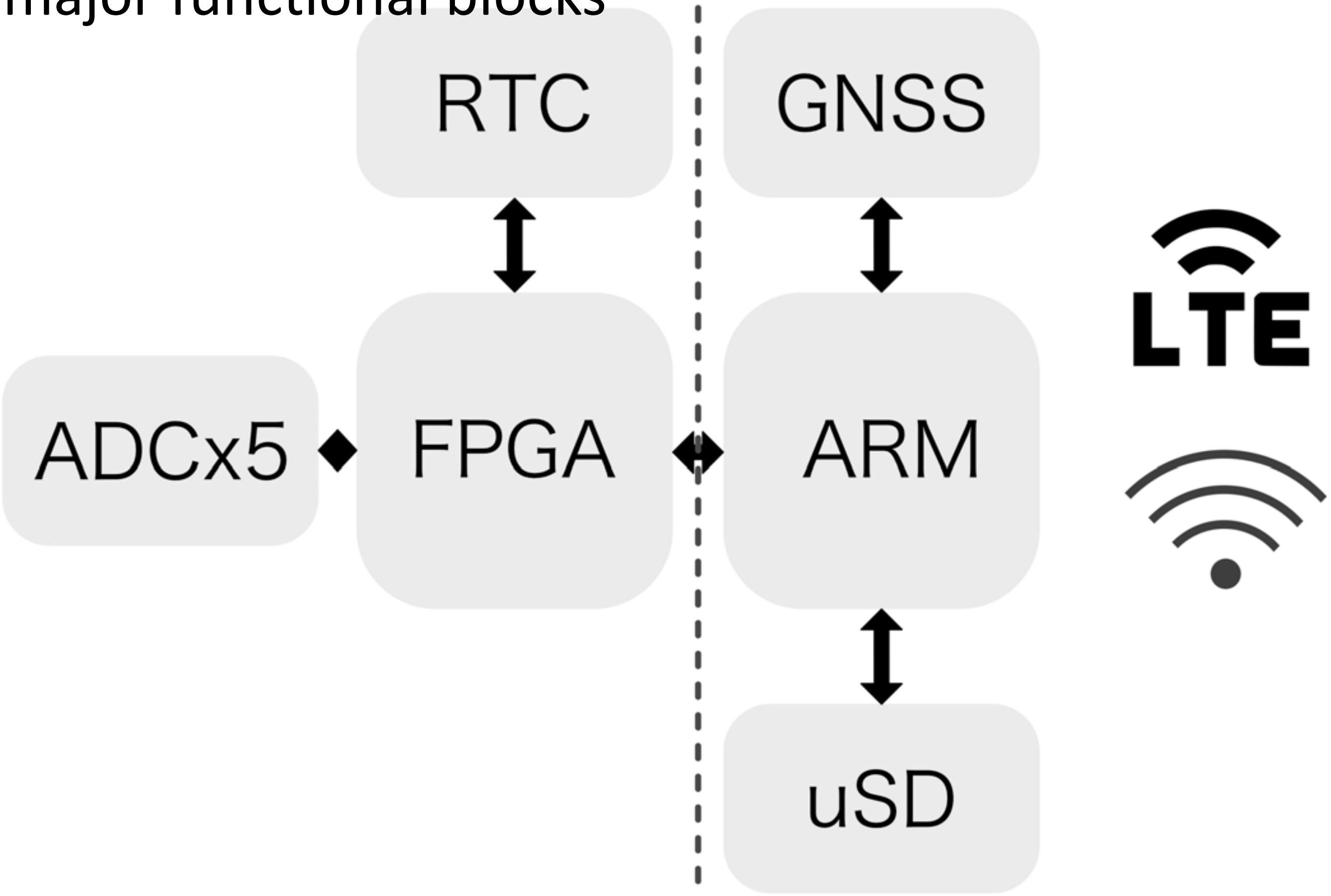




(left) Narod NIMS MT time series

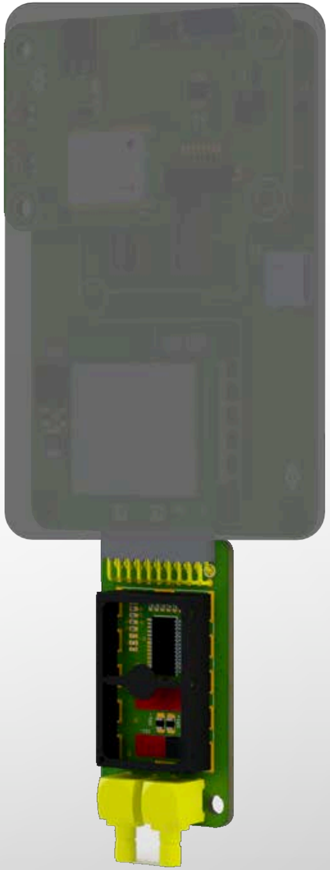
(right) µPuck with Bartington MAG649

DART – major functional blocks



ADCs

- 5 channel input
- 32-bit ADC per channel
- Up to 38.6k SPS



*Placement for demonstration purposes

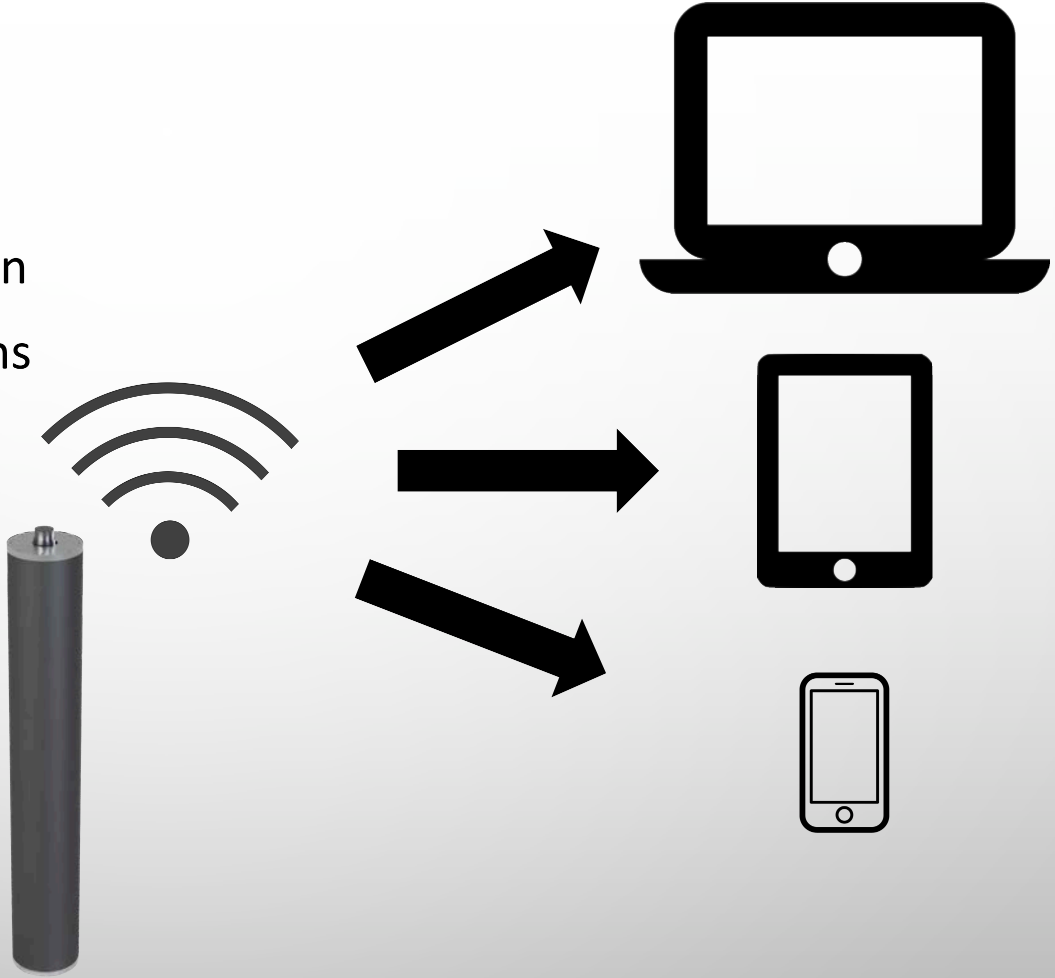
GNSS

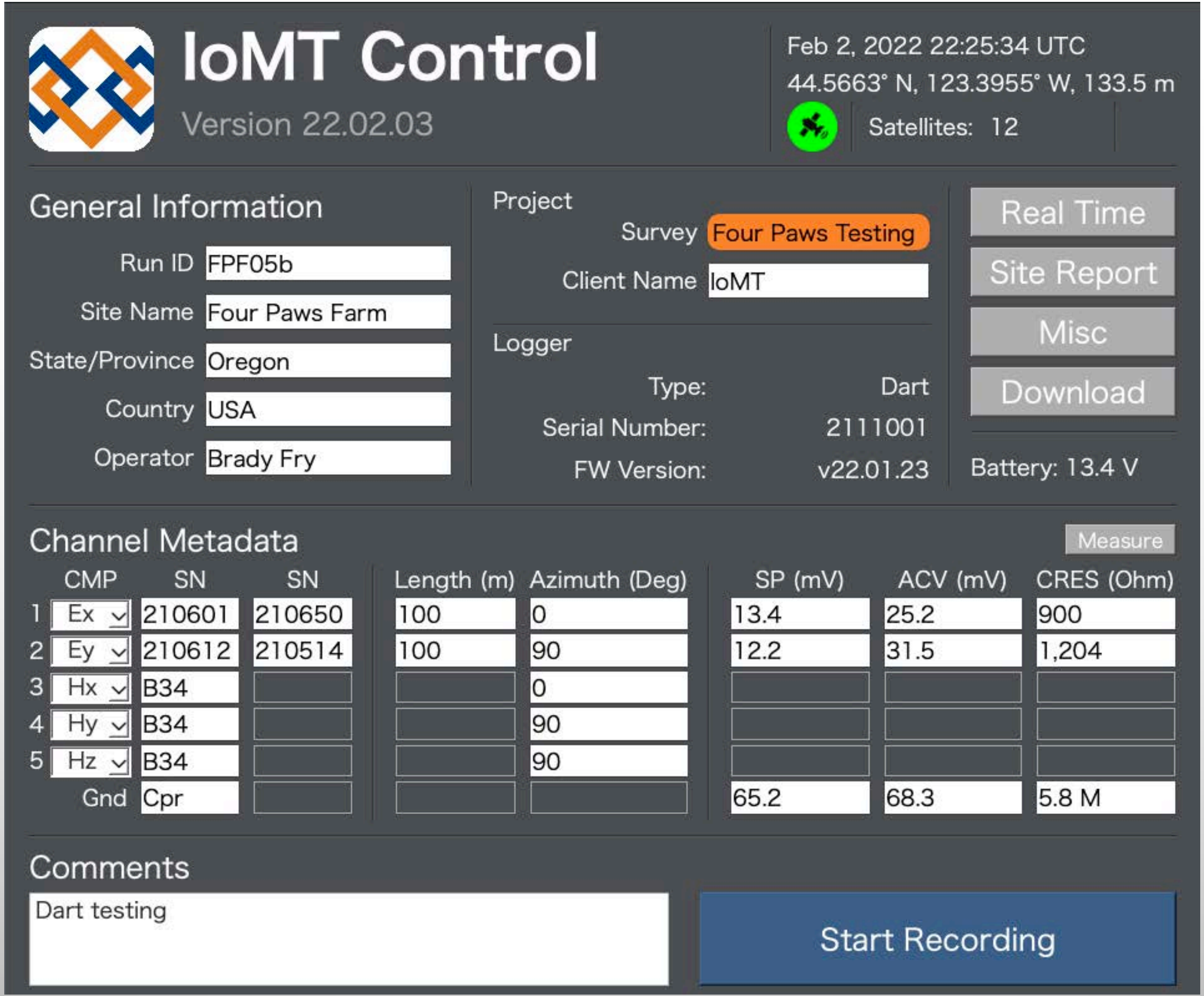
- 72 channel multi satellite receiver
  - All major constellations
    - GPS
    - GLONASS
    - Galileo
    - Beidou
- Modular and upgradable
- 21 ns time pulse resolution

WIFI

- Fast wireless communication
  - Control device operations
  - Download data

- Software for
  - Desktop
  - Mobile (coming soon)

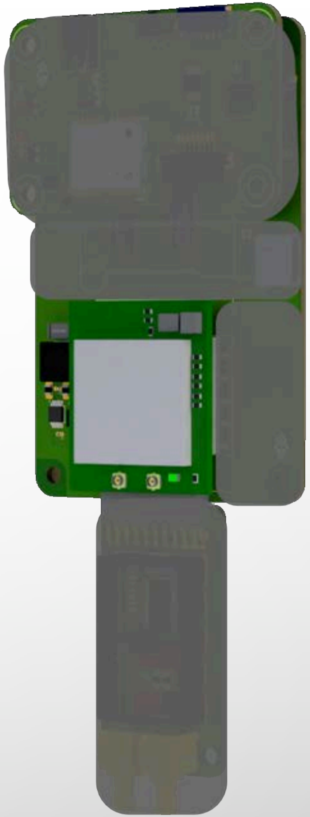



IoMT Control
Version 22.02.03
Feb 2, 2022 22:25:34 UTC
44.5663° N, 123.3955° W, 133.5 m
Satellites: 12
General Information
Run ID FPF05b
Site Name Four Paws Farm
State/Province Oregon
Country USA
Operator Brady Fry
Project
Survey Four Paws Testing
Client Name IoMT
Logger
Type: Dart
Serial Number: 2111001
FW Version: v22.01.23
Real Time
Site Report
Misc
Download
Battery: 13.4 V
Channel Metadata
Measure
CMP SN SN Length (m) Azimuth (Deg) SP (mV) ACV (mV) CRES (Ohm)
1 Ex 210601 210650 100 0 13.4 25.2 900
2 Ey 210612 210514 100 90 12.2 31.5 1,204
3 Hx B34 0
4 Hy B34 90
5 Hz B34 90
Gnd Cpr 65.2 68.3 5.8 M
Comments
Dart testing
Start Recording

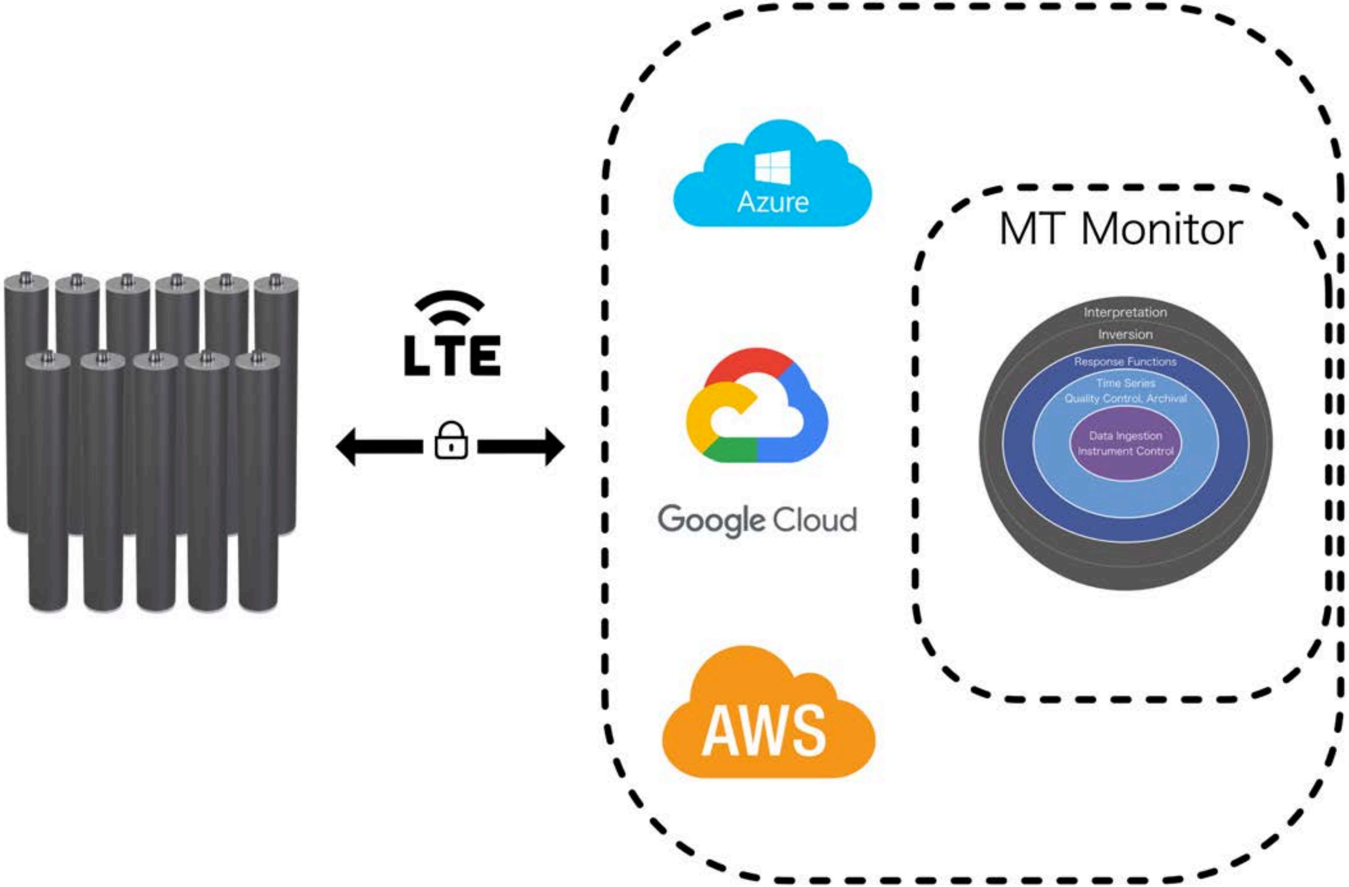
LTE Communications

- Currently Certified for North America
  - PCB swappable for other regions
- Auto-switching Major Carriers (Verizon, T-Mobile, ATT)

*Possible satellite-based telemetry for long term installations: Starlink, Kuiper, etc.

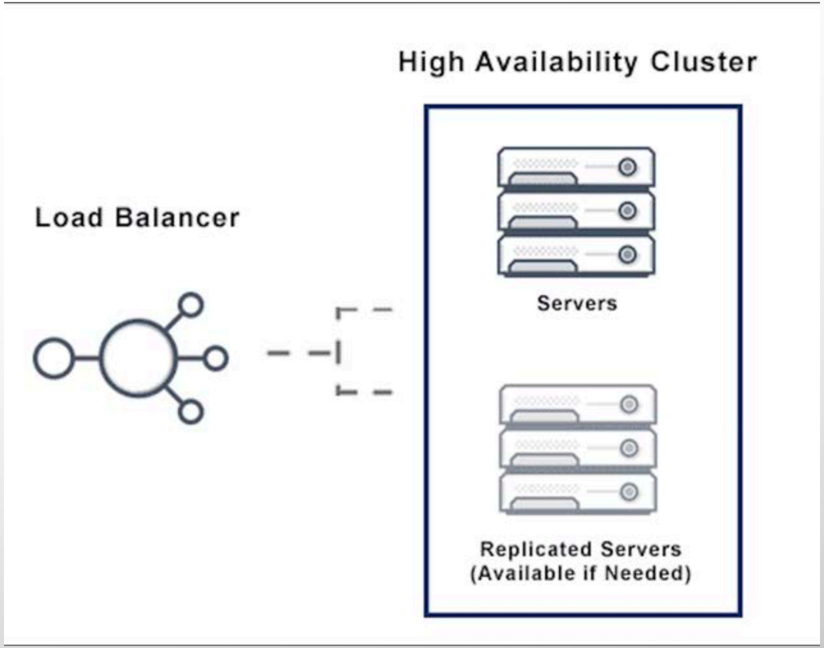


IoMT


LTE
Azure
Google Cloud
AWS
MT Monitor
Interpretation
Inversion
Response Functions
Time Series
Quality Control, Archival
Data Ingestion
Instrument Control

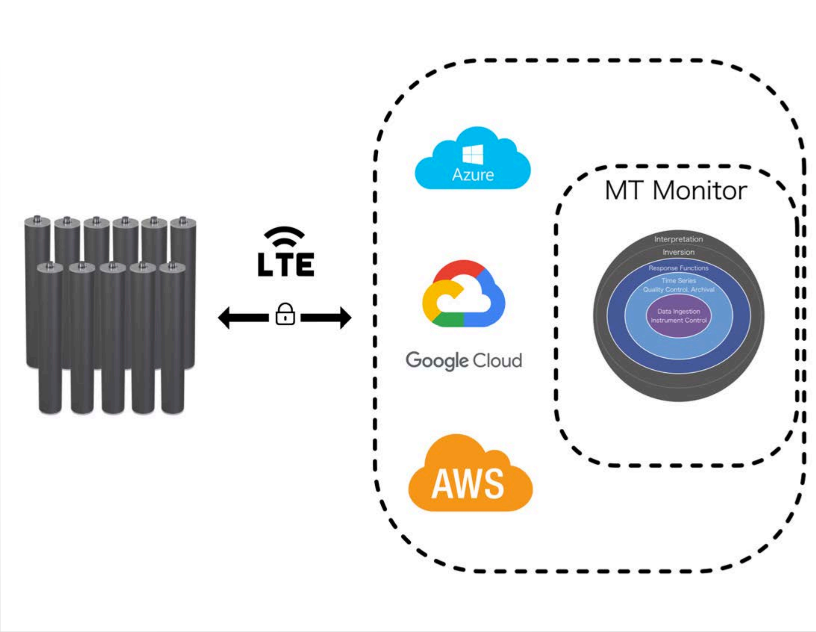
IoMT: Cloud Services

- Robust
  - High-availability
  - Geolocated



IoMT: Cloud Services

- Robust
  - High-availability
  - Geo-located
- Secure
  - End-to-end encryption

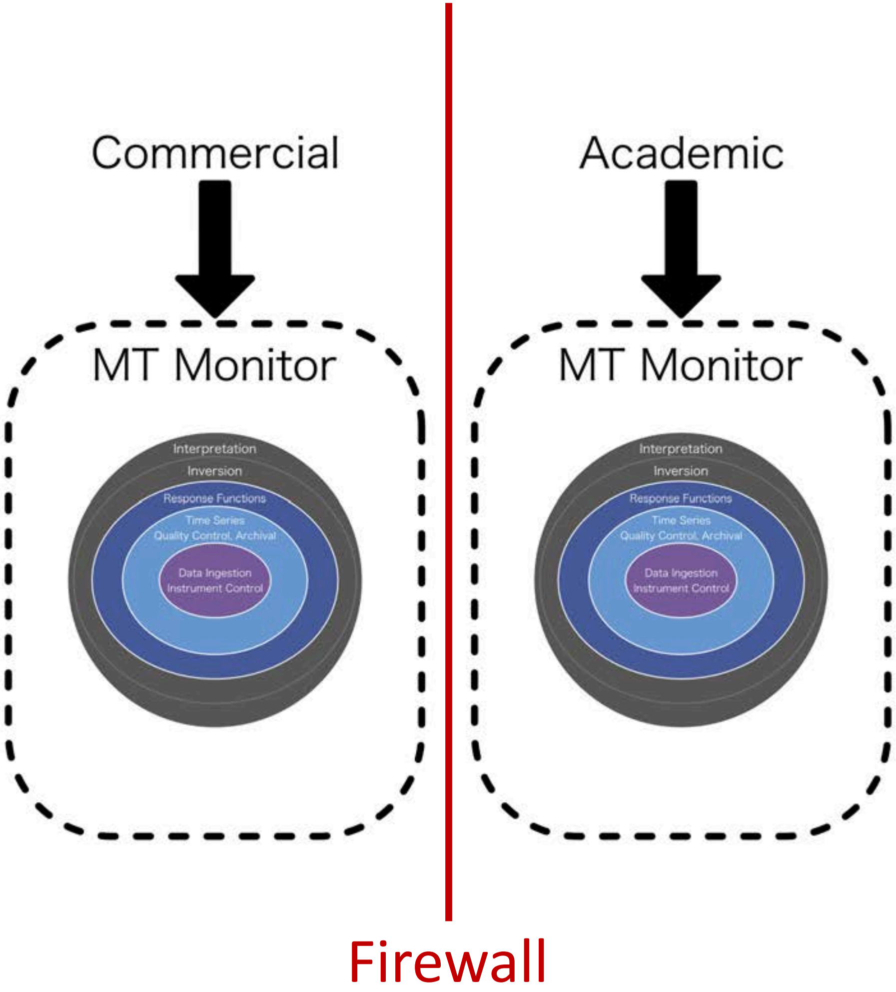


IoMT: Cloud Services

- Robust
  - High-availability
  - Geo-located
- Secure
  - End-to-end encryption
  - Login credentials
    - Industry standard password encryption and storage
    - User defined roles and accessibility

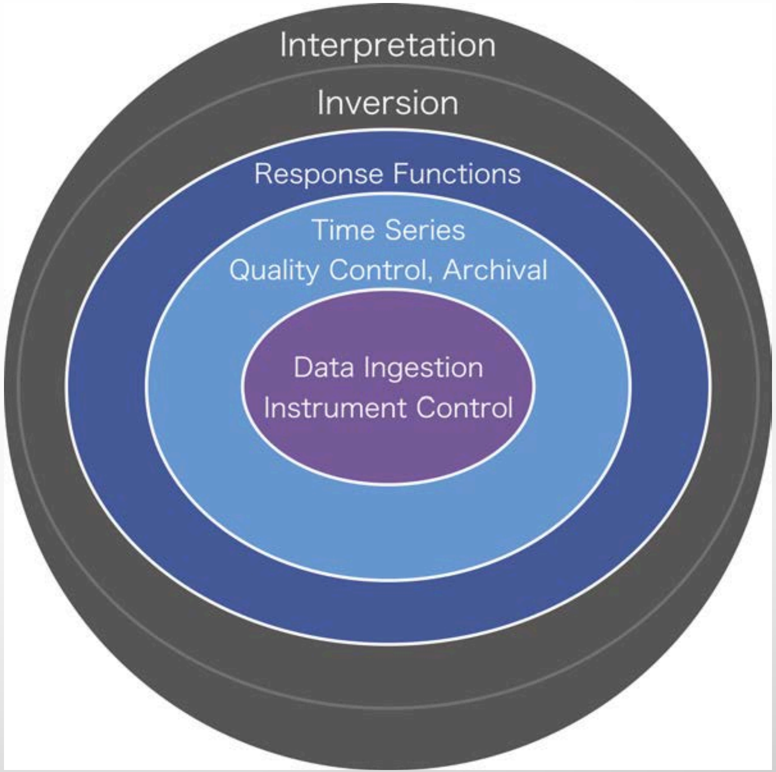
IoMT: Cloud Services

- Robust
  - High-availability
  - Geo-located
- Secure
  - End-to-end encryption
  - Login credentials
    - Industry standard password encryption and storage
    - User defined roles and accessibility
    - Robust data security and storage


Commercial
MT Monitor
Interpretation
Inversion
Response Functions
Time Series
Quality Control, Archival
Data Ingestion
Instrument Control
Academic
MT Monitor
Interpretation
Inversion
Response Functions
Time Series
Quality Control, Archival
Data Ingestion
Instrument Control
Firewall

IoMT Multiple Layers of Service

- Tailored to client needs

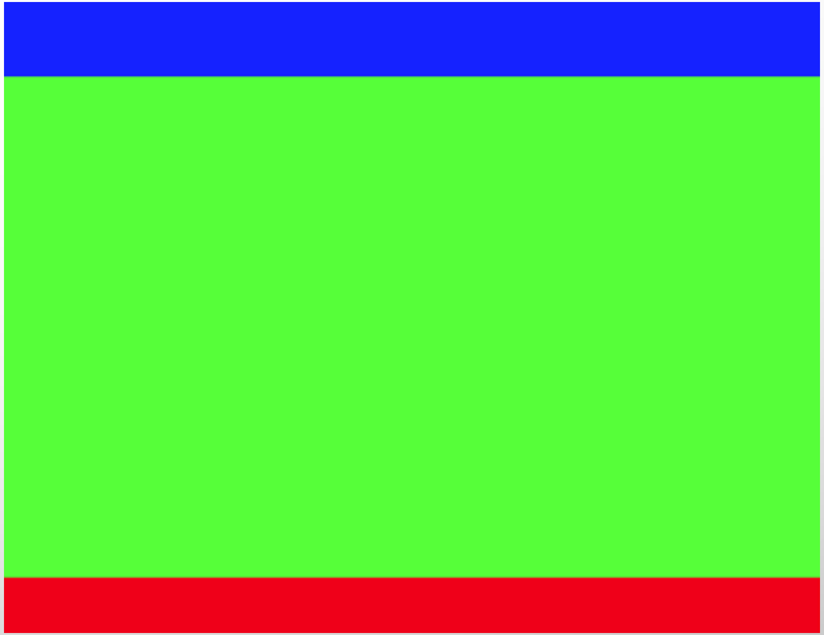


IoMT Data Ingestion and Instrument Control

- Receive IoMT data
- Validate accurate transmission of data
- Ensure proper behavior of IoMT devices
- Remote instrument control (coming soon)

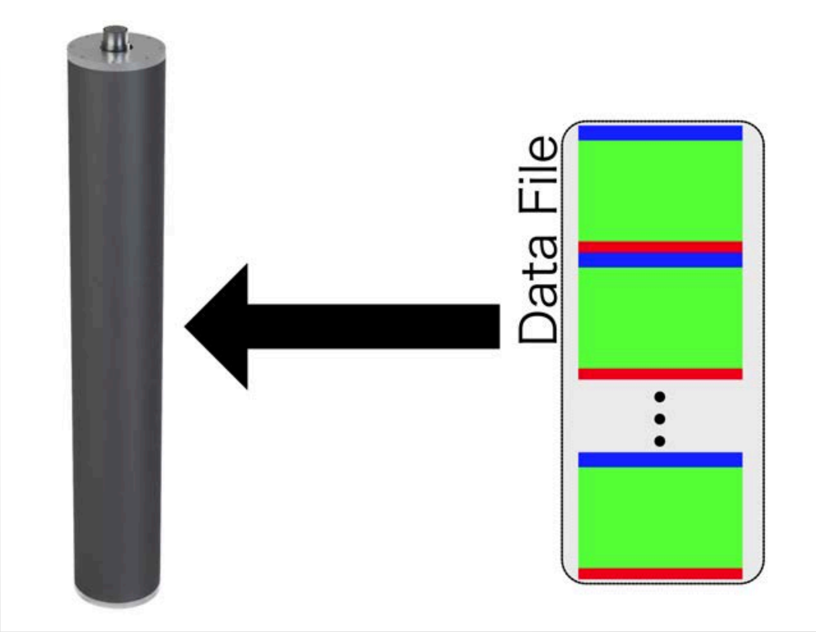
IoMT Data Transmission

- Secure transmission
- Block of data
  - Header (blue)
    - Timestamp
    - Temperature
    - Battery Voltage
      - LiFePO4 batteries with BlueTooth control
  - Data (green)
  - Validation (red)



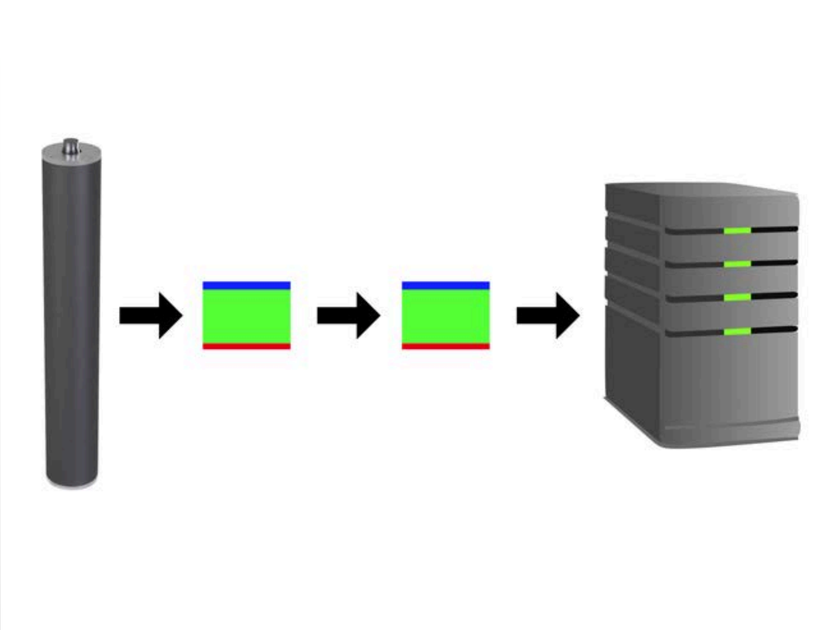
IoMT Data Transmission

- Blocks of data assembled into a file
- Data saved locally first



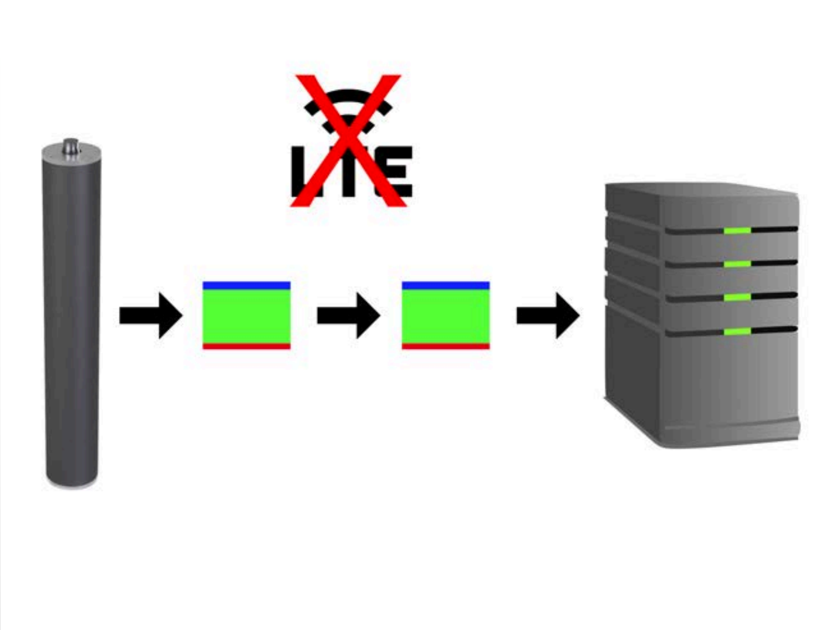
IoMT Data Transmission

- Blocks sent to servers
  - 1 minute of data typical
- Server validates data
  - If failed, retransmit
- Save data in database
  - Header ensures order of block



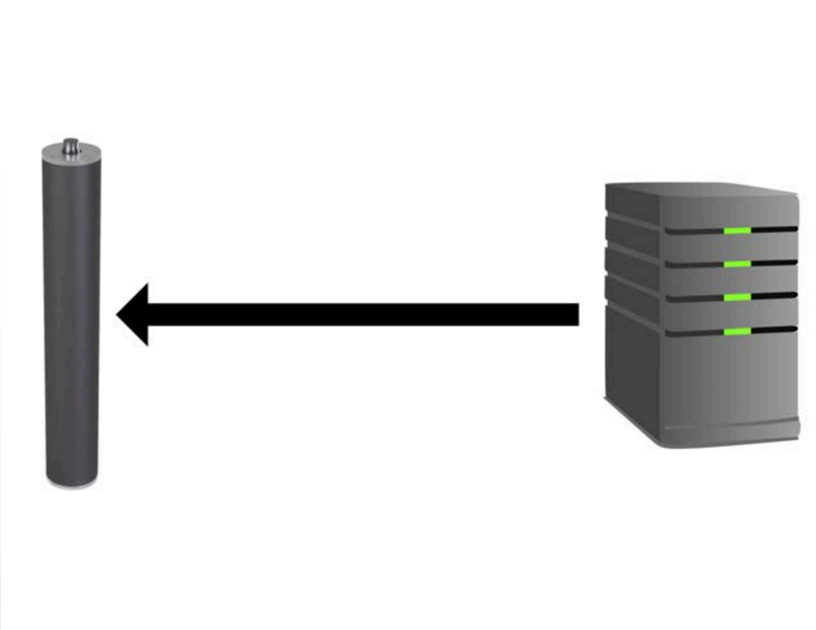
IoMT Data Transmission

- Block transmission failure
  - Poor or no LTE
- Transmit missing blocks
  - Server will reassemble in order



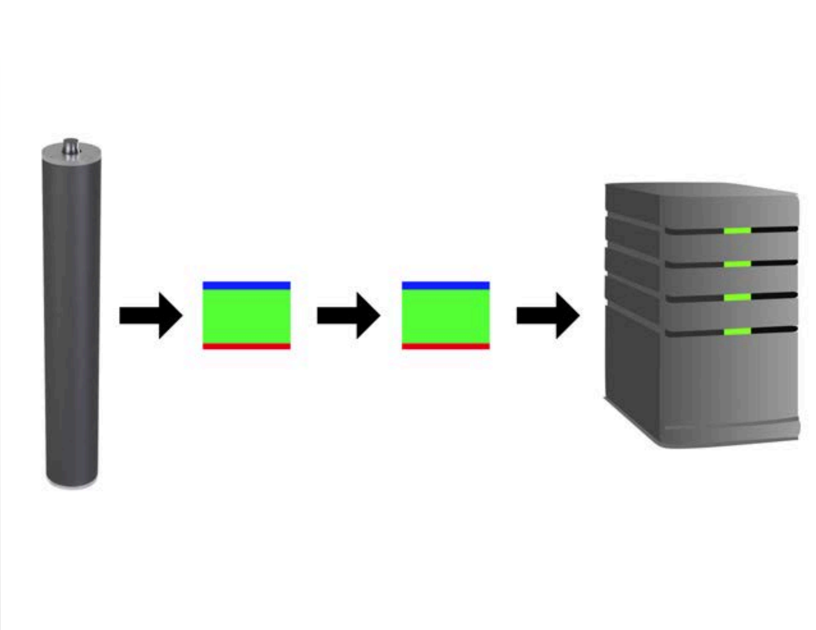
IoMT Data Transmission

- Server requesting data
  - Last ditch effort before site visit

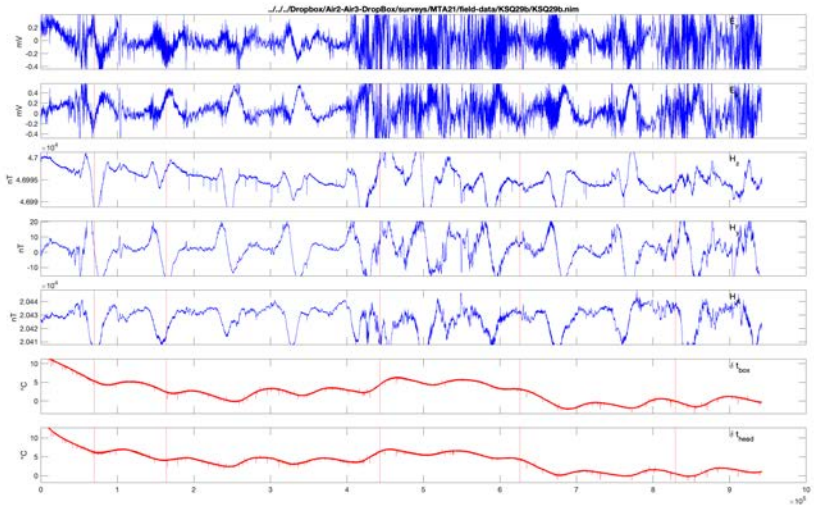


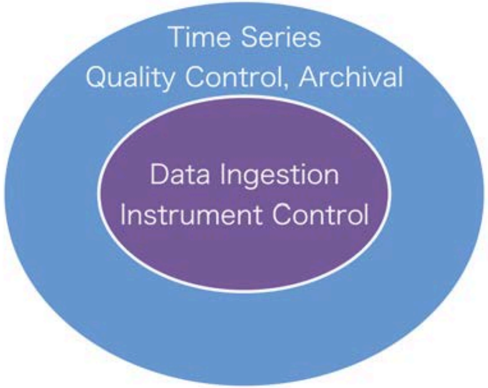
IoMT Data Transmission

- Server requesting data
  - Last ditch effort before site visit



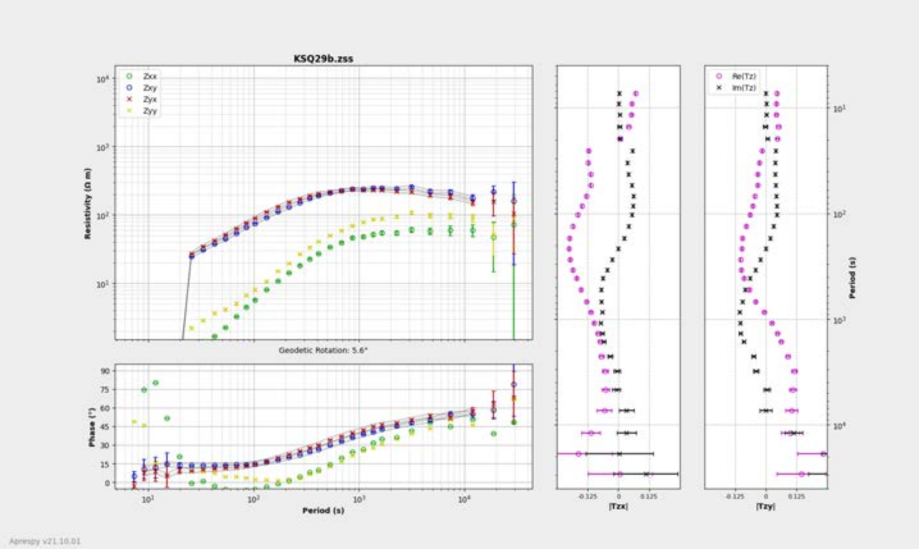
Time Series Storage, Quality Control, and Archival

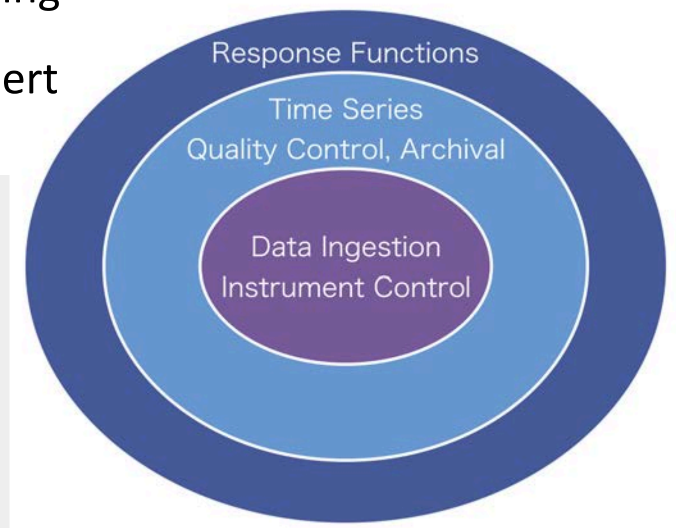




Response Functions

- Semi-automated functions and processing
- Current processing codes based on Egbert and Eisel





MT Monitor

MTA22

Active Archive

UTC: 2022-02-09 12:02:33

Search:

	Run ID	Run Start	Total Days	Last Updated	Battery Voltage
>	OKW38f	2021-12-04 20:55:52	10.93	2021-12-15 19:28:27	11.4
>	OKW38e	2021-11-21 20:43:25	12.88	2021-12-04 19:58:33	11.2
>	OKW38b	2021-11-12 22:45:11	8.81	2021-11-20 18:14:56	11.9
>	OKW37b	2021-11-03 22:48:40	7.74	2021-11-11 16:40:02	12.5
>	KSQ29b	2021-10-11 22:26:44	11.2	2021-10-22 20:09:51	12.1

Showing 1 to 5 of 5 entries

MT Monitor

MTA22

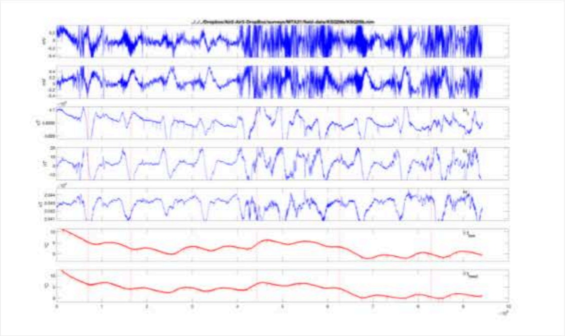
Active Archive

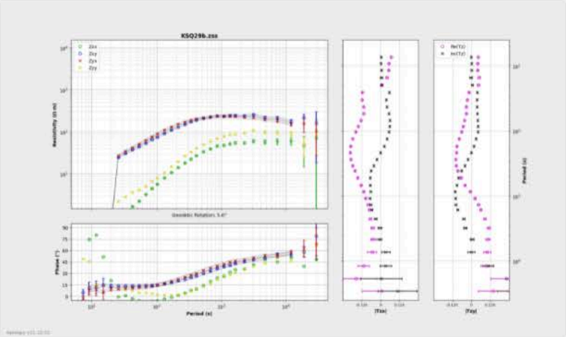
UTC: 2022-02-09 12:03:19

Search:

	Run ID	Run Start	Total Days	Last Updated	Battery Voltage
>	OKW38f	2021-12-04 20:55:52	10.93	2021-12-15 19:28:27	11.4
>	OKW38e	2021-11-21 20:43:25	12.88	2021-12-04 19:58:33	11.2
>	OKW38b	2021-11-12 22:45:11	8.81	2021-11-20 18:14:56	11.9
>	OKW37b	2021-11-03 22:48:40	7.74	2021-11-11 16:40:02	12.5
v	KSQ29b	2021-10-11 22:26:44	11.2	2021-10-22 20:09:51	12.1

PROCESS **Status:** Processed 2021-10-23 00:0:00 DOWNLOAD



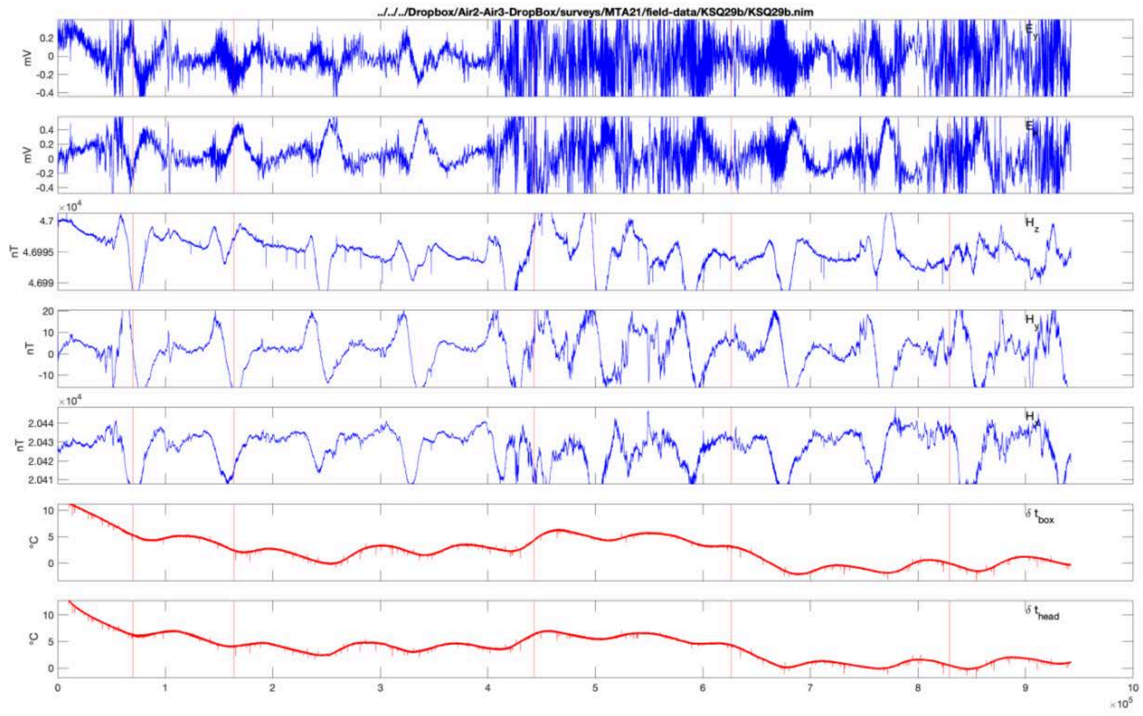


Showing 1 to 5 of 5 entries

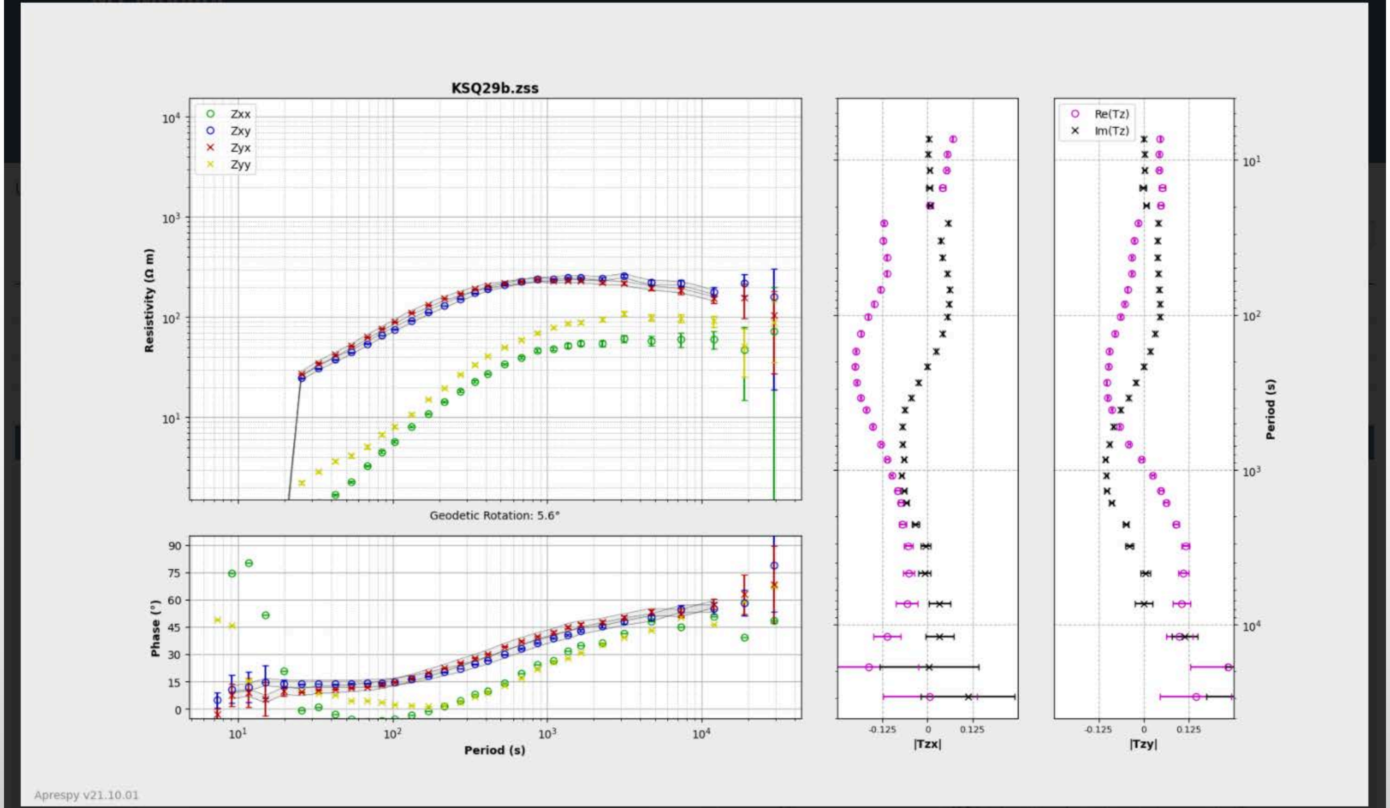
NATIONAL GEOELECTROMAGNETIC FACILITY

HOME ADMIN SETTINGS LOGOUT

MT Monitor

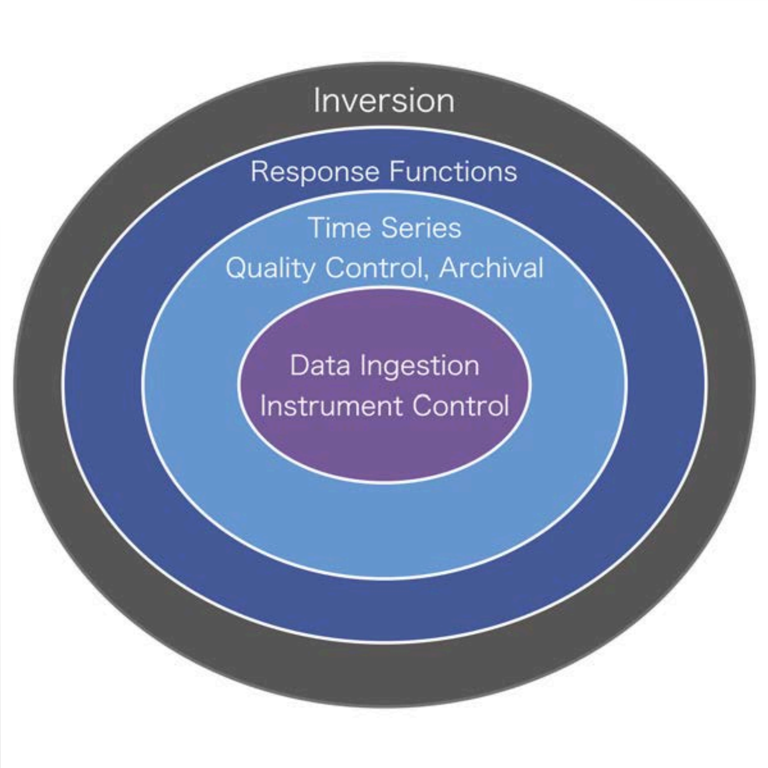


Showing 1 to 5 of 5 entries


KSQ29b.zss
Zxx
Zxy
Zyx
Zyy
Resistivity (Ω m)
Geodetic Rotation: 5.6°
Phase (°)
Period (s)
|Tzx|
Re(Tz)
Im(Tz)
|Tzy|
Period (s)
Aprespy v21.10.01

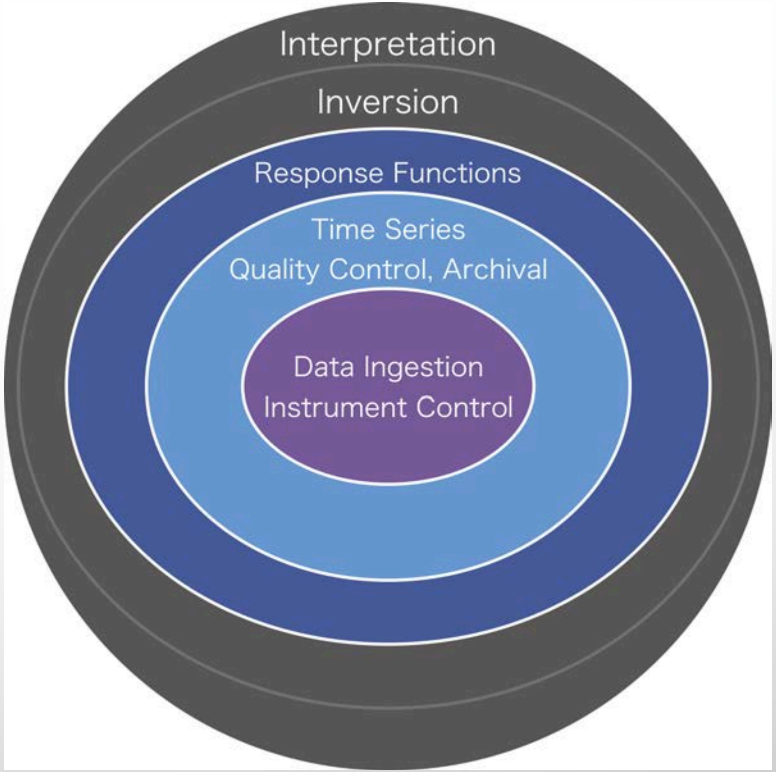
Inversion

- Cloud-based SAAS (Software as a Service)
- Currently under development by Xiaolei Tu at OSU using adjoint approach with strong GPU acceleration, suitable for both time- and frequency-domain methods



Interpretation

- Cloud-based human+ML
- Planned



Cost Targets for Initial Implementation

Dart Hardware

- Target < $5,000* USD per unit commercially
  - With fluxgate magnetometer; addt'l for wideband induction coil version
  - With telemetry

*Significant academic discounts. Once produced in quantity anticipate significant cost reductions

IoMT Cloud

- Dependent on service required
  - <$200*/month base service including MTMonitor telemetry, remote instrument control, archival storage
  - Other service layers include data licensing validation and attribution, response function processing, inversion, interpretation

Summary

- Low-cost hardware/software and telemetry
- Nested cloud-based services
- Conditions for wider acceptance of MT by lowering the cost of admission and level of expertise needed to get started

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NASA Grant Number 80NSSC19K0232/IRIS Subaward SU-19-1101-05-OSU

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Questions? Adam.Schultz@oregonstate.edu