Low Noise, Lightweight EM and AMT sensors for Unmanned Airborne Systems (UAS)

UASEM

Jim Macnae:

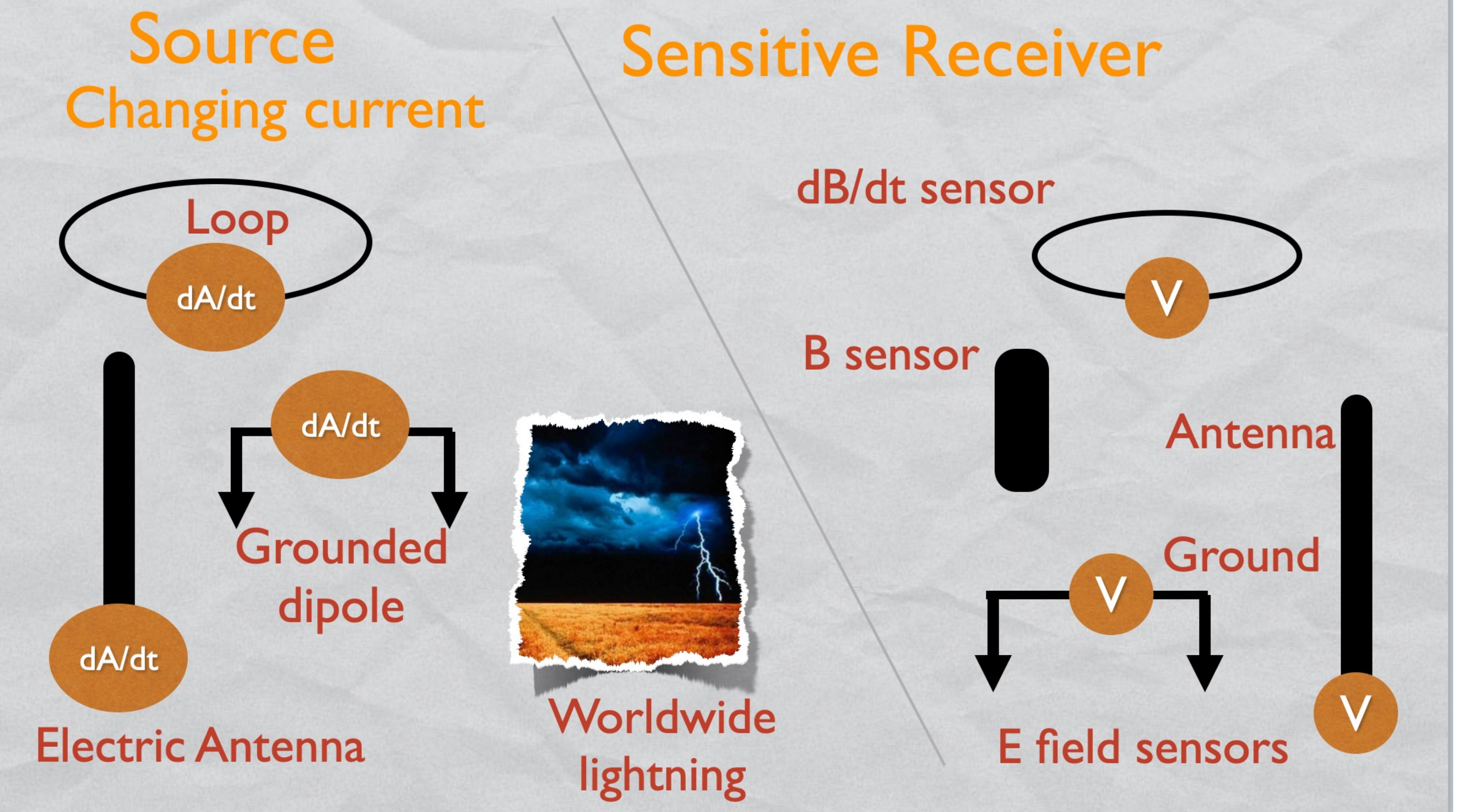
3 June, 2021

Particular thanks to Macquarie and RMIT Universities, Abitibi Geophysics, Monex Geoscope, Thomson Airborne, as well as the many mineral industry sponsors of AMIRA Projects P407b, P460, P462, P1036, P1036A, P1204 who funded research that (after confidentiality requirements have expired) provided extracts I am showing today.

Abbreviated Agenda

- Electromagnetics (EM)
- Airborne EM (AEM)
- Unmanned Aerial Systems (UAS)
- UASEM Challenges in adding useful EM to a UAS
- AUSEM – Amazon-style Delivery of EM ground-stations
- EM on the Moon
- New-generation quantum and electric field sensors

COMPONENTS OF AN EM SYSTEM



Some common varieties of usable scalar/vector source and sensor components for ElectroMag-netic (EM) systems

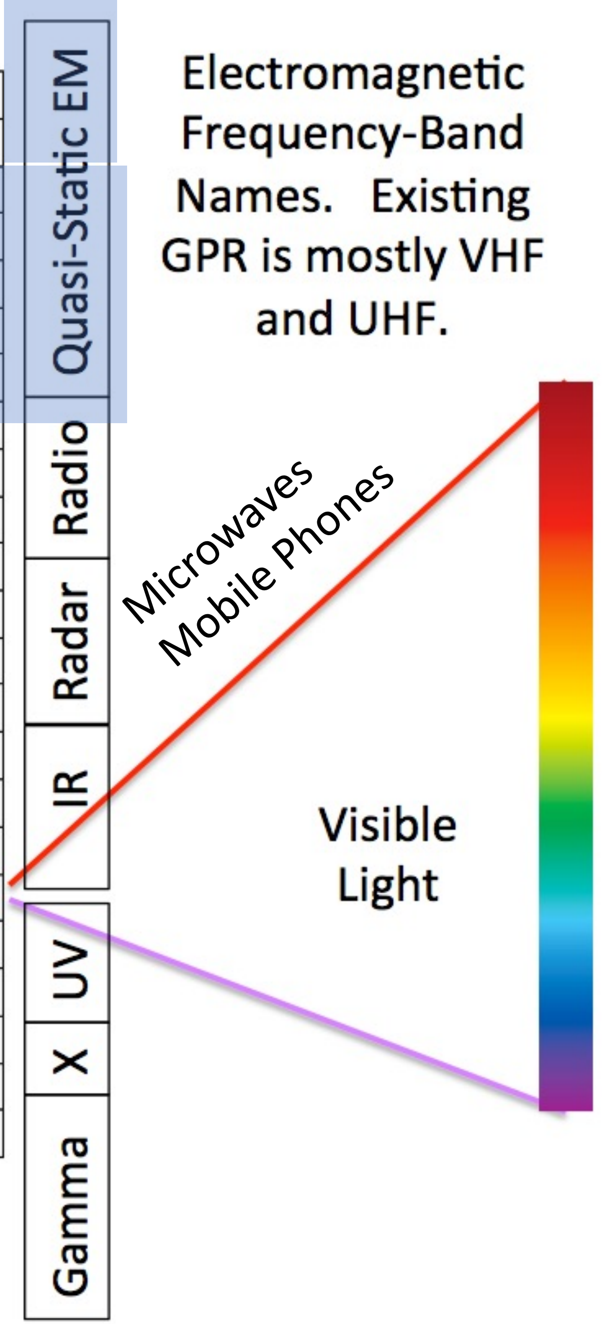
Frequency Decade Terminology for Electromagnetic Waves

MT

AMT

GPR

Band	Code	Frequency	Wavelength
		...	...
TLF	Tremendously	0.3 – 3 Hz	1 – 0.1 Gm
ELF	Extremely	3 – 30 Hz	100 – 10 Mm
SLF	Super	30 – 300 Hz	10 – 1 Mm
ULF	Ultra	300 – 3000 Hz	1 – 0.1 Mm
VLF	Very	3 – 30 kHz	100 – 10 km
LF	Low	30 – 300 kHz	10 – 1 km
MF	Medium	300 – 3000 kHz	1 - 0.1 km
HF	High	3 – 30 MHz	100 – 10 m
VHF	Very	30 – 300 MHz	10 – 1 m
UHF	Ultra	300 – 3000 MHz	1 – 0.1 m
SHF	Super	3 – 30 GHz	100 – 10 mm
EHF	Extremely	30 – 300 GHz	10 – 1 mm
THF	Tremendously	300 – 3000 GHz	1 – 0.1 mm
IHF	Incredibly	3 – 30 THz	100 – 10 µm
MHF	Monstrously	30 – 300 THz	10 – 1 µm
LHF	Ludicrously	300 – 3000 THz	1 – 0.1 µm
PHF	Prodigiously	3 – 30 PHz	100 - 10 nm
NHF	Numbingly	30 – 300 PHz	10 – 1 nm
AHF	Amazingly	300 – 3000 PHz	1 nm – 1 A
DHF	Dangerously	3 – 30 EHz	1 – 0.1 A
BHF	Boundlessly	.....	.....



Electromagnetic Frequency-Band Names. Existing GPR is mostly VHF and UHF.

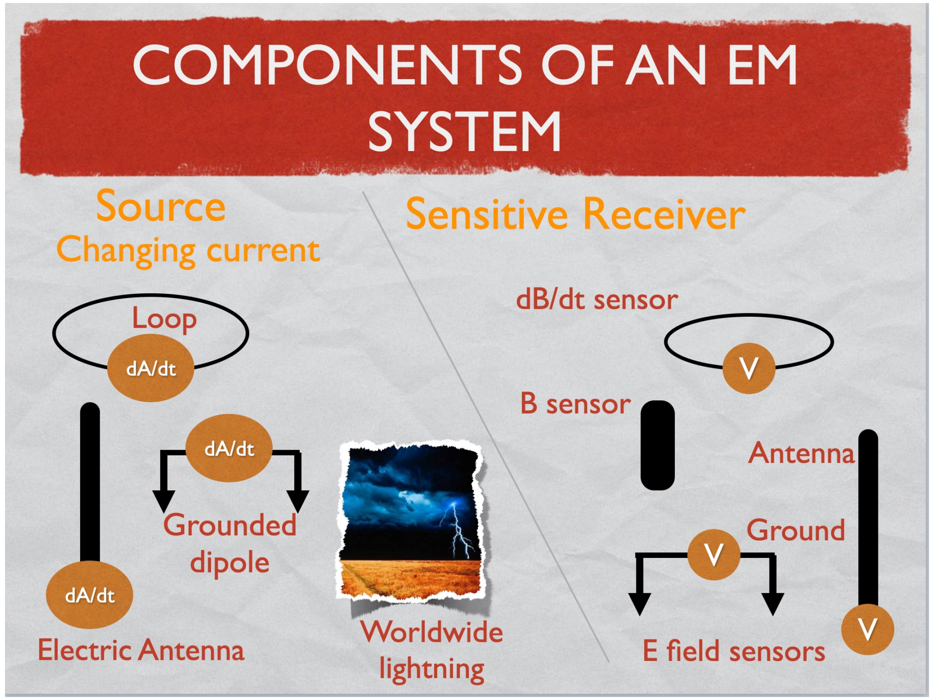
DC electric and magnetic fields are potential fields, not waves, and diffusion dominates wave-like behaviour in the quasi-static domain

Some Abbreviations in case you are not a specialist already

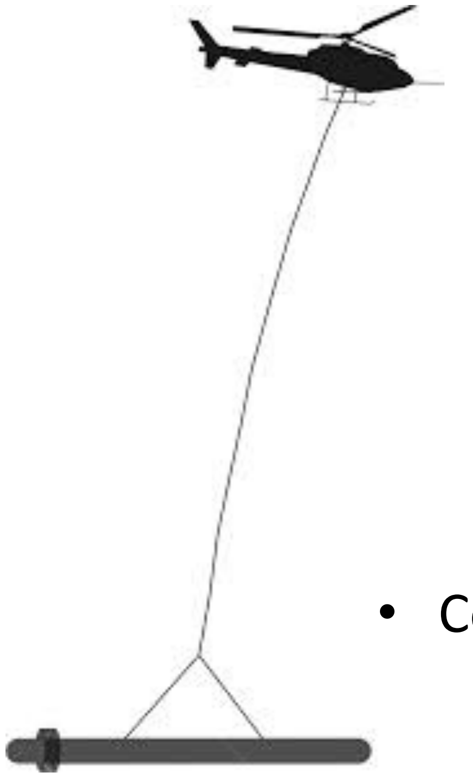
- UAV – Unmanned (or Uncrewed for the politically correct) Aerial Vehicle, often called a Drone
- UAS - Unmanned Aerial System: includes the UAV, plus ground control, payload, communications etc. etc.
- MT – magnetotellurics E/H ratios at frequencies less than 3 Hz (TLF and lower)
  - 1000 second period measurements using buried 15 kg sensors might seem utterly incompatible with airborne/UAS, but let us see
- AMT – Audio-freq MT between 3 Hz and 30 kHz (ELF, SLF, ULF and VLF radio bands)
- AFMAG – magnetic only tipper of natural fields, "ZTEM" one commercial airborne system
- VLF = "Very low frequency from a radio communications perspective": 3 to 30 kHz, used in submarine communication and as a method description in exploration geophysics
- GPR – Ground Penetrating Radar around 30 MHz: VHF and UHF, more recently MF for deeper penetration
- AEM - Airborne EM

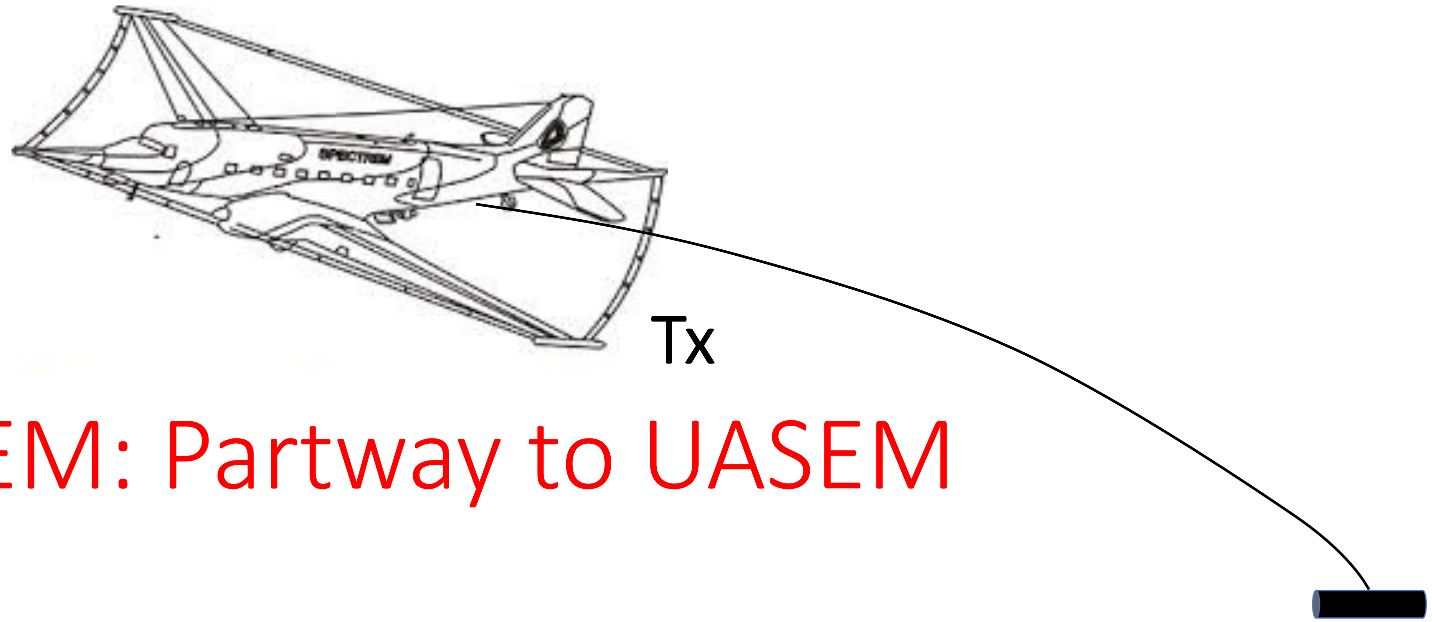
AMIRA's P1204 "Developing UAV-mounted geophysical sensor arrays" project completed end 2020

- Provided a summary of geophysical state of the art systems in exploration geophysics including EM considered for UAS implementation
- Investigated Ground EM's many variations
  - TEM Time domain / FDEM Frequency Domain
  - Wideband / Narrowband(s) within 11 decades of frequency 0.003 Hz to 300 MHz
  - Sources: Moving Loop / Fixed Loop / Natural / Cultural / Grounded
  - Transmitters Low power lightweight (shallow) / High power heavyweight (deep and/or distant)
  - Measure B or dB/dt or E or combinations



https://amira.global/project/developing-uav-mounted-geophysical-sensor-arrays/





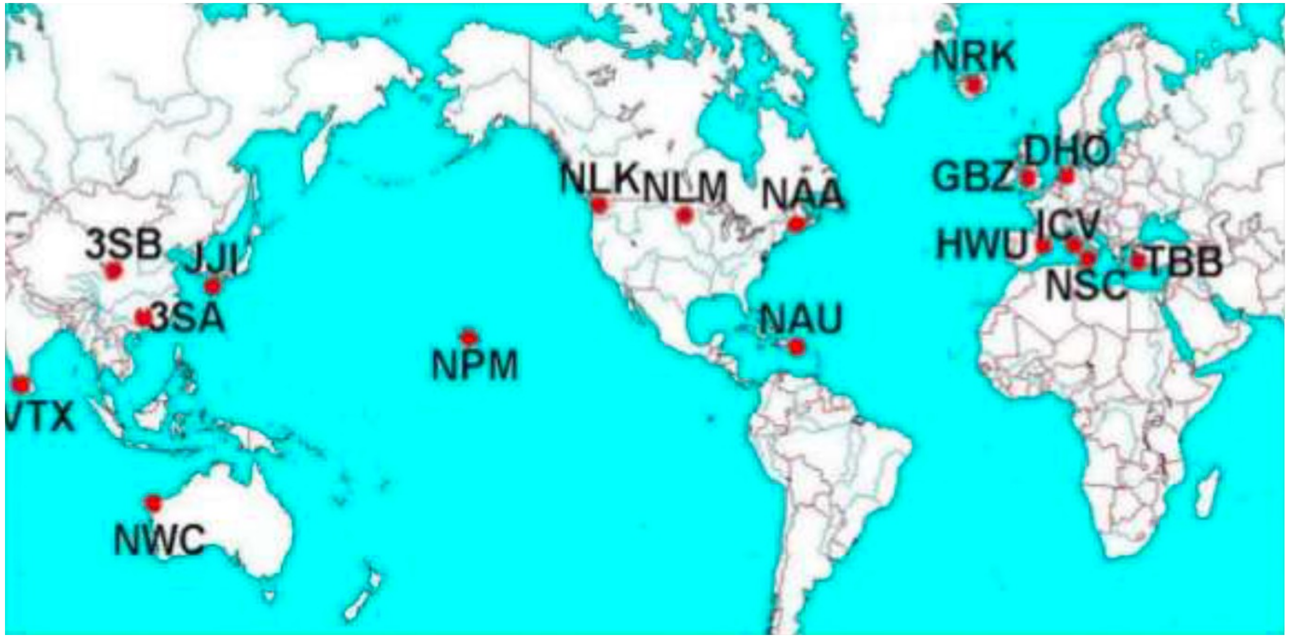
Airborne EM: Partway to UASEM

- Controlled Source
  - TEM. Time domain / FDEM Frequency Domain systems
  - Wideband / Narrowband(s) in bands upwards of 25 Hz (lower freq systems exist but are noisier and "unproven")
  - Transmitter Sources: Airborne Loop / Ground Loop / Natural / Cultural
  - Low power lightweight systems not extensively used except in UXO applications…. Aircraft altitude decreases shallow resolution compared to ground systems
  - High power heavyweight
    - E.g. Spectrem has a Lexus car engine in the plane to drive a generator
  - dB/dt sensors; E and B not used, although integrated dB/dt sold as B
  - Existing systems cannot penetrate much of e.g. West Australian conductive cover
- Natural/cultural source
  - AFMAG (low spatial resolution)
  - VLF (limited depth penetration)

Why are UAS attractive at first sight?

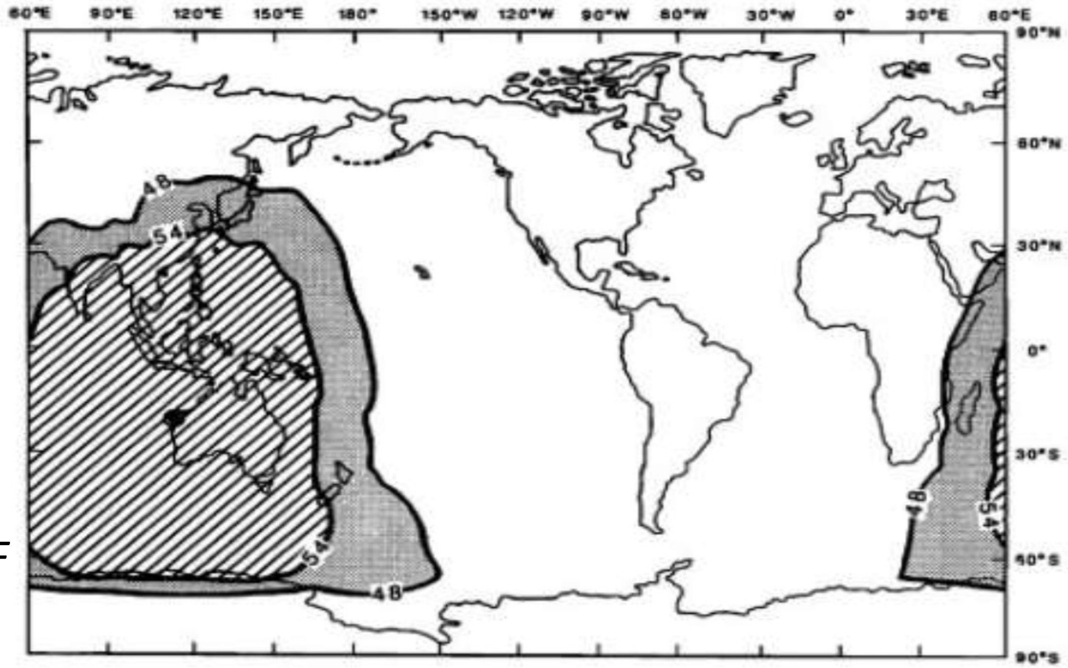
- The myth
  - Safe
  - Permit swarms
  - Efficient
  - Reliable
  - Inexpensive
  - Easy to operate
- The reality
  - Cannot fly in regulated airspace due to danger to piloted aircraft
  - Obstacle avoidance imperfect
  - Charging/transport/size an issue
  - Existing regulations may require one pilot per UAV
  - Limited flight times require close base of operations and significant personnel time
  - MTBF 1 in 100 hours for cheap UAS, 1 in 1000 for “expensive UAS’s” …. commercial aviation reliability 1 in 100,000 hours.
  - Enormous cost of unreliability of UAS’s, loss of $20k+ instruments
  - Most jurisdictions require trained and licensed pilots for commercial operation
  - Beyond line of sight (BLOS) heavily regulated and “pilot intensive”

Submarine communications: world's most powerful EM transmitters operate at VLF – an obvious source for UAS with a lightweight sensor



Operating transmitters

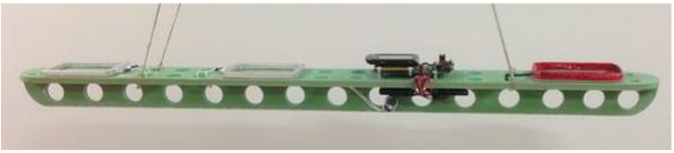
Easily detectable signals from NWC



Hauser & Rhoads, Coverage Predictions for the Navy's Fixed VLF Transmitters, NAVAL RESEARCH LAB WASHINGTON DC, 1974.

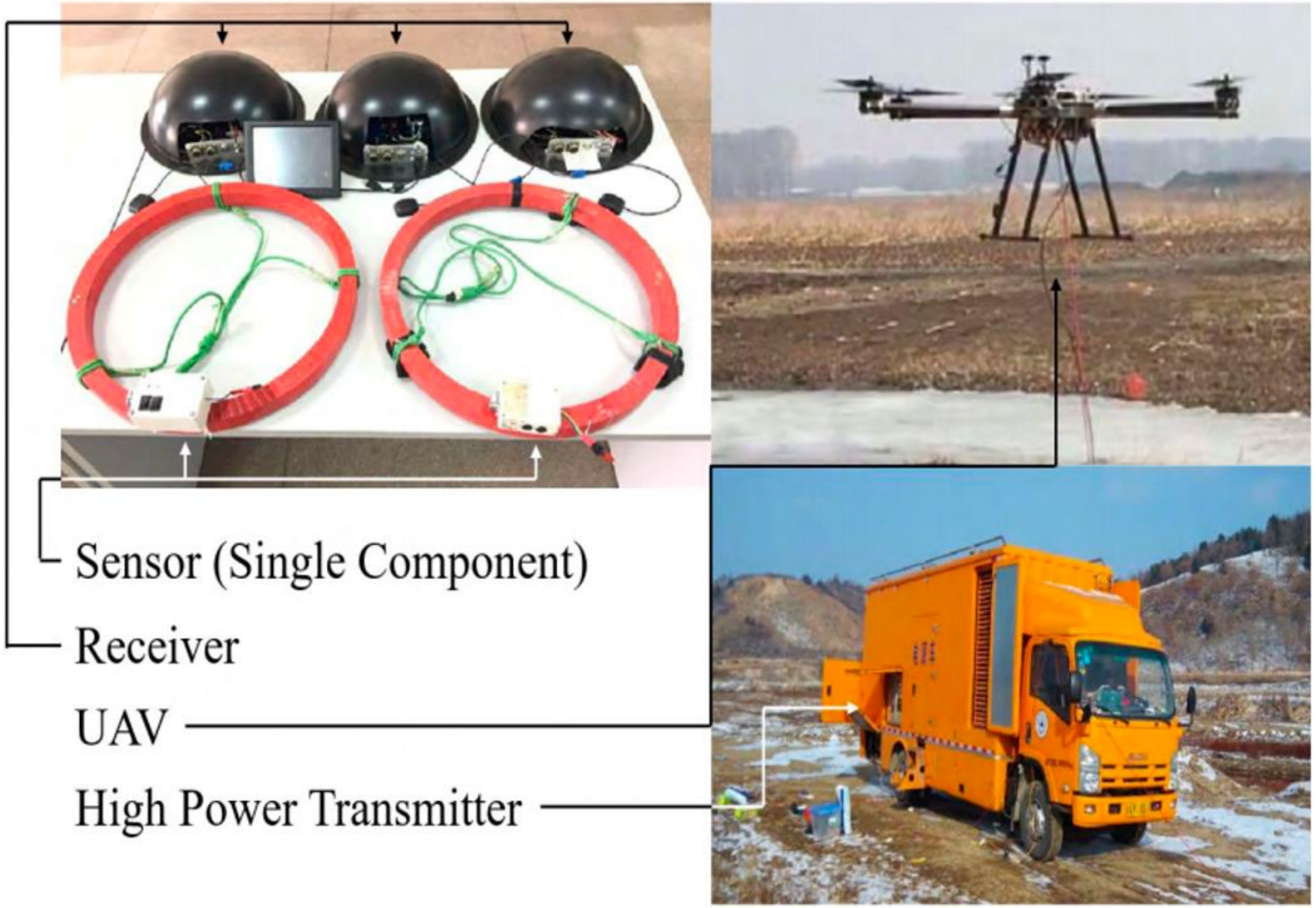
What can UAS do OK now?

- Several lightweight EM systems / VLF / RF receivers hung below UAV's and collected useful data in e.g. UXO detection.
- Tether because of significant electromagnetic noise (Communications, PWM power supplies, magnetic servos, power distribution, alternators etc).
- Limited upside for investment in further development of these "incremental" advances as depth of investigation shallow.



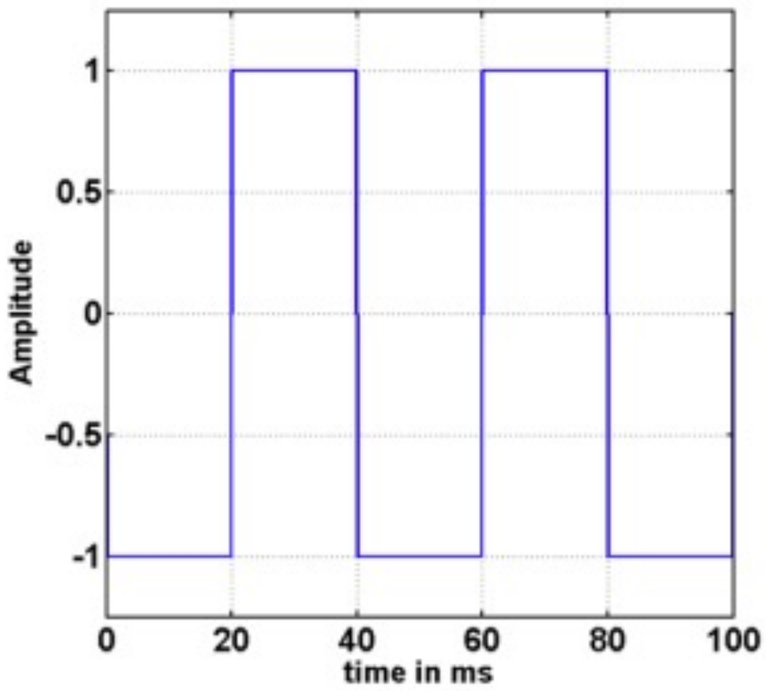
Images from internet advertisements

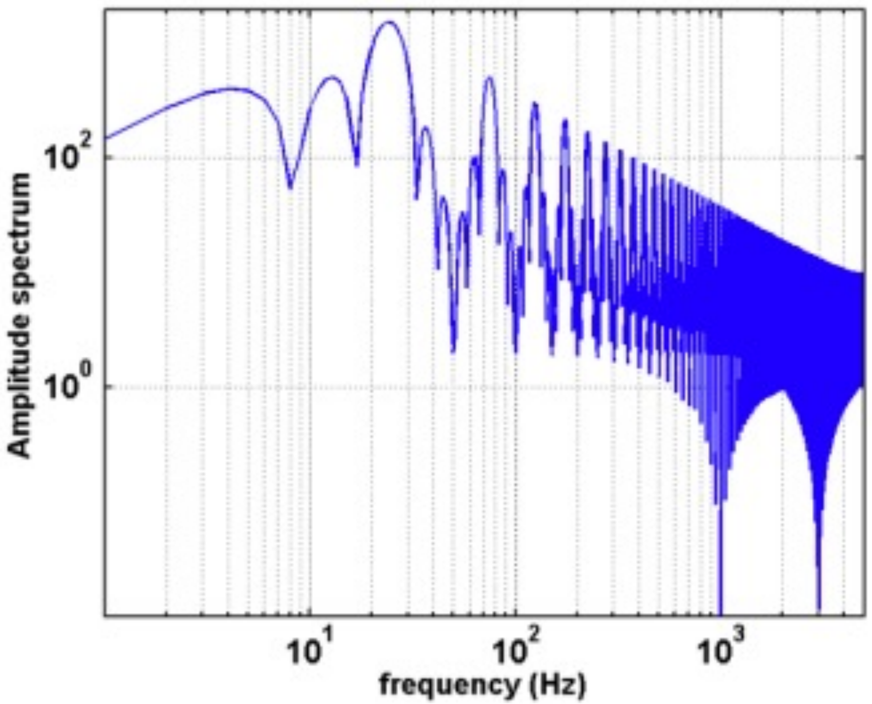
What do UAS do badly now? Fixed ground Tx, UAV Rx surveys



- Grounded bipole / large loops with UAV mounted receiver (inefficient compared to AEM).
- Tethers still needed.
- Low S/N achieved: motion noise, lack of sensor suspensions used in airborne and averaging time.
- No obvious way forward to improve concept.

The Development and Applications of the Semi-Airborne Electromagnetic System in China, Wu et al, IEEE Access, 2019





Grounded wire source current waveforms and spectral response, but published data not analysed in terms of subsurface physical properties and has inadequate S/N ratio for deep EM prospecting. Much R&D required before being useful

Semi-Airborne electromagnetics using a multicopter, *Stoll et al.,*
2019 Xi'an: International Workshop on Gravity, Electrical & Magnetic Methods and Their Applications

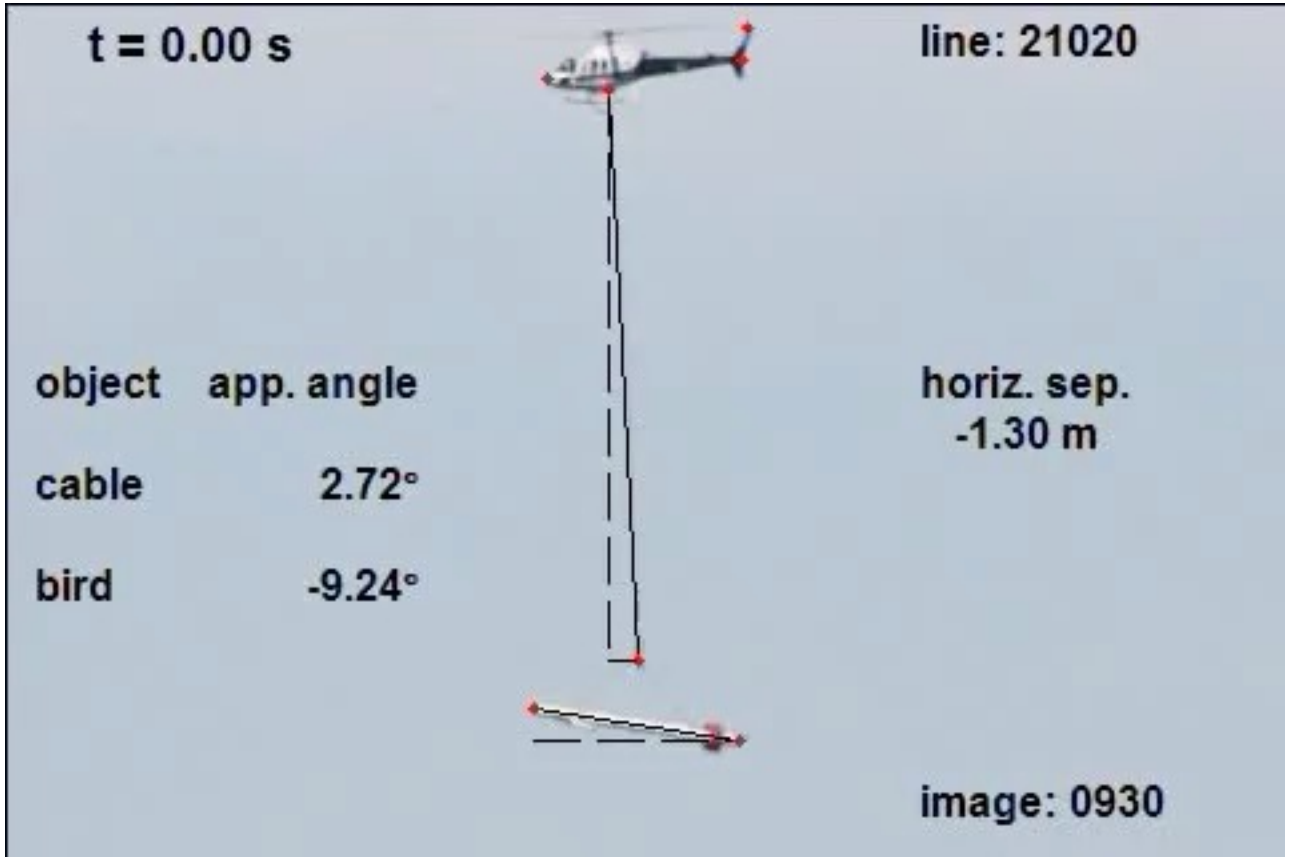
Ignoring UAS, what are the unsolved problems of existing AEM systems?

- Inability to get good data at low frequency (motion/rotation noise) limits conductive cover penetration, detection of high grade massive sulphides (Cu Ni) ores, detection of Induced Polarization effects from economic disseminated sulphides
  - Neither B nor E field airborne sensors operational, only dB/dt with its comparatively high-frequency sensitivity due to 1/f amplitude falloff, and resulting poor low-frequency sensitivity
- Aircraft electromagnetic noise means that long sensor tethers are needed, complicating operation
- Safe flight speed /economics means limited averaging times possible for noise reduction, critical at low frequencies
- Slightly Expensive

Tethered systems are complex pendulums (AMIRA P407b)

Main pendulum goes back quicker than forward (air pressure), Different in-line period(~9 s) compared to side-to-side(~10 s) pendulum Yoke point has second pendulum (~2 s period)

Video sped up in time



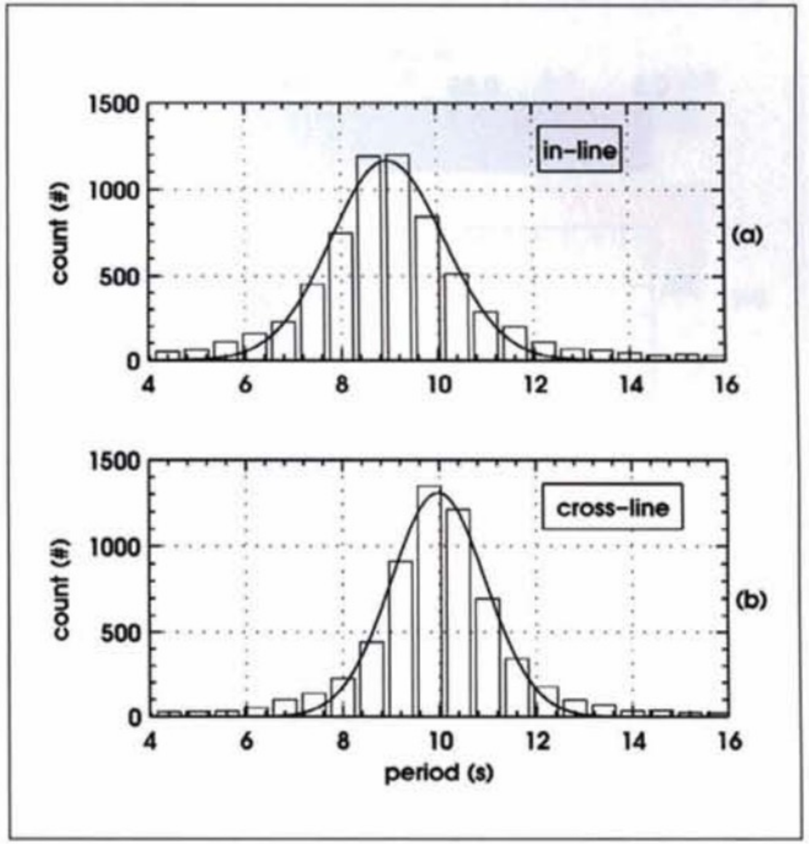


Fig. 6. Distribution of the period of oscillation for the in-line component of bird swing (a) and the cross-line component of bird swing (b). In each, the histogram is superimposed by a fitted normal distribution. For the in-line oscillation, the distribution is (8.97 ± 0.35) s with a mean of (8.97 ± 0.01) s, while for the cross-line oscillation, the distribution is (9.98 ± 0.24) s, mean value of (9.98 ± 0.01) s.

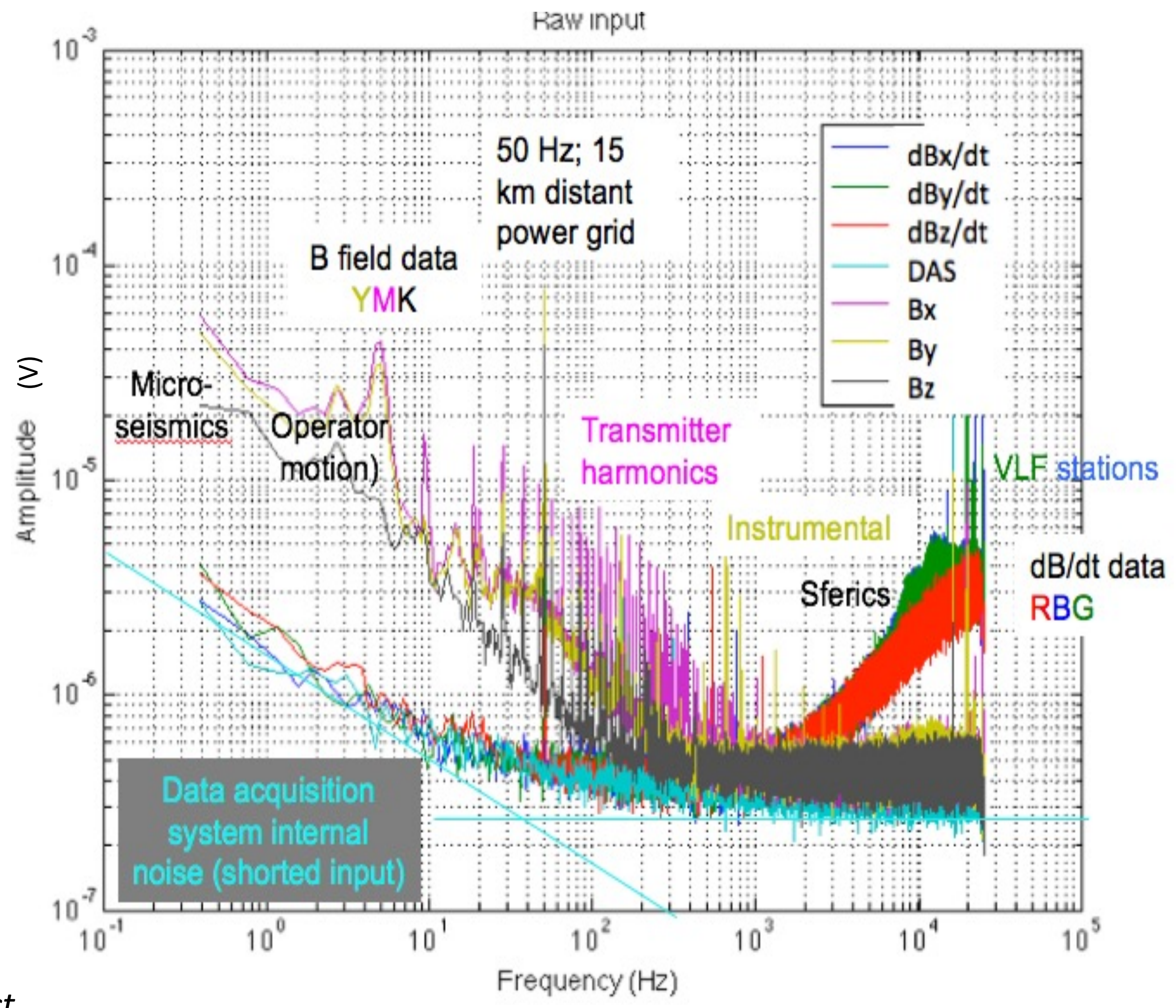
Induction Sensor Noise

Low-frequency data improved with B measurement

High frequency data improved with dB/dt measurement due to linear increase with f

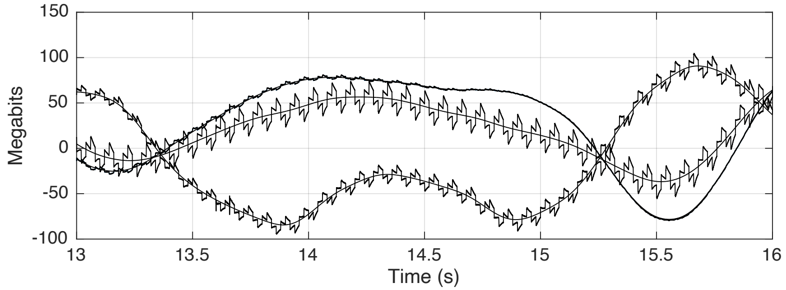
[Actually S/N ratio the critical parameter for which the (internal) sensor noise is identical between B and dB/dt, however B data linearly requirements and "bit depth" lower for same accuracy]

From an Abitibi Geophysics funded project



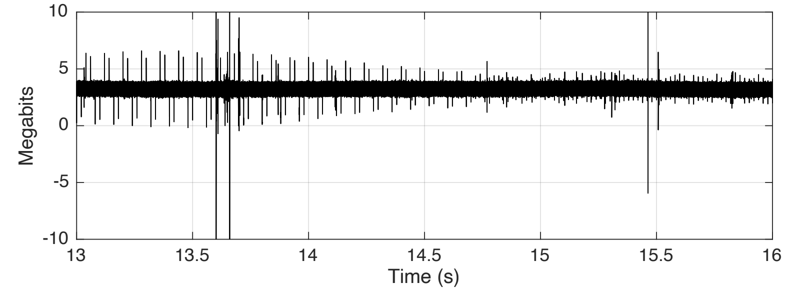
Sample Airborne BIPTEM data from AMIRA P1036a

Raw data over Tx loop shows EM signals on slowly varying (rotation noise) background



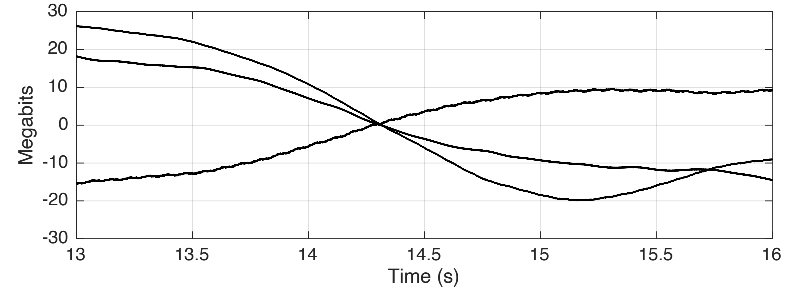
ARMIT B field

Strong VLF and sferics evident in dB/dt. Rotation noise still there



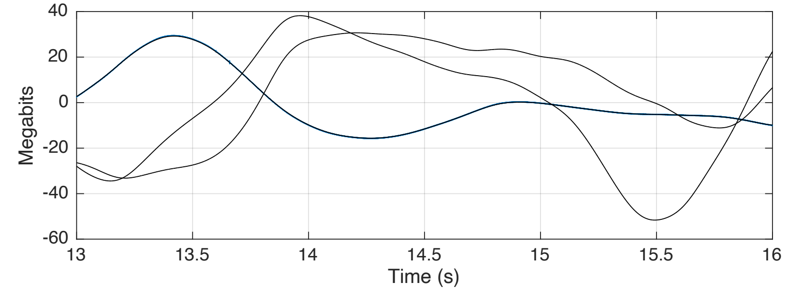
ARMIT dB/dt

Mean fluxgate on bird subtracted to show variations



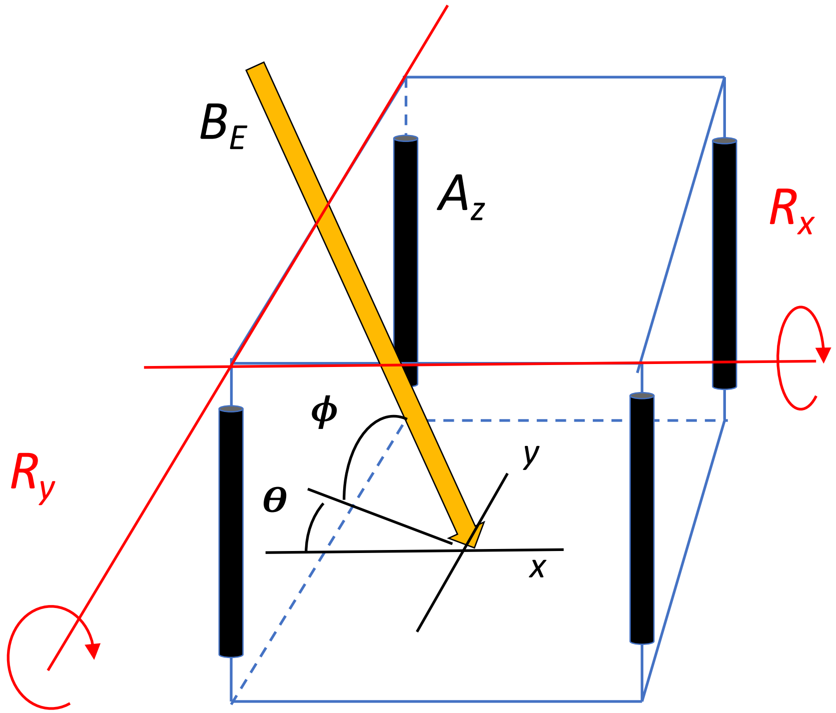
Fluxgate B field

Note rotation rate has same general "frequency content" as ARMIT B



Rotation rate

Effect of Rotation



- Earth's field B_E has components
  - $B_z = B_E cos(\phi)$
  - $B_x = B_E sin(\phi)cos(\theta)$
  - $B_y = B_E sin(\phi)sin(\theta)$
- B_z field sensor (e.g. fluxgate) "sees" effects of rotations in *x* and *y* directions, but insensitive to rotations around *z* axis.

- ARMIT A_z sensor detects changes in B_z above corner at 7 Hz and changes in dB_z/dt below the corner.

50 fT anomaly sensitivity compared to 50,000 nT Earths field requires pointing accuracy of 1 part in 10^9 if vector sensor is sine rather than cosine coupled.
When sine-coupled, equivalent to angular resolution of 1 mm at a distance of 1000 km!!!!

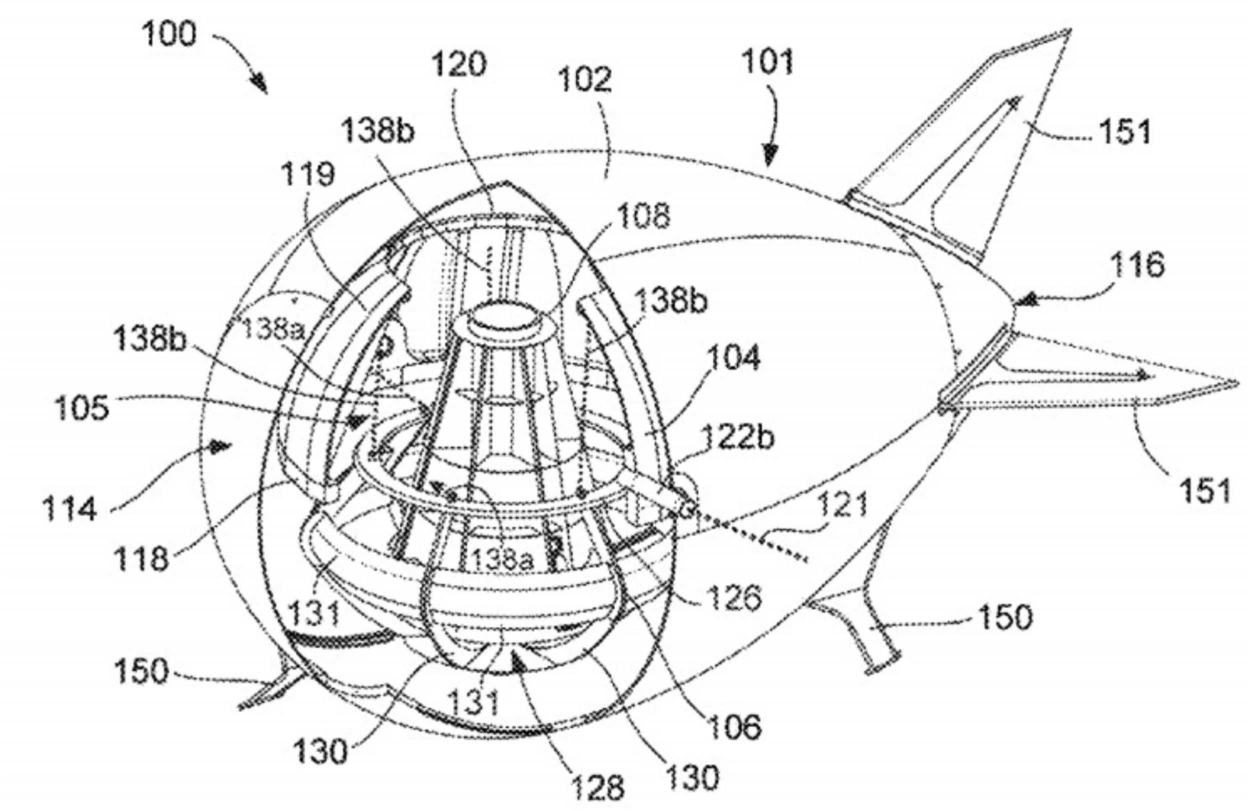


Figure from US **Patent number:** 10838100
Ben Polzer et al, ass. Vale S. A.

Massive assemblages with “air-hockey” suspensions have achieved sub 10 Hz performance, but unsuitable for UAV

HeliSAM total field magnetometers have flown to collect low-freq. EM data from ground transmitter using drone

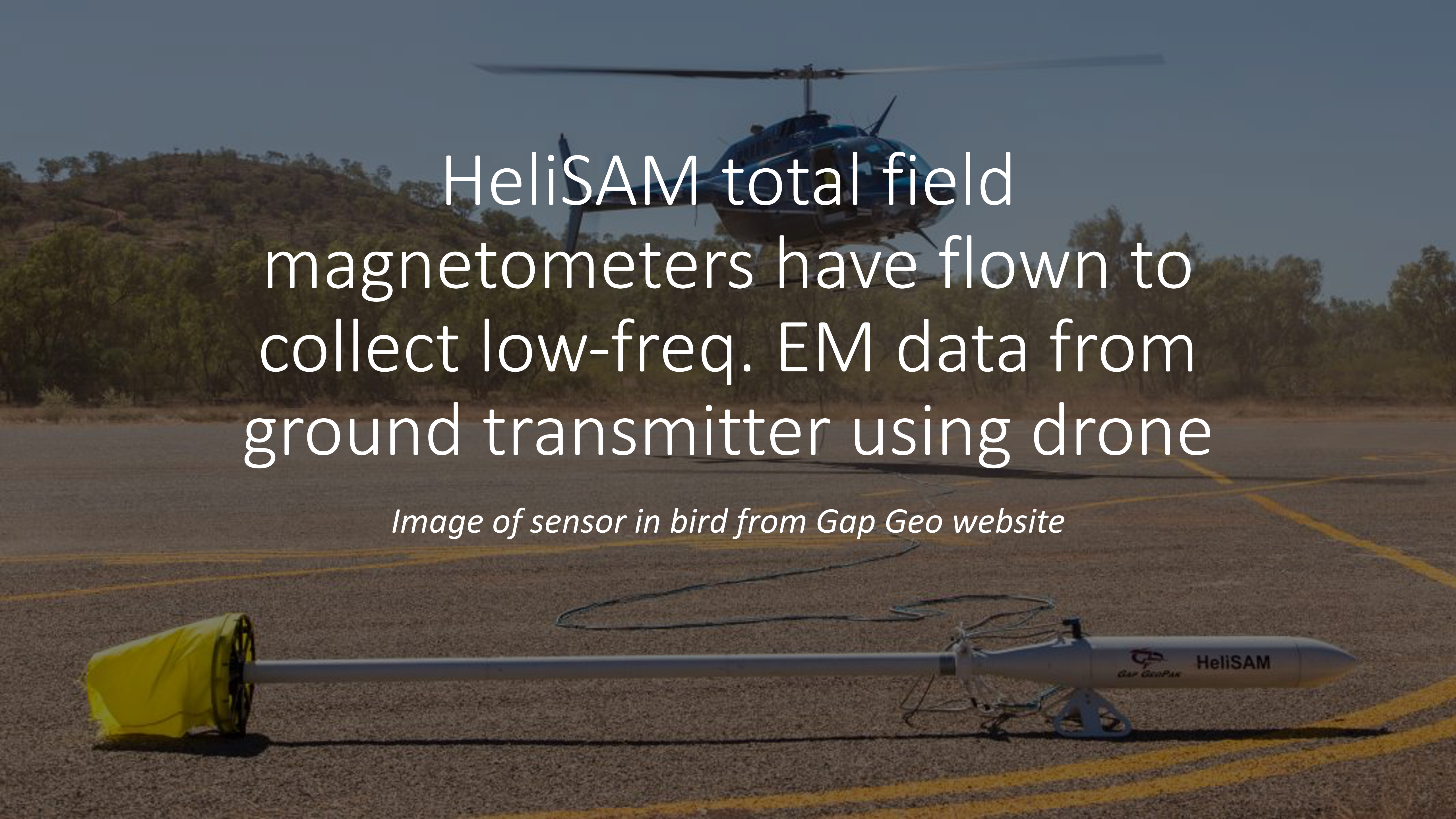
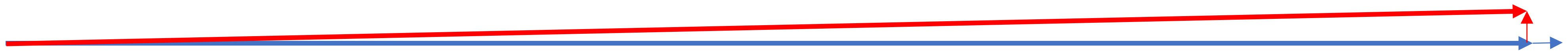


Image of sensor in bird from Gap Geo website

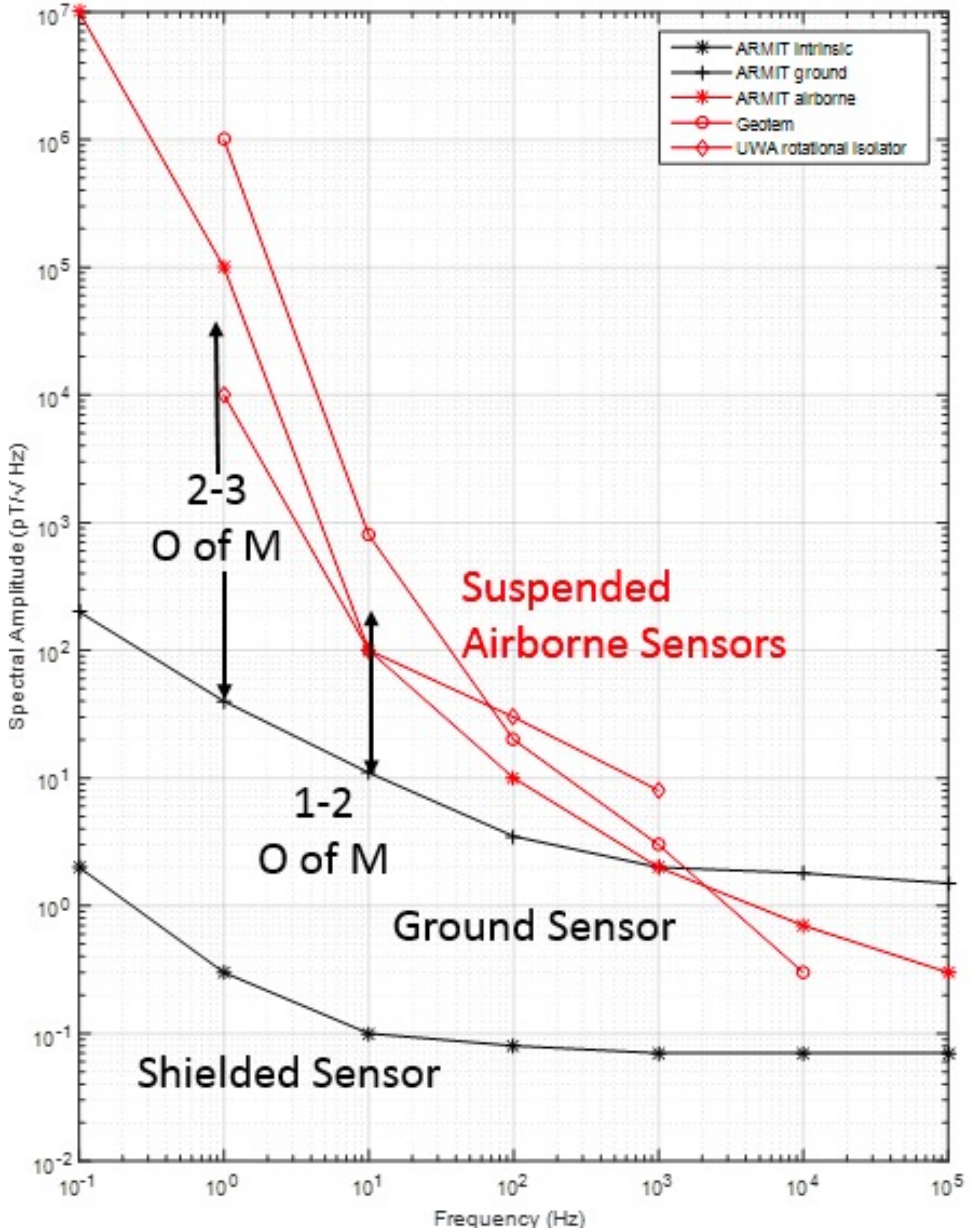
Total field measurements (Optical pumping)

- Presently bandwidth limited to < 1 or 2 kHz so not ideal
- “Dead zones” so sensor orientation can be challenging
- Only measure component of secondary field in direction of Earth’s field. [sub-vertical near the magnetic poles, horizontal in India]
  - May have coupling issues to some targets, avoidable if target location known and source geometry controllable, but this is not always the case
- Much higher noise than induction magnetometers or Squids, so require much more powerful transmitters



Why might UAS as "replacement AEM systems" not be much use?

- Grounded wire / loop sources inefficient if chosen
- Powerful, reliable helicopters for AEM transmitters are multimillion$ devices…. No short term incentive to go UAS except maybe night-time operations which have regulatory issues
- Lightweight vector sensors have more motion noise than heavy ones, so next to no incentive to go UAS for receivers alone with ground or airborne transmitters, particularly at low-frequency
- Airborne B vector sensors are more susceptible to motion noise than dB/dt, so UAS exacerbates issues for obtaining desirable B field data
- No obvious benefit of UAS to replace helicopter/fixed wing airborne EM, as UAS systems would have severe limitations?



Rotation Noise: need sensors on the ground for low freq.!

- Plot shown noise levels of ARMIT B field sensors
- Measured noise levels of a Geotem dB/dt coil with conventional and UWA rotational isolators
- At 100 Hz, airborne systems 0.5 to 1 order of magnitude noisier than ground sensor
- At 10 Hz, the airborne sensors are 1 to 2 orders of magnitude noisier than ground sensors, while at 1 Hz, the airborne sensors are 2 to 3 orders of magnitude noisier.
- CGG/Skytem claim now to be doing much better than shown here but technology not yet proven

The grasshopper UAS array vision

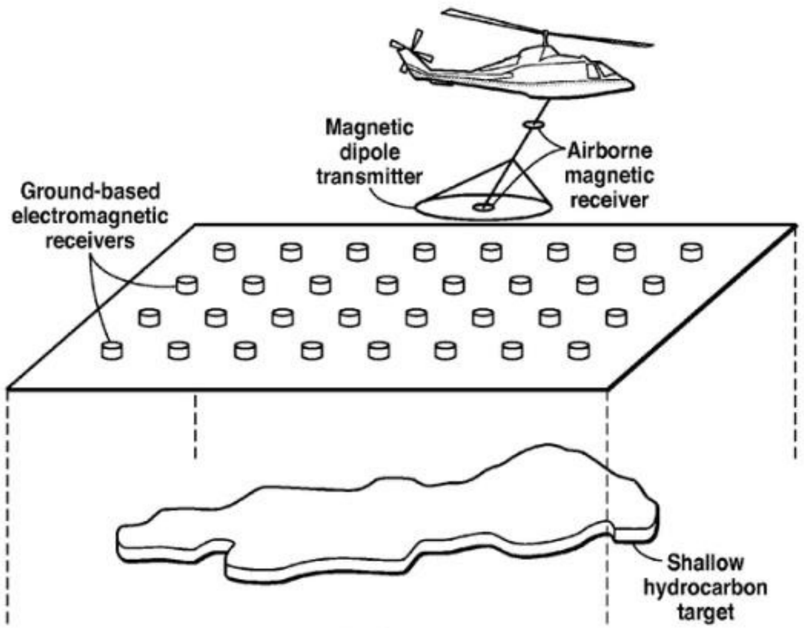
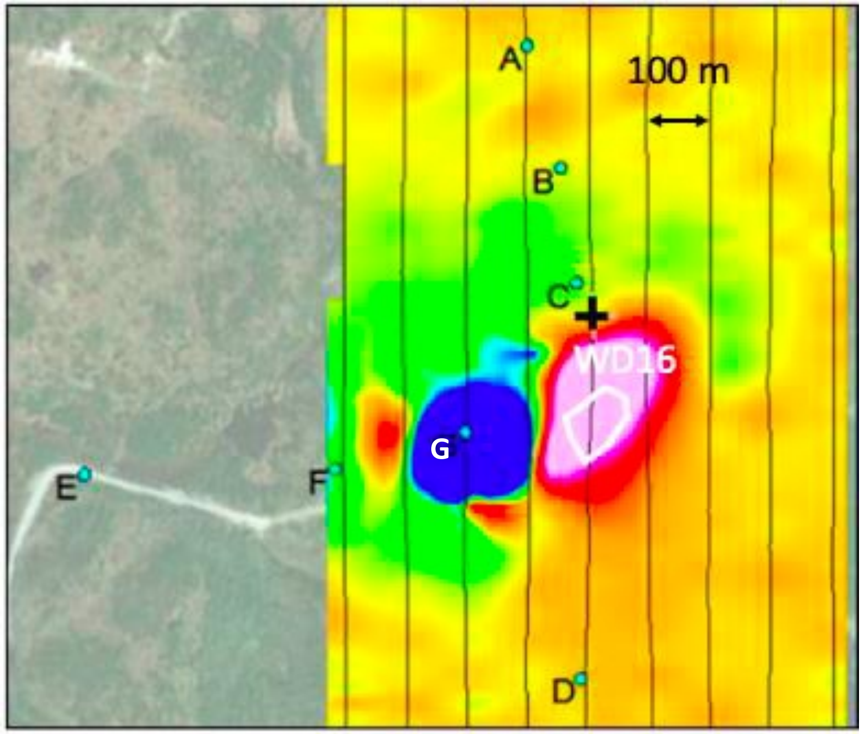


FIG. 2

- ExxonMobil Upstream Research Co Patent CA2846317A1

- Bengaert et al. Groundfloor EM station G (in middle of blue blob) located roughly 200 m west of the small, near-surface WD16 Nickel deposit located north of Sudbury, Canada

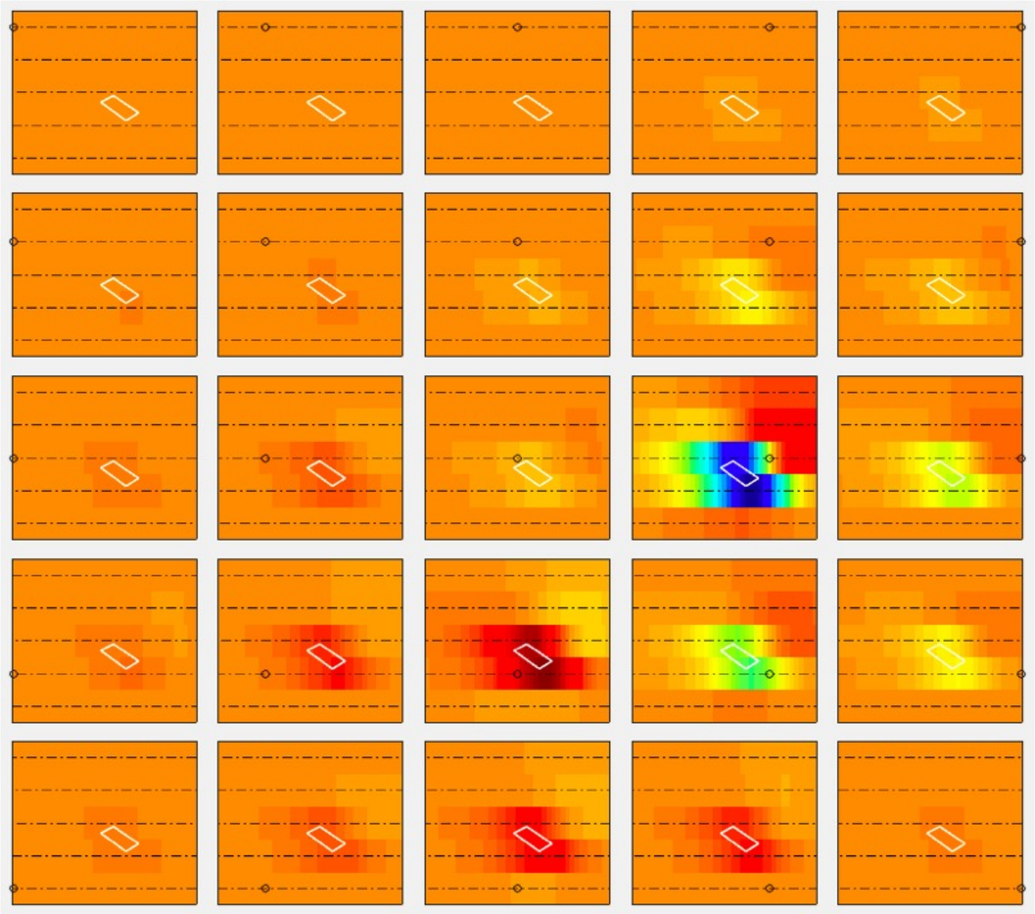


B-field data collected using a Zonge induction magnetometer, streaming DAS, 30 Hz base frequency VTEM transmitter

As well as ground sensors eliminating motion noise and enabling E fields, simultaneous acquisition has S/N advantages, so can lead to "better" data, provided that:

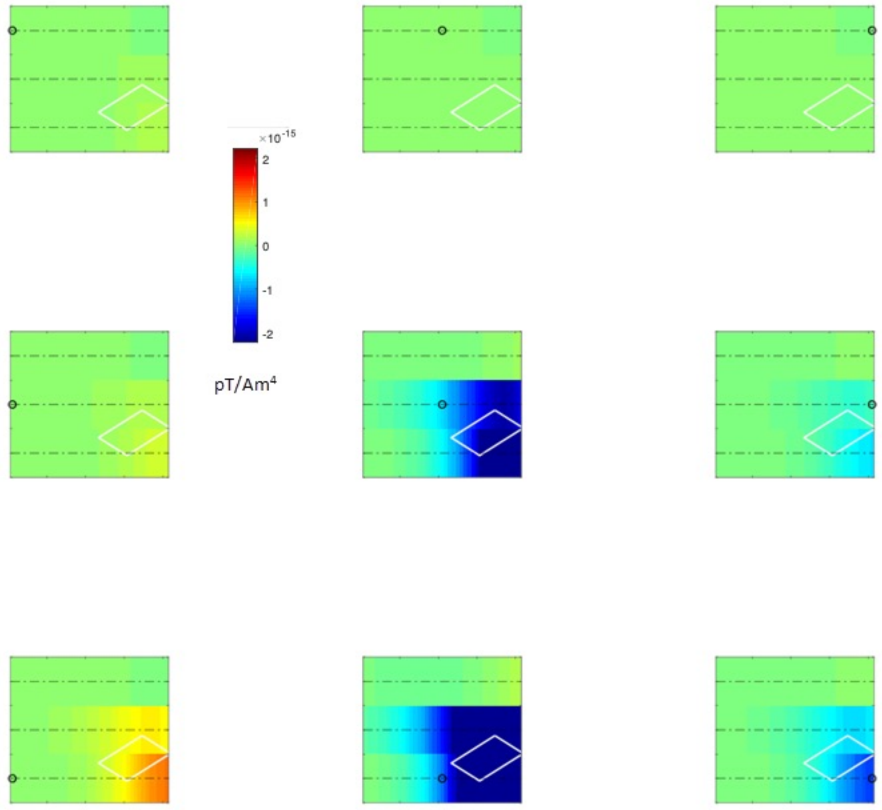
- a) Low enough internal noise as the effective internal noise amplitude increases by 41% if data from 2 sensors subtracted
- b) The data acquisition systems have sufficient linear bits after A/D conversion and the different data channels are accurately synchronised
- c) The unwanted signals (noise) need to be strongly correlated with each other, and corrections may need to be made for direction dependent speed of light delays

Modelling shows we can use wider-spaced lines with increased resolution



- Numerical model of 25 “Groundfloor” late-delay time B-field responses of a 1 km square survey area with 250 m spaced ground stations shown by circles, 250 m survey line separation
- Sulphide target 200 by 100 m, 60º dipping and 45º striking at a depth to top of 200 m.
- Each square is an image of the response from the ground site shown by a circle.

Bigger EM targets (400 by 200 m) easily detected with 500 m spaced ground stations and 500 m airborne line spacing



- Detection obvious even for target between the survey lines
- Target was 100 S conductance at 300 m depth to top, with 45º strike and 60º dip.

Use the Amazon UAS delivery model to plant and move EM systems for AMT / transmitter overflight

- B and/or dB/dt data from lightweight induction coils
- Tripod sensors with IMU/GPS/accelerometer orientation will minimise wind noise
- E field data from ground contact (high impedance electrodes or “Taser” implantation)
    - E sensitive to resistors as well as conductors

Get better data than AEM at lower frequencies. Get the high spatial density that AMT or even MT needs but does not currently provide

AMIRA P1204 Conclusions: UAS supported grasshopper arrays should be developed to operate with existing Tx's (hybrid system)

- EM
  - Grasshopper E/B sensor array with Tx grid pattern flight solves exiting AEM issues of motion noise and aircraft noise, permitting conductive cover penetration and deeper exploration
  - E fields permit detection of resistive as well as conductive targets, and AMT data can be collected
  - Permits longer stacking times without loss of spatial resolution, even with wider-spaced flight lines
  - No "null-coupled" targets, increasing coverage of variable strike angles
  - Needs inexpensive (mass produced) B and E sensors, allowing improved characterisation of both conductors and resistors
  - Needs significant investment to realise this.

There are of course challenges (over and above Intellectual Property issues) to implement AUSEM

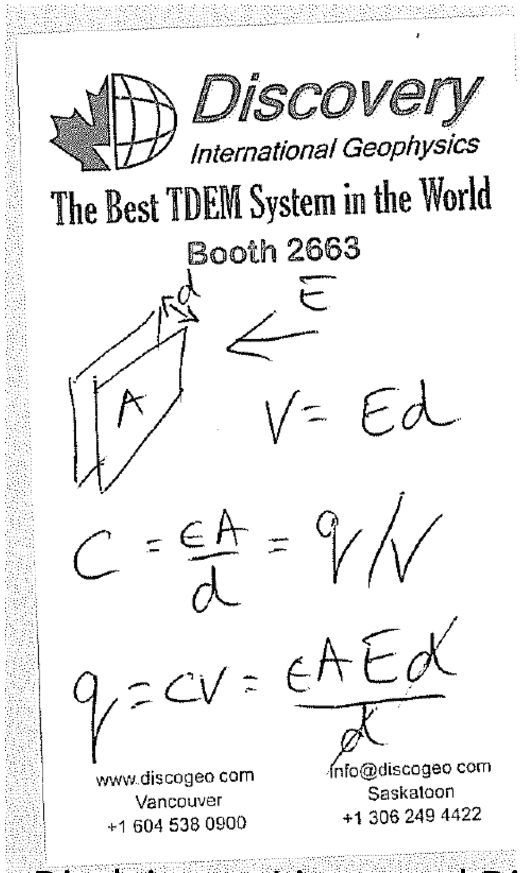
- Geophysical
  - Today one ground node with induction magnetometer and crossed E dipoles \$30k+
  - Realistically can shrink to <\$10k per node if mass produced
  - Electric dipole emplacement (or could replace 2*E with other 2 components of B field in some areas)
  - Significant software development for acquisition and modelling needed
- UAS
  - Cost effective multi UAS (swarm) flying at low altitude BLOS
  - Planting and retrieving receivers
  - Absolute avoidance of helicopter with Tx
  - Range/payload issues for inexpensive reliable UAV (with 500 m stations and 500 m survey line spacing with 5 km UAS flight per line swap and 4 or 5 lines emplaced need ~100 km range and 2-5 kg payload)

What about the Moon?

- Locating limited water/ice of great interest, as is geological mapping/sounding
- Materials electrically resistive compared to earth so higher frequencies needed to get same depth-penetration… 20 MHz MARSIS radar system achieved several km of penetration on Mars and has mapped geological boundaries/ice
- Due to solid cores (no dynamo possible), very small ambient magnetic fields so rotation noise not an issue in magnetic field EM measurements

- No earth-ionosphere electric field gradient on the Moon
  - Can potentially use non-contacting electrodes for AMT/MT from an orbiter without ground contact
  - One of such electrodes have noise levels 1 μV/m in a Faraday cage on earth.
- 20 nT diurnal variations on Mars due to solar wind, similar variations on the Moon but much longer days.
- Need lightweight, compact systems for transport and rover operation
- Updated GPR/EM systems for Moon/Mars are coming, alas I’m under Embargo awaiting government announcement

Thin non-contacting E field Sensors: "Back of the Envelope". AMIRA P1036a, 2012

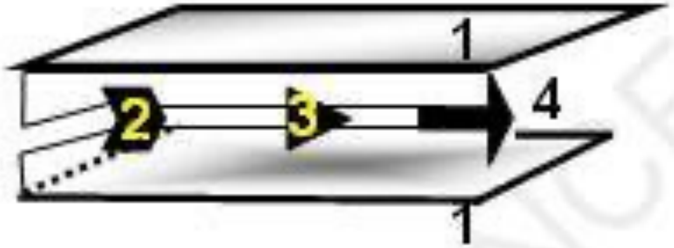


- In attempting to determine optimum Area and separation of sensor plates, showed that to first order, plate separation irrelevant to charge (as opposed to Voltage) sensitivity ***q = εAE***
  - Charge given by product of dielectric permittivity, plate Area and external Electric Field

Sensor measuring E in air perpendicular to copper sheets. Measured charge movements required to keep two thin copper sheets with an insulator between them at constant potential (active E measurement)

Disclaimer: I just used Discovery's free notepad for my "back of envelope" calculation, and do not endorse their claim to have the Best TDEM system

Enc3 sensor
1: Conductive Electrodes top and bottom of case
2: Charge Amplifier
3: Voltage Amplifier
4: FM modulator and transmitter
……………………
5: Receiver & Data Recorder



"2011 vintage Slide, AMIRA P1036"

Noise levels <10 μV/m in Faraday cage
Better design (not shown) had < 1 μV/m in Faraday cage
Both designs encountered noise of many mV/m in the air due to wind-blown charge on dust, 100V/m ±200V/m earth-ionosphere electric field gradient

Version might be good for compact, non-grounded AMT on the moon

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Low Noise, lightweight sensors for “cheap UAS” rather than the Amazon style delivery?

- Probably need total field sensors to avoid rotation noise on a small UAV, but 3 component vector sensors[#] could also work
- Light-Shift Dispersed Mz Mode* optical mags are being designed to fit on a single chip with <20 fT √Hz total field sensitivity and VLF bandwidth
- Variety of quantum devices under investigation with significant defence support

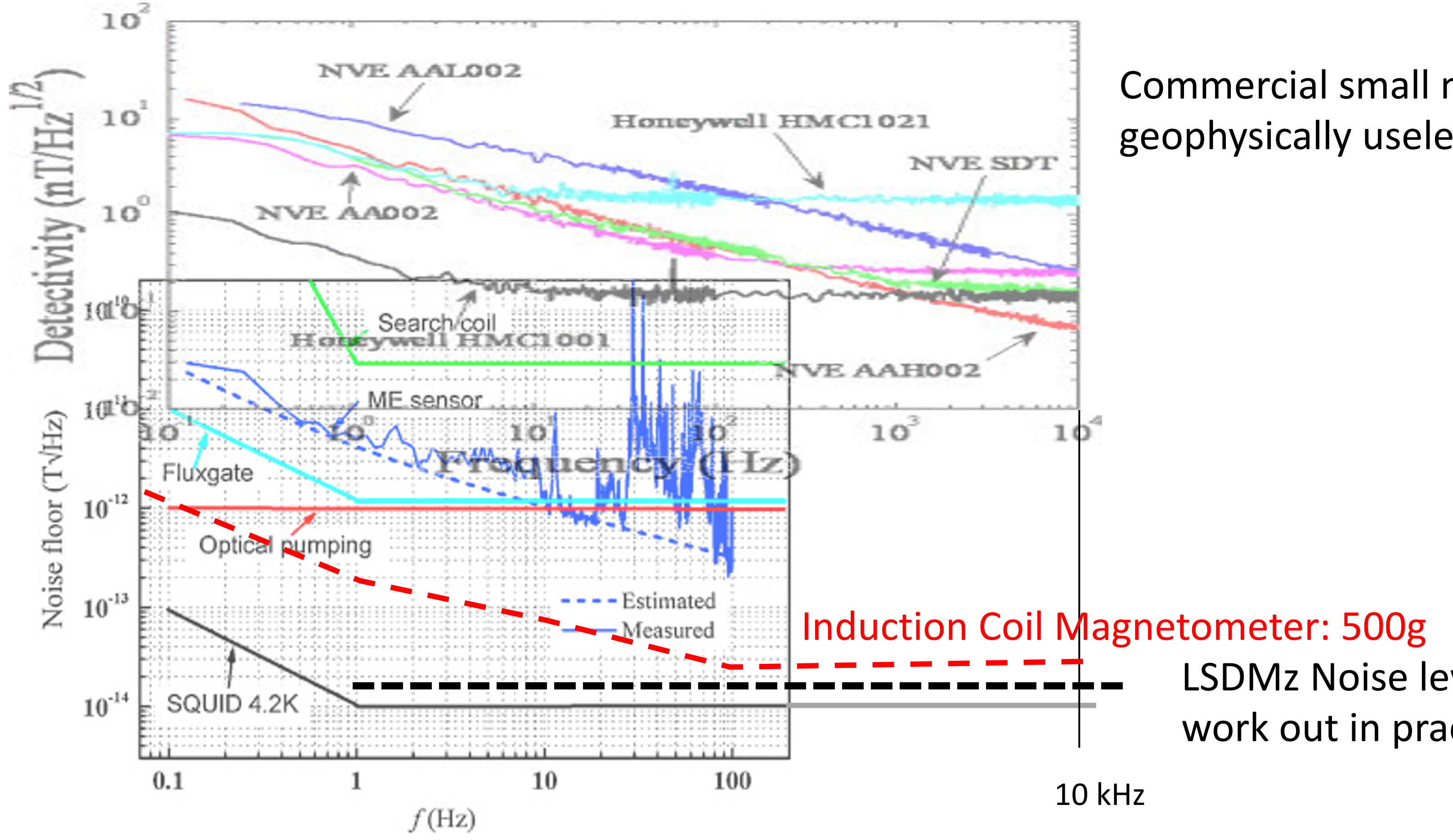
- Why Quantum?

The atom standard quantum limit defines maximum sensitivity. For warm vapour sensors, this limit reaches 1 fT/√Hz for vapour volumes less than a cubic centimetre. As such, there is considerable scope for miniaturisation compared to induction coil sensors with comparable sensitivity.

[#]*P. Bevington, et al., Object Surveillance with Radio-Frequency Atomic Magnetometers, Rev. Sci. Instrum. 91, 2020*

** Schultze et al, Sensors 2017, https://doi.org/10.3390/s17030561*

Spectral noise of a few commercial and future magnetometers that could be used for UASEM



Commercial small magnetic sensors all geophysically useless (ME, GMR, Hall effects)

LSDMz Noise levels in theory. Will they work out in practice on a single chip?

So, when will we see these “new” quantum/electric sensors?

1. When Defence Research Completed and Successful
    1. Or if research unsuccessful and sensors do not meet design expectations, and investigators choose to publish their failure
2. When Defence relaxes confidentiality constraints, such as
    1. Submarines not a threat
    2. Tunnel detection unimportant
    3. Other sensor technology better
    4. When ITAR regulations drawn up
    5. If Universities not constrained by Defence contracts commercialise recent discoveries
3. E field sensors suitable for the Moon already operational

What about MT? Developments may improve spatial limitations

- Chip sized quantum vector sensors theoretically “on the way” with less than 0.1 pT/√Hz sensitivity, bandwidth 100 seconds to 100 kHz
  - Potentially vector sensors on a chip suitable for ground operation, with costs a fraction of current sensors
- AMT feasible with lightweight induction sensors
- Tasered? E field sensors with wide dipole separation operational from UAS
- UAS regulations/reliability/safety improve enormously to permit BLOS planting of arrays

In summary

- There are very limited applications for lightweight, low-power transmitters capable of being moved by UAS
- Hybrid controlled source systems may be feasible (piloted airborne transmitters, array of UAS supported ground stations) as described in the public AMIRA 1204 report
- Natural and cultural source EM systems may be able to benefit from UAS and small sensors in the long run, on Earth now, the Moon soon, and other planets in the future.

Thank you