3-axis unshielded HTS SQUID geomagnetic sensor in an urban environment

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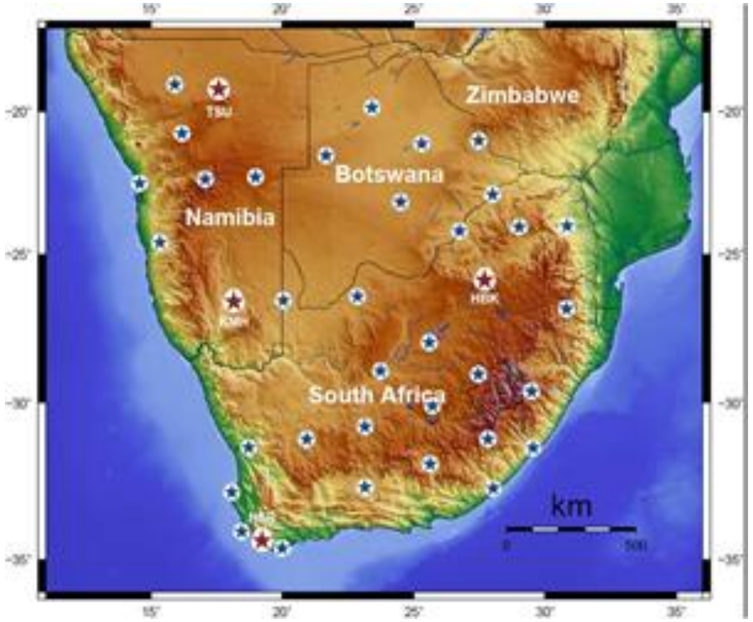
HTS SQUID system at SANSA Space Science

Project started as collaboration with LSBB, France, 2009
Czech Technical University, 2018

Location

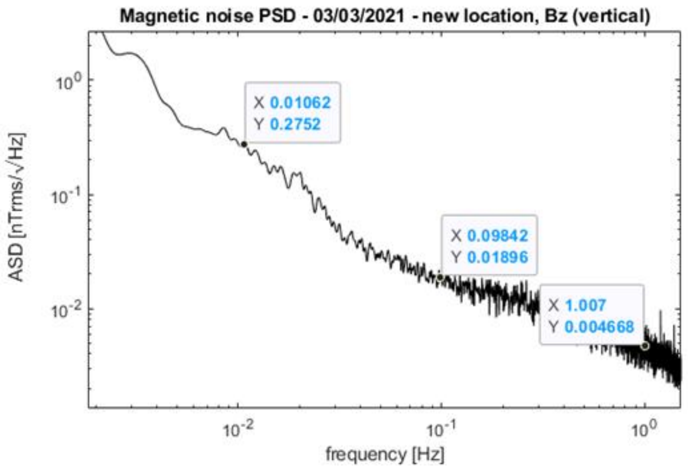
- Located at INTERMAGNET Hermanus Magnetic Observatory (HER) in Hermanus, South Africa
- 100 km from Southern most point of Africa
- 16 hectares buffer zone in medium town, 400 m from coast
- Surrounded by light industry, residential housing and hospital



Environment

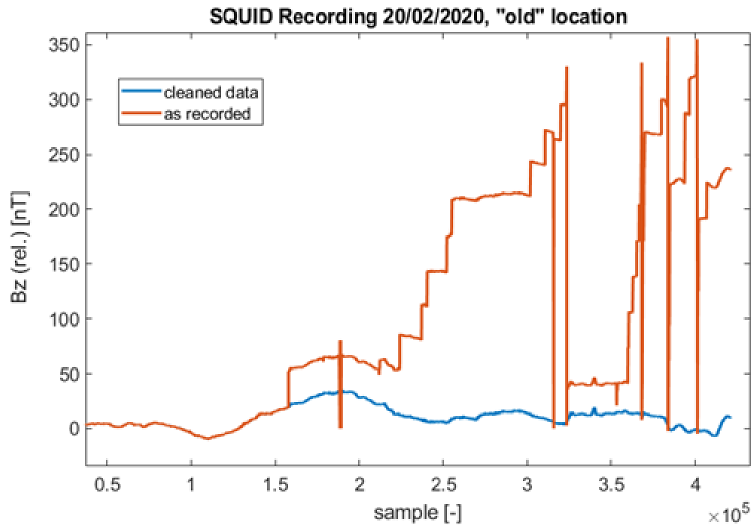
- Non-magnetic environment
- Located 50 m from closest PC and 50 Hz supply
- Co-located (100 m) with Observatory fluxgate magnetometer
- Low geomagnetic field, 25.5 uT

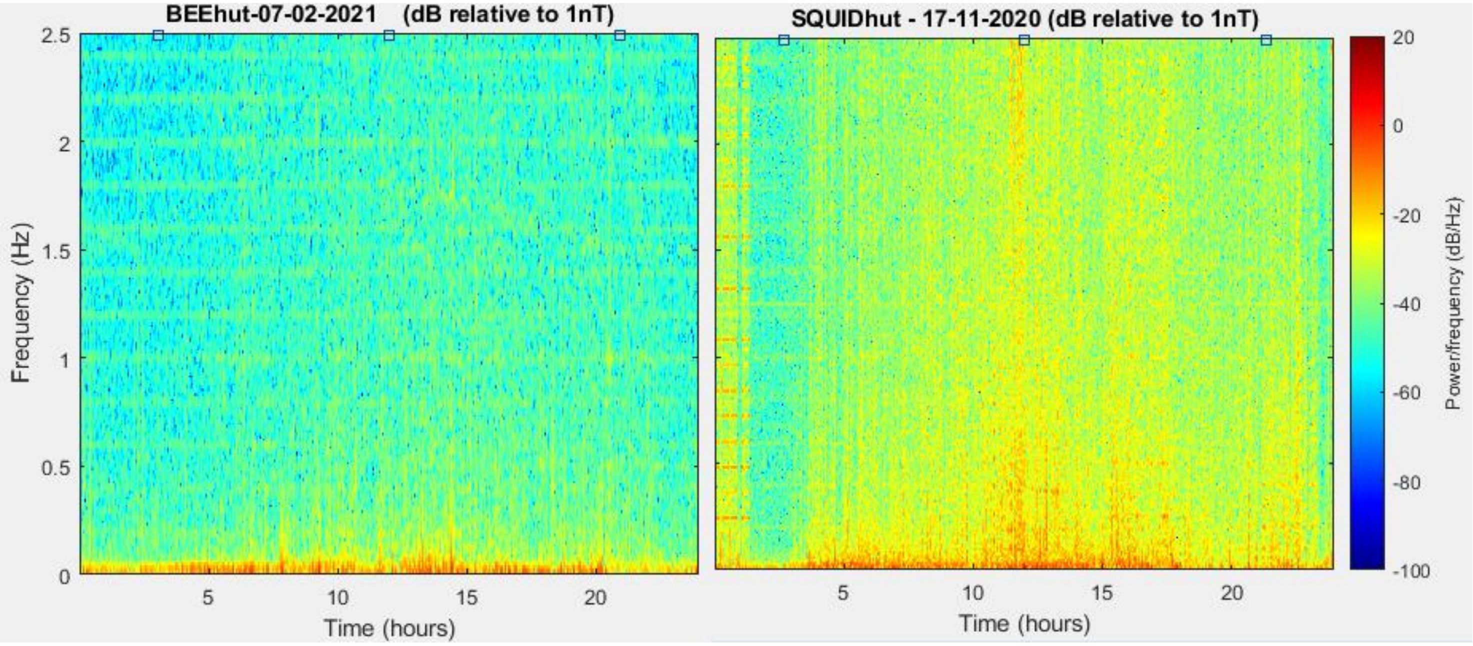
Current (2020+) SQUID performance vs historical



New location (left) – sandy soil
4.5pT@1Hz night-time,
stable 24/7

Old location (right) - rocky area
Flux jumps (RF EMI), noisy 90% of day (magnetic noise)





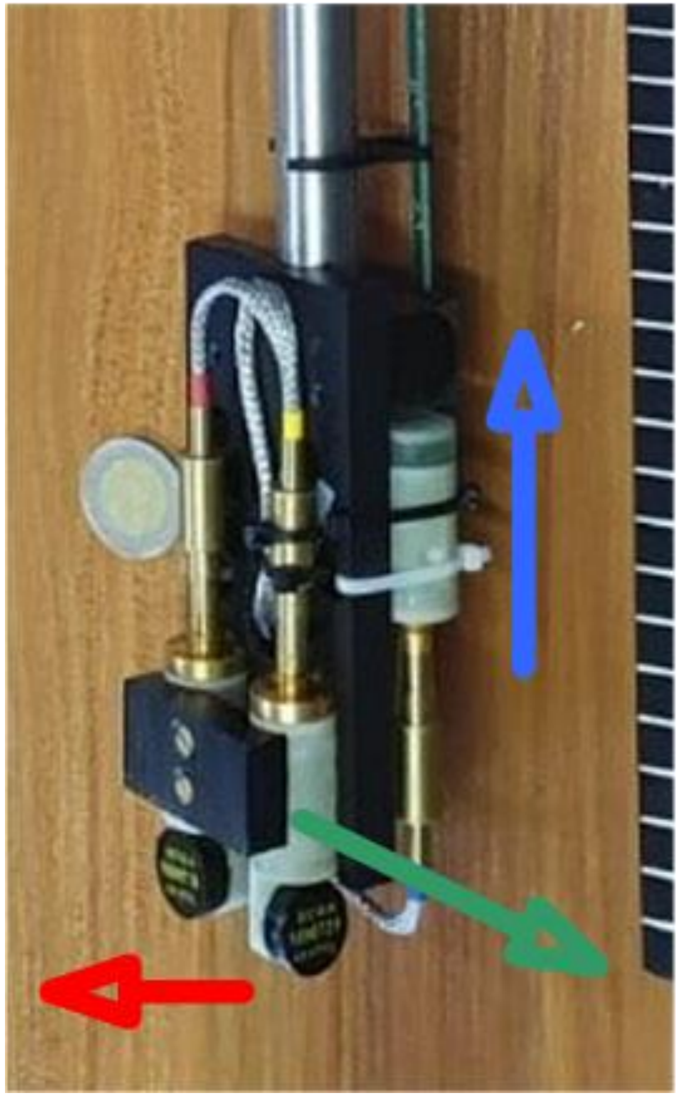
Current HTS SQUID system at SANSA Space Science

Older SQUID sensors:

- **Z axis:**
- M2700 high-Tc SQUID magnetometer from STAR Cryoelectronics (about 10 years old)
- Field sensitivity 32 nT/Φ_0
- Theoretical noise 300 fT/√Hz @1Hz
- Operates quite well unshielded in geomagnetic field

New SQUID sensors:

- **NS and EW axis:**
- 2 x HTS dc-SQUID magnetometer model HTM-8 from FZ Jülich
- Field sensitivity 4.5 nT/Φ_0
- White noise < 65 fT/√Hz
- Both in horizontal orientation
- EW SQUID operates unshielded, but problems
- NS SQUID has a very high bias current, not able to lock in FLL, so operates in Open loop

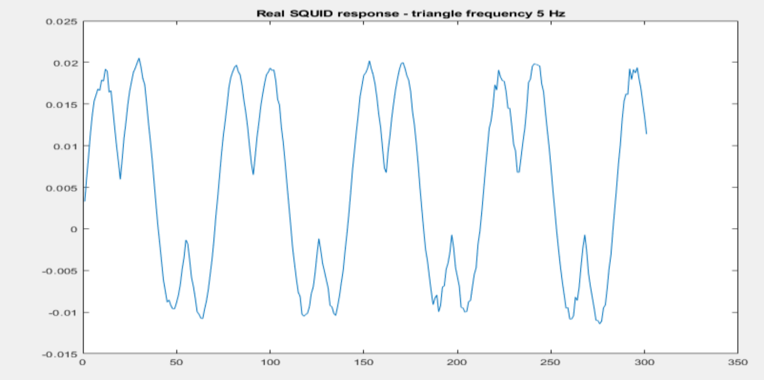


- Aim is a complete 3-axes SQUID magnetometer, not there yet

Cooling and control and data acquisition

Cooling at 77K:
- Liquid N_2 cooling using aluminum Bio 34 Dewar from Statebourne Cryogenics, at atmospheric pressure
- Operates up to 24 days between refills: Liquid N_2 @ 2 EUR/litre

Control Electronics:
- Magnicon SEL-1 FLL and control electronics

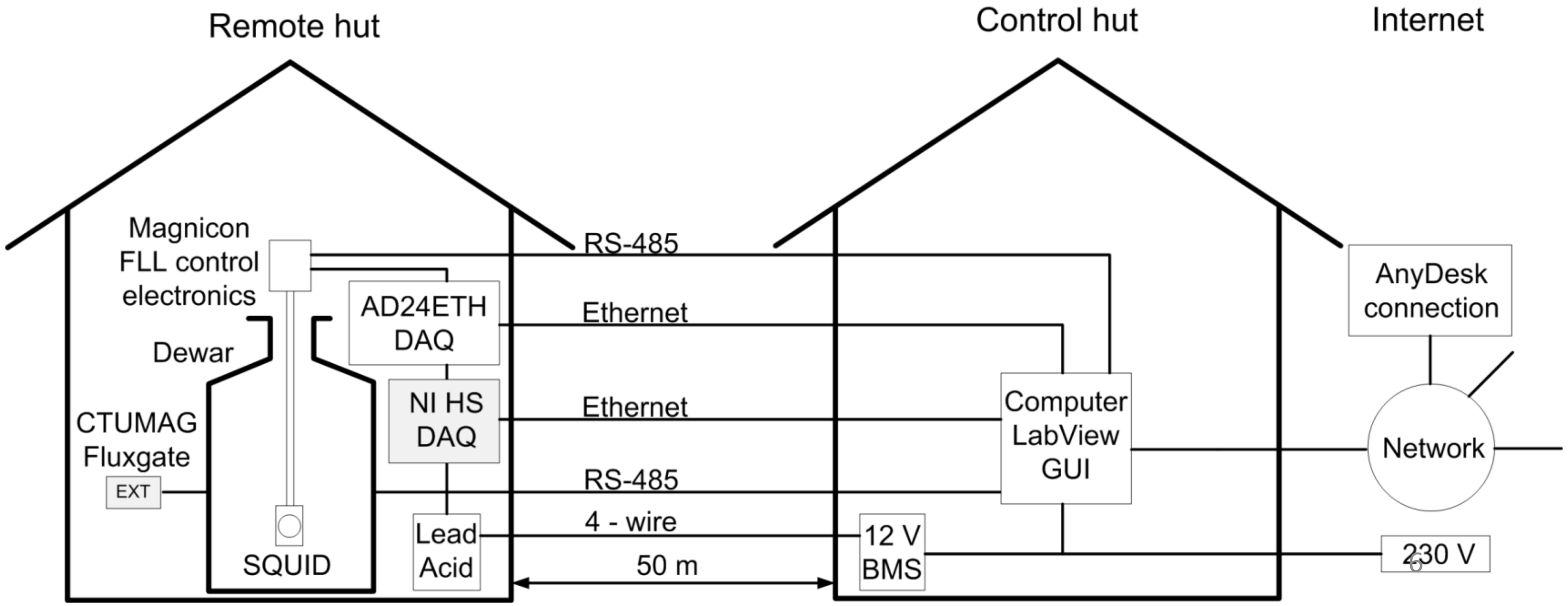


Data acquisition:
- acquisition @ 12.5 Hz with a JANASCARD 24-bit integrating DAU
- National Instruments NI 9252 DAQ, 50 kSa/s
- Sampling of SQUIDs will be possible up to 2kHz, however aluminium dewar limits the response to few tenths of Hz

Interface, connections and display

Current set-up:

- Magnicon control electronics connected via RS485
- JANASCARD AD24ETH DAQ connected via Ethernet
- NI Data Acquisition for fast data connected via Ethernet
- LabView GUI displaying SQUID Z axis (red) as well as HERFGM2 as reference (yellow) 100 m away
- CTU magnetometer as reference magnetometer(fluxgate just 4m away) connected via RS485
- All instruments in remote hut on DC power (12V)



Reference fluxgate magnetometer

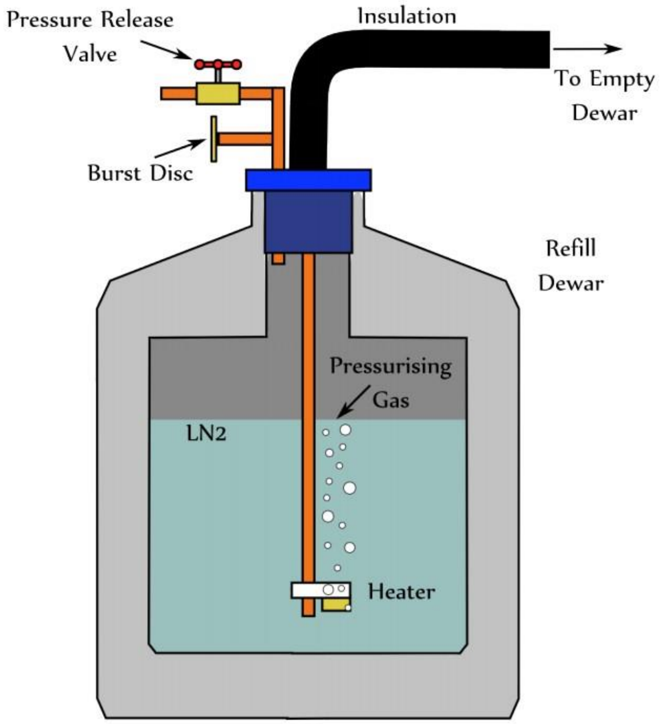
New Reference Fluxgate magnetometer

- SQUID is a relative sensor, therefore needs a reference for absolute measurements
- Low-noise fluxgate magnetometer VARIO15 from CTU in Prague
- Noise <= 4pT/√Hz @ 1Hz
- **In Z axis can replace SQUID**
- Will also serve for data alignment (H,D,Z)

Refilling of liquid Nitrogen

Manual low-cost pump method:

- Evaporate liquid N_2 using heater – volume expands
- Pressure builds up in sealed dewar- liquid N_2 forced through pipe into empty dewar
- SQUID remains cooled during refill process
- HOWEVER – SQUID disturbed during refilling and some time after due to temperature variation in the liquid N_2
- Phase separator to be upgraded to minimise splashing



Effectiveness:

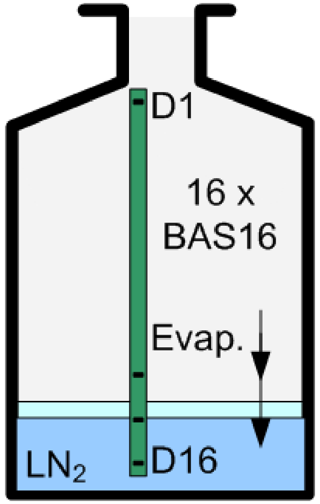
- Transfer rate ± 2 litre/min
- Losses ± 10%
- Operates 24 days between refills

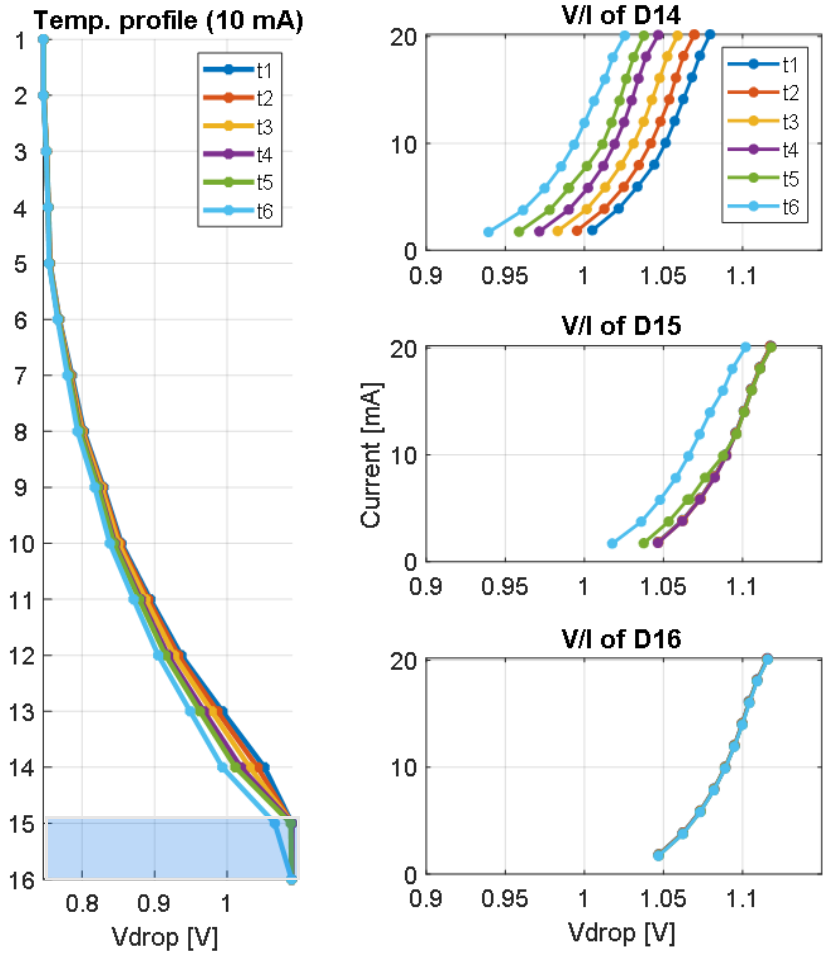
Measurement of liquid Nitrogen levels

Mechanical method:
- Dipping of plastic dipstick into liquid N_2 – listen for "sizzle"
- Disturbs SQUID operation as a person needs to enter the hut
- Bubbles created by "sizzling" creates noise

Electronic method:
- Electronic dipstick consists of row of diodes
- Voltage drop over diodes indicates temperature of diode
- Will also disturb SQUID due to small currents in diodes, but only momentarily, can be done remotely, no need to enter SQUID hut

Current method:
- Current setup evaporation rate well known
- 0.8 cm/day, lasts 24 days



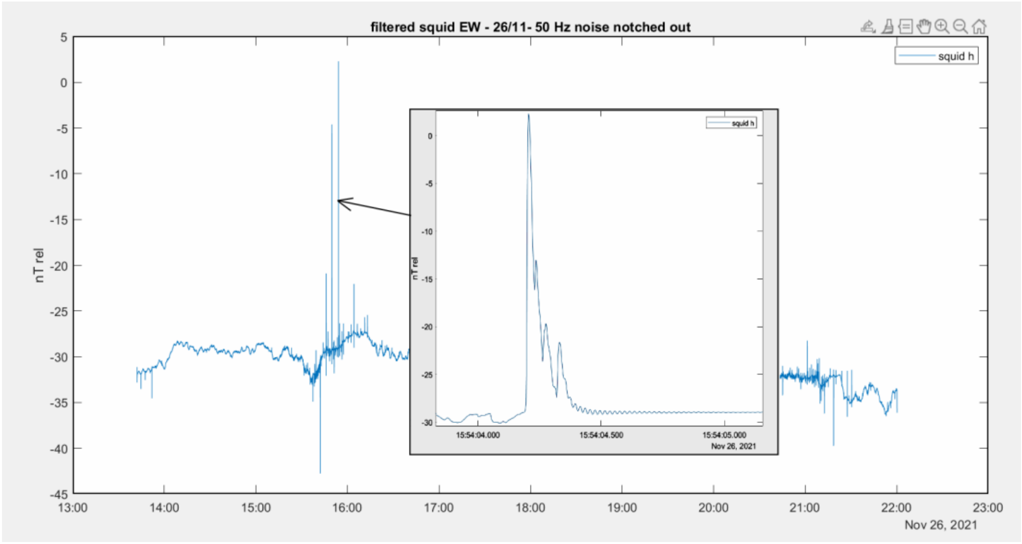


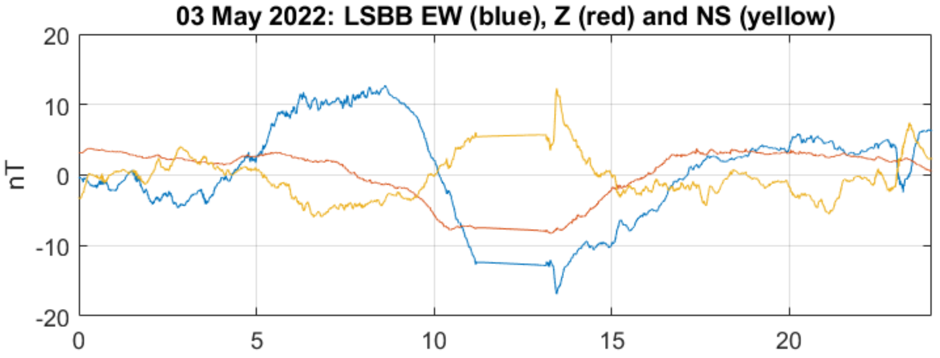
Initial results from thermos test:
- Current > 1mA brings no benefits
- Sub-res. interpolation possible

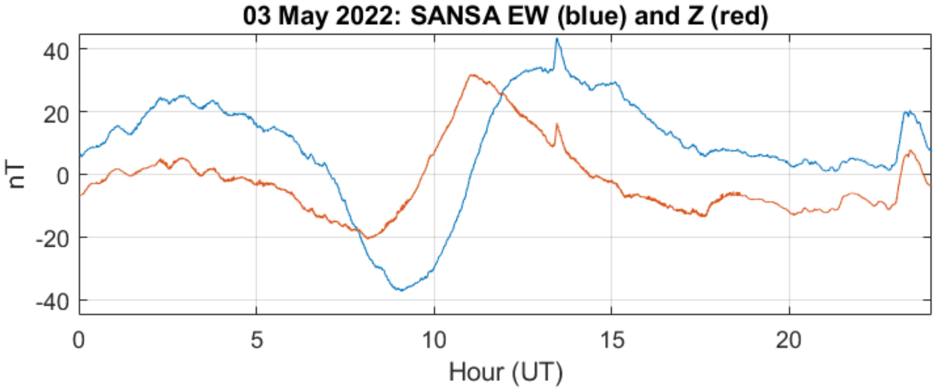
Observations with SQUID setup

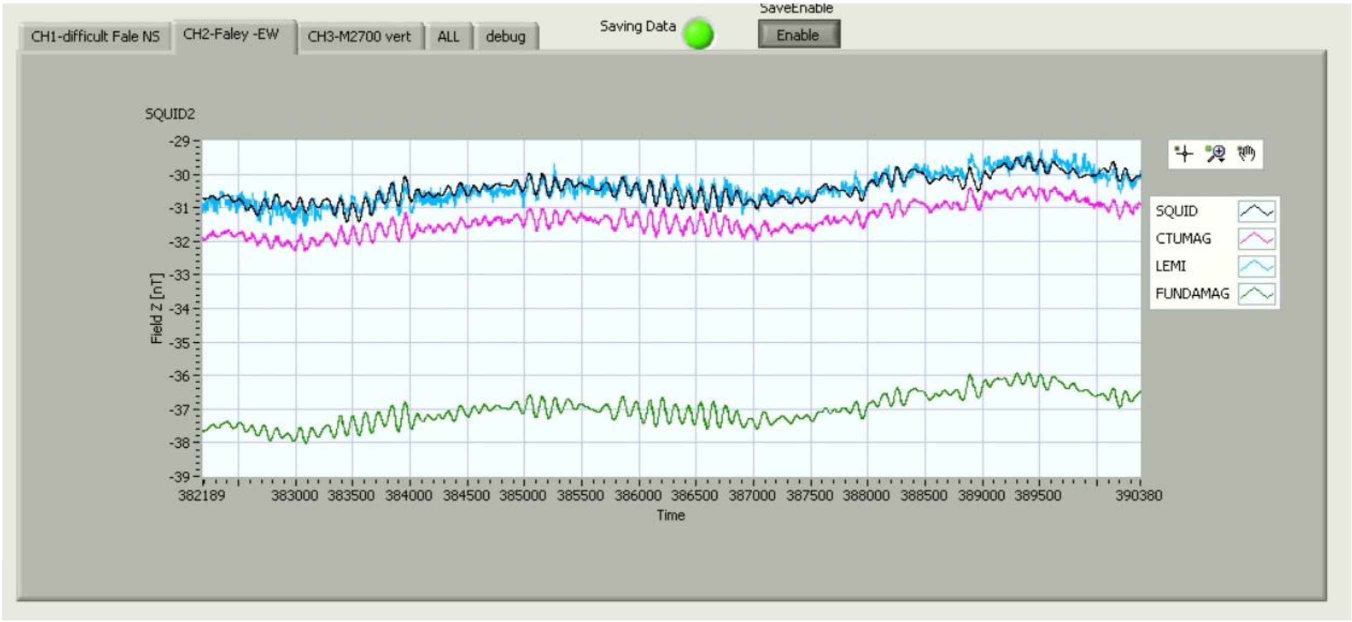
Natural variations:

- Lightning
- Geomagnetic pulsations
- Solar Flare Event with LSBB

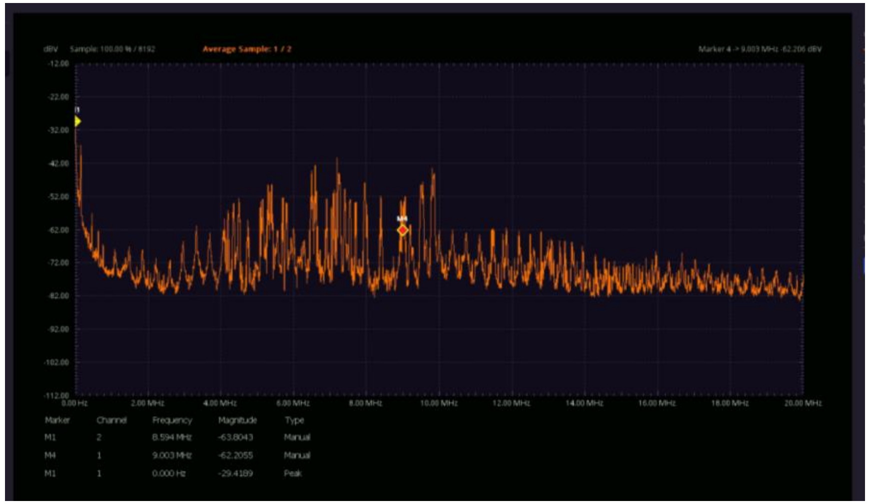






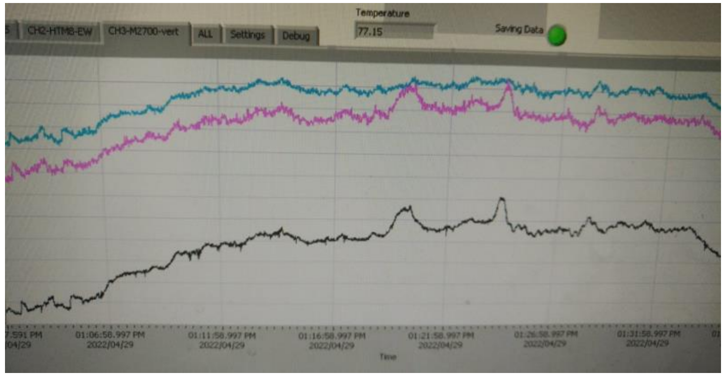


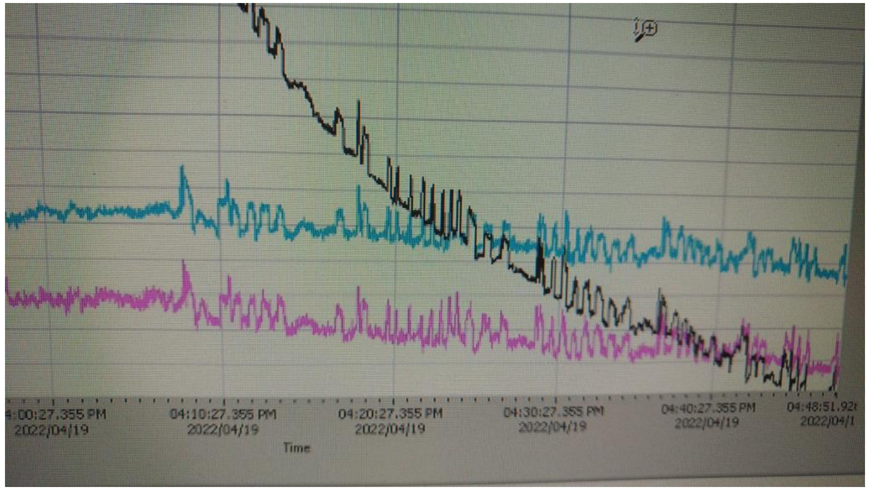
Observations with SQUID setup

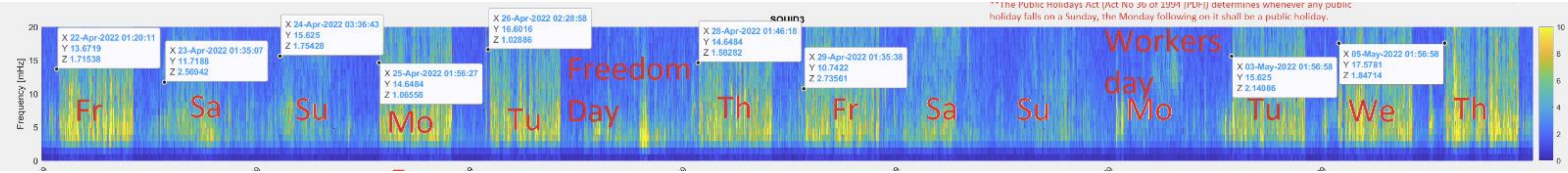


Man-made disturbances:

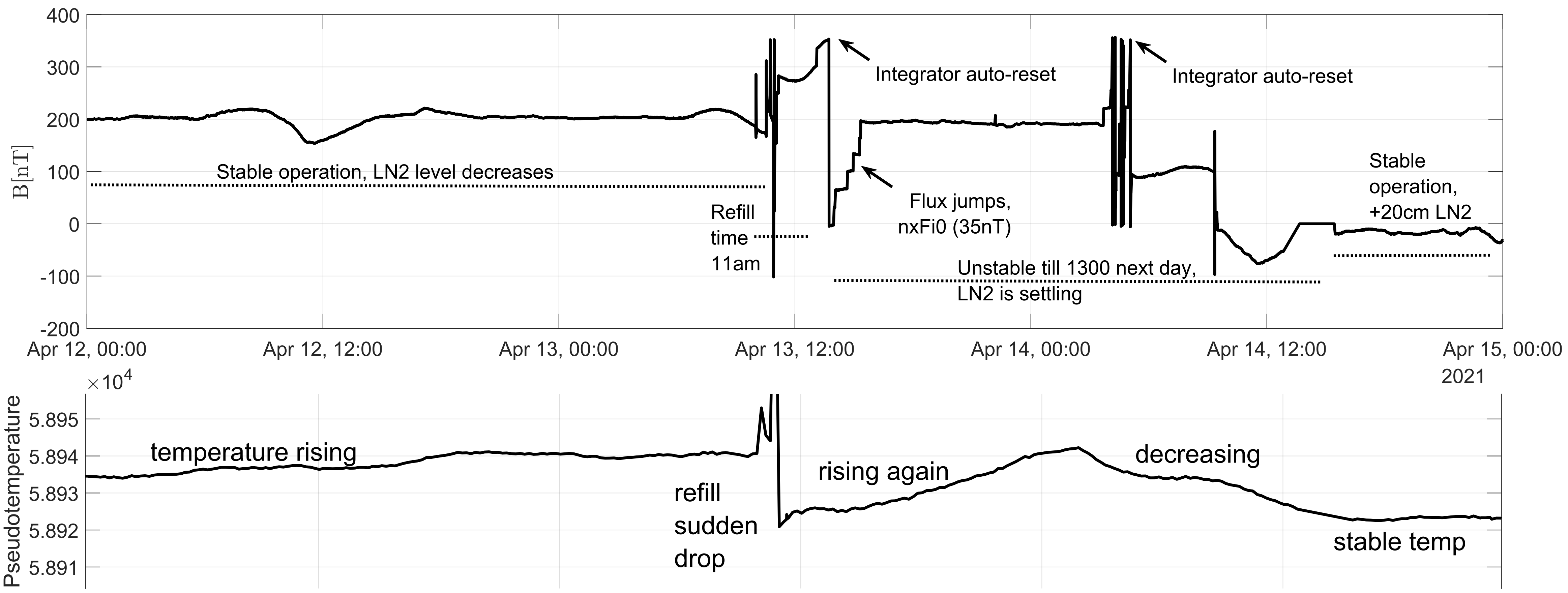
- Ionosonde and Whisper beacon
- Electric fence
- Hospital Solar panels
- “Submarines” ??
- General SANSA and surroundings Magnetic Noise





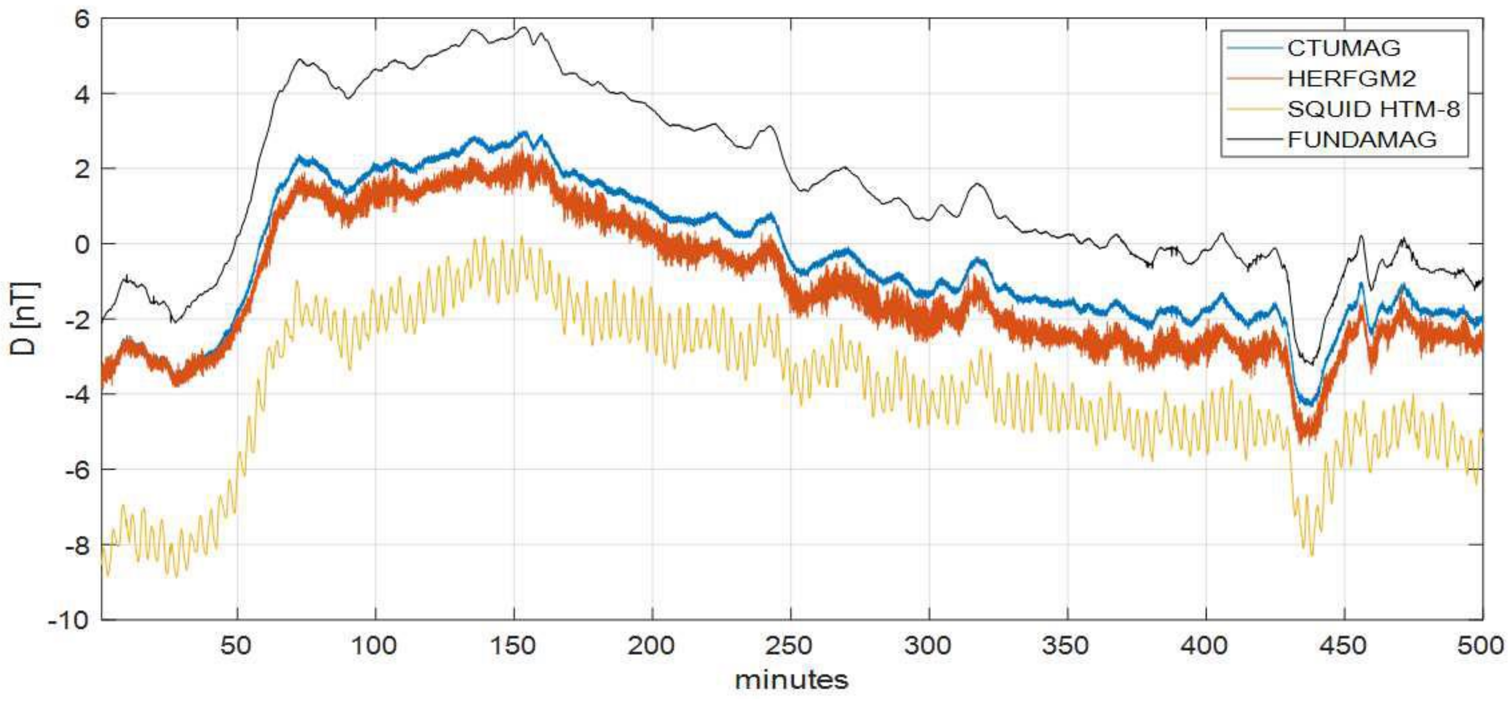


Refilling of liquid Nitrogen

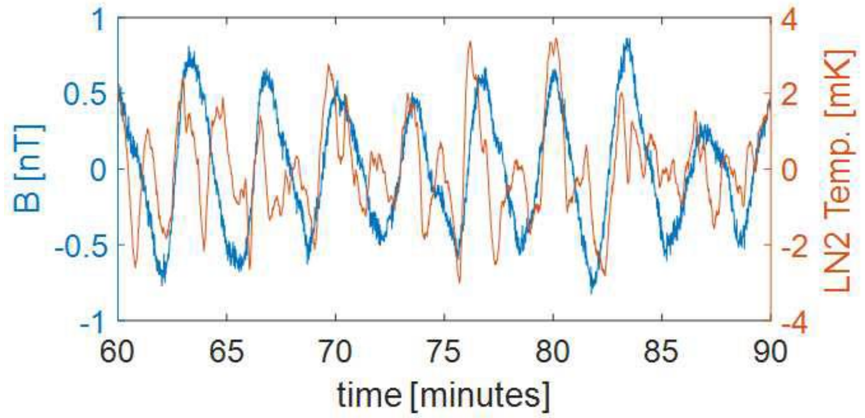


Temperature dependence of HTM-8 SQUIDs

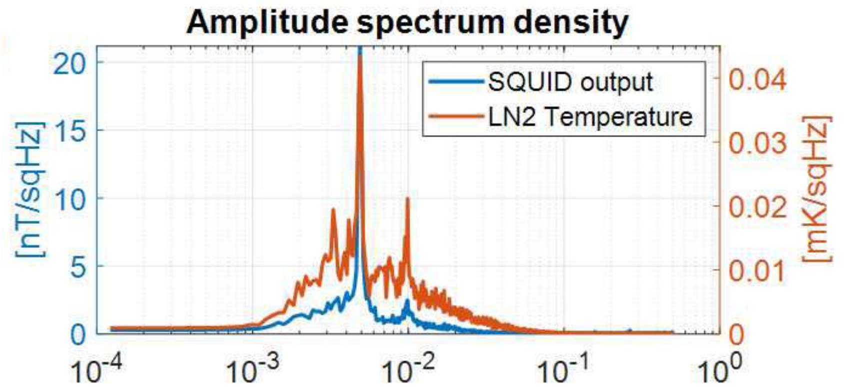
- 2 nT p-p, frequency around 5mHz



Correlation of the temperature variations and magnetometer output oscillation is visible in time domain as well as in frequency domain, close to 5 mHz.

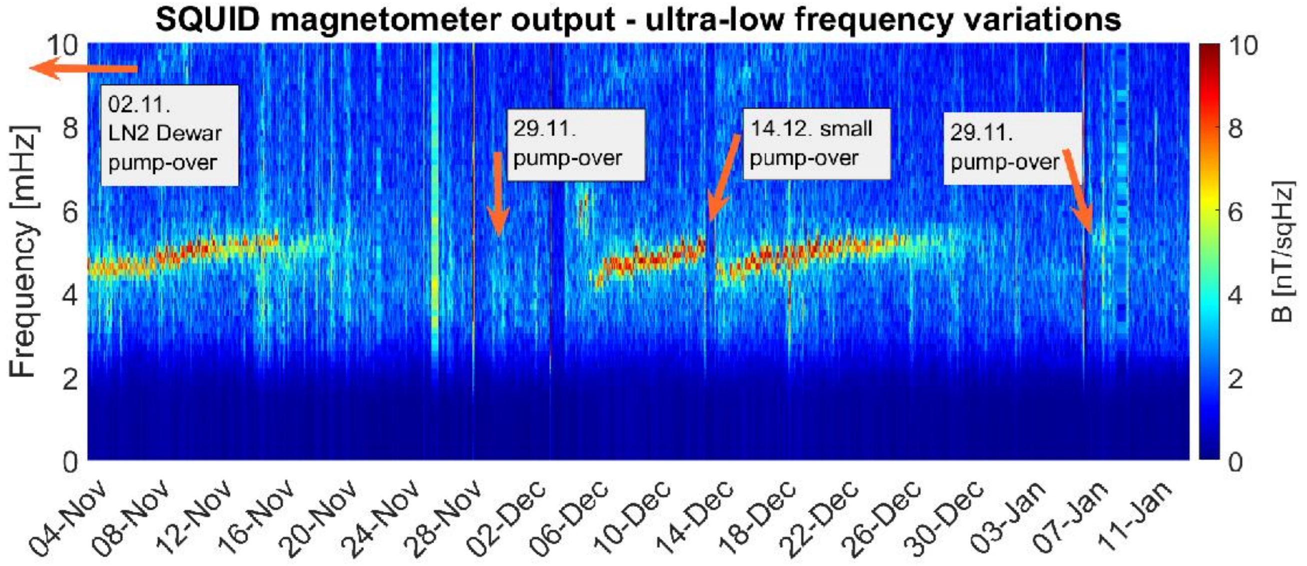


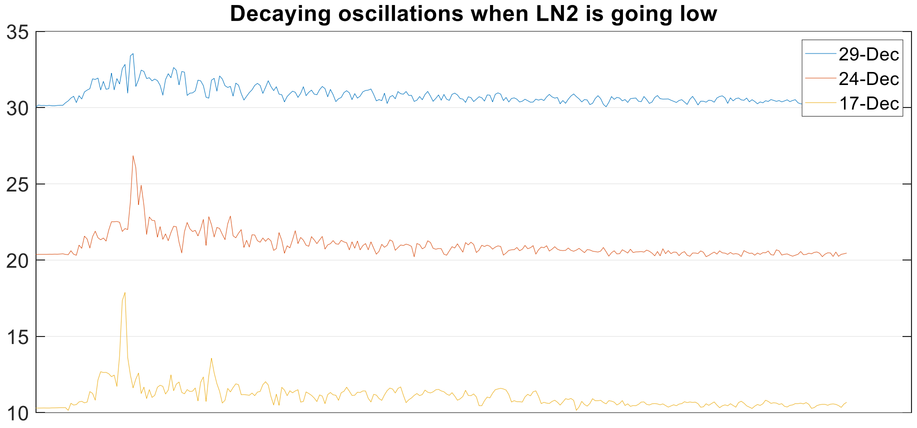
PT1000 (non-cryo) At 77 K :
6 mKpp → 2 nTpp peaks @ 5 mHz

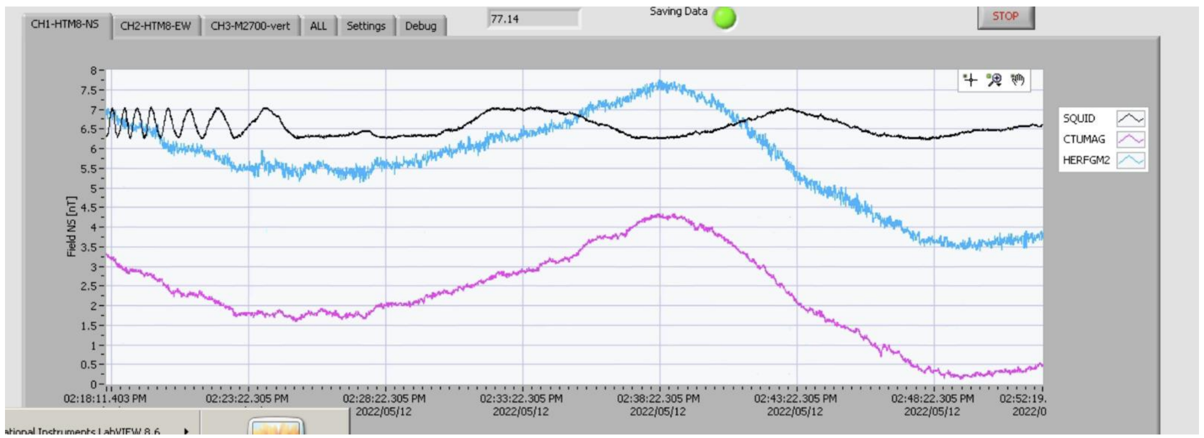


Temperature dependence of HTM-8 SQUIDs cont…

- Oscillations in HTM-8 SQUIDs appear only a day after refill process – LN2 in neck of dewar
- Amplitude decreases over time, nearly disappears before next refill
- Volume of the vapour phase in dewar changing with decrease in LN2 level





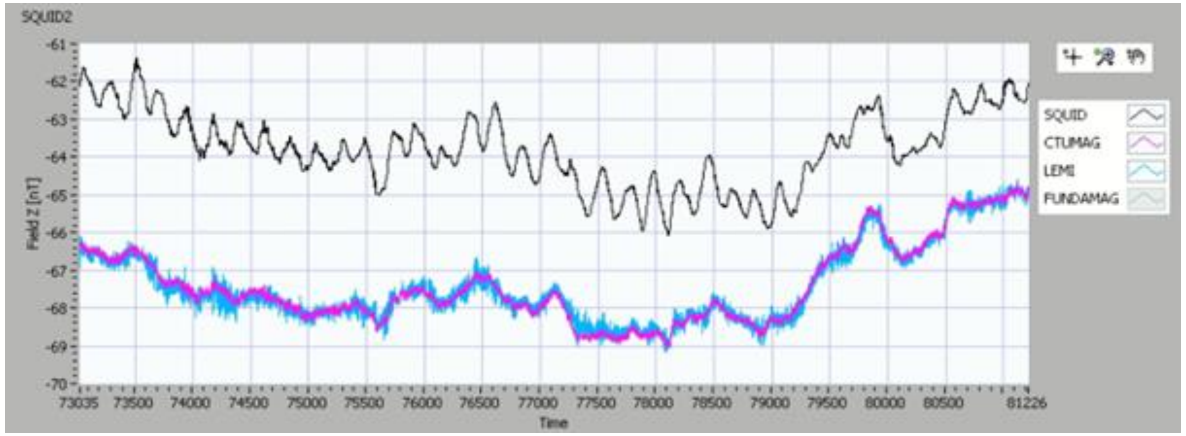


- Open loop SQUID periodic response to linear change

Temperature dependence of HTM-8 SQUIDs concl.

- Both HTM-8 SQUIDs exhibit excess noise in form of the offset oscillation with slowly changing period and amplitude
- Amplitude of temperature variations is only 6 mK_{pp} which translates to 2 nT_{pp} oscillation of the SQUID
- HTM-8 immediate response to refill almost 5x > M2700 in amplitude and recovery time
- Temperature fluctuations change with LN2 level / gas volume
- Resonance disappears towards the end of refill period

- The oscillations compromise the operation of the SQUID as a geomagnetic sensor
- Mitigation techniques are under investigation (CTU)



But what is the future of an HTS SQUID as geomagnetic sensor?

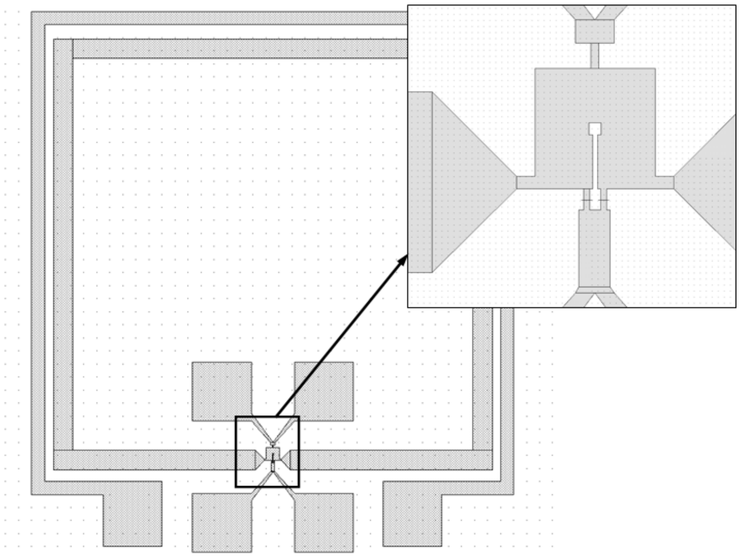
Our Vision:
- Multiple HTS SQUID geomagnetic sensor systems at various remote locations over the world
- Use the data for Space weather, geomagnetic, (and maybe seismic precursor) research projects

BUT:
- HTS SQUID sensors are not off-the-shelf items
- Long wait period for manufacturing ± 1 year (only a few manufacturers)
- HTS SQUID sensors are prohibitively expensive (5500 EUR /USD)
- Control electronics also prohibitively expensive (12500 EUR)

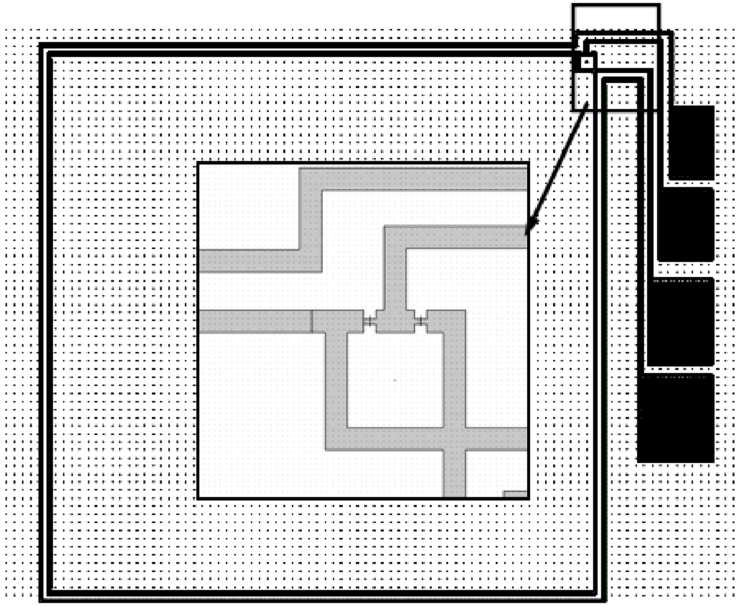
What we plan to do about this:
- Design our own HTS SQUID sensors, possibly with ion irradiated junctions (ESPCI Paris)
- Manufacture and test with collaborative research partners (USMB, CTU)
- Design and manufacture own FLL and control electronics

Design of HTS SQUIDs

2 Designs of HTS SQUIDs for manufacturing in France @ ESPCI during 2019



Josephson Junctions:
- Junctions to be created by process of ion irradiation at ESPCI in France



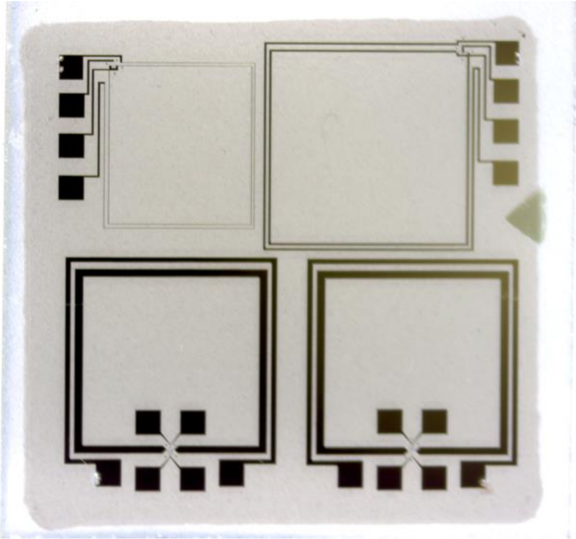
Design 1:
- ~ 70 pH effective SQUID loop inductance
- ~ 12 nH pickup loop inductance
- Trace-width 800/45 µm (Pickup, SQUID) to see effect of flux trapping
- Additional modulation/Feedback coil

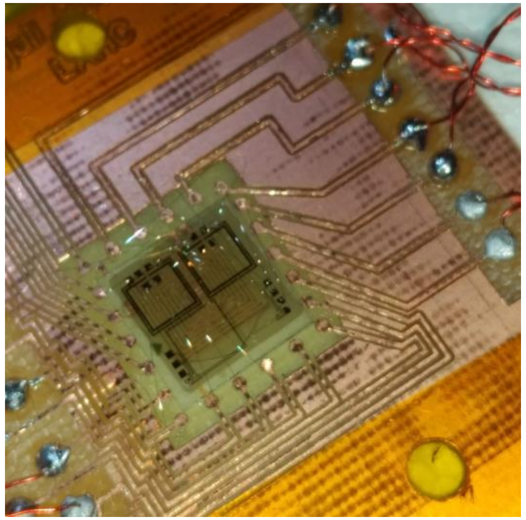
Design 2:
- ~ 400 pH effective SQUID inductance (Inductex) but about same pickup area as #1
- Thin 40 µm lines in SQUID to totally exclude flux trapping
- more white noise than #1 (larger L_{sq}, same A_{eff})

Manufacture and testing of HTS SQUIDs

HTS SQUID development procedure:

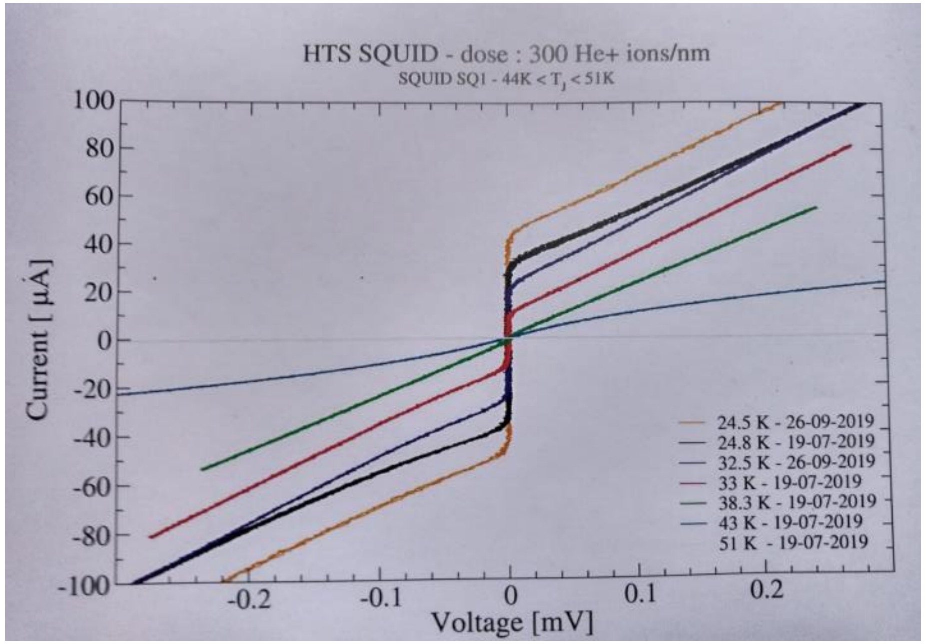
- **Designed** by CTU, SU and USMB
- **Manufactured** at ESPCI in Paris, France, using ion irradiation for JJ's
- **Wire bonded** at USMB, Chambery, France
- **Tested** by the superconducting group in the IMEP-LAHC laboratory at USMB, Chambery, France





Results:

- Tested between 24K and 51K in a cryostat
- JJ worked for one of the 4 designs, but SQUID modulation (if any) buried in thermal noise – SQUID behaviour not observed
- other designs failed due to manufacturing and/or wire bonding



Conclusion

- Current system runs continuously since early 2020 with only brief interruptions by liquid N_2 refilling – we have improved measures to allow to refill in one batch when needed, instead of interim refills
- **In the near future** we hope to solve the temperature dependence of our EW SQUID as well as the problem with the bias current of the NS SQUID in order to have a state-of-the art 3-axes HTS SQUID geomagnetic sensor system running continuously at SANSA Space Science
- We would be able to record, supply and do research with our data on Space weather and geomagnetism

In the future:

- Improve our own HTS SQUID design and have another chip set manufactured for testing
- Develop a simplified control FLL and electronics – possible because requirements are relaxed for low noise geomagnetic monitoring
- Upgrade dewar to non-metallic shell – increase frequency range – difficult to find manufacturer

Acknowledgement

The authors would like to express appreciation for the financial support of Stellenbosch University and SANSA Space Science.