UNIVERSITY OF ALBERTA

# Next Generation Fluxgate Magnetometer (NGFM) on the Norwegian ICI-4 Sounding Rocket: FINAL REPORT

| Document Control # | ISSET-NGFM-FR-001 |
|---|---|
| Revision | Initial Release |
| Last Revised | 2015-06-02 |
| Project Name | Next Generation Fluxgate Magnetometer on the Norwegian ICI-4 Sounding Rocket |
| Contract # | Class Grant and Contribution |
| CDRL Item No | N/A |
| Prepared for | Canadian Space Agency |
| Prepared by | I. R. Mann, D. M. Miles, D. K. Milling and D. Barona on behalf of The Governors of the U. Alberta<br>Edmonton, AB, Canada<br>T6G 2E1 |

## Executive Summary

Fluxgate magnetometers are an essential tool for solar-terrestrial research and monitoring space weather. They provide high precision magnetic measurements for inferring information about processes which transport momentum and energy in geospace. U. Alberta's Next Generation Fluxgate Magnetometer (NGFM) preserves and expands Canada's international excellence in fluxgate magnetometry by providing world-leading measurement capability.

The CSA's Contribution Agreement enabled U. Alberta to accept a no-cost flight of opportunity for the NGFM instrument on the Norwegian fourth Investigations of Cusp Irregularities (ICI-4) sounding rocket campaign to investigate how space weather interferes with GPS navigation. The NGFM was optimised for ICI-4, flight hardware was manufactured, tested, calibrated, and integrated with the rocket in Q3 2013. Unfortunately, the subsequent failure of a rocket using the same motor configuration (S-30 first stage and an Improved Orion second stage) grounded the ICI-4 rocket. The resulting launch failure review board and remediation of the rocket motors delayed the launch of ICI-4 until Q1 2015. During this period U. Alberta continued to improve the NGFM design and the flight hardware was removed from the rocket, reworked, and reinstalled.

U. Alberta PhD candidate David Miles and undergraduate student Charles Nokes participated in person in the ICI-4 sounding rocket campaign in January/February 2015. After a week of delays due to gale force wind and a lightning strike, the ICI-4 rocket was launched on February 19, 2015 at 22:06:41 UT. ICI-4 successfully intersected a region of strong GPS scintillation providing an excellent dataset to study how this region was interfering with GPS signals. The NGFM payload survived launch and boom deployment, operated nominally, and >99.9% of the science data recovered over real-time radio link. The French magnetometer failure means NGFM magnetic data is the only science grade magnetic data and is hence critical for mission success. Detailed analysis of the data is ongoing, and the data appears robust and scientifically promising.

The successful operation of the U. Alberta NGFM payload on the ICI-4 sounding rocket has demonstrated Technology Readiness Level 7 - "System prototype demonstration in a space environment" (TRL-7) providing significant credibility and risk-reduction for future satellite applications. The success of the Canadian payload led the Norwegian PI, Jøran Moen, to offer a no-cost flight on the follow-on ICI-5 rocket. U. Alberta further negotiated space on the six daughter payloads which will be released at altitude to form a measurement constellation. This mission formed the basis of a successful FAST proposal and, if successful, will demonstrate a powerful and scalable tool to add multipoint measurements to future space science missions. Overall, the project has met all its objectives: the Next Generation Fluxgate Magnetometer has demonstrated TRL-7, the mission provided cradle-to-grave experience to Canadian HQP including a PhD student instrument PI, Canada secured ongoing role in the international ICI science team, and ICI-4 science data appears robust and is anticipated to provide high-impact science return.

# 1 Document Approval

Prepared by: David Miles — 2015-06-02 (Date)

Approved by: 2015-06-02

# 2 Status of Major Tasks

All tasks in the project are complete.

| | Task Name | Duration | Start | Finish | | Resource Names | Status |
|---|---|---|---|---|---|---|---|
| **1** | Phase A: Mission Initiation and Concept | 2 days | Thu 12-04-12 | Fri 12-04-13 | | | Complete |
| **1.1** | Mission Initiation Meeting (U. Oslo) | 2 days | Thu 12-04-12 | Fri 12-04-13 | | Miles | Complete |
| **2** | Phase B: Preliminary Desgin | 199 days | Mon 12-04-16 | Thu 13-01-17 | | | Complete |
| **2.1** | Design and Manufacture of Prototype | 6 mons | Mon 12-04-16 | Fri 12-09-28 | 1 | Miles | Complete |
| **2.2** | Test and Characterise of Prototype | 2 mons | Mon 12-10-01 | Fri 12-11-23 | 4 | Miles | Complete |
| **2.3** | Design Review (Andøya Rocket Range, Norway) | 1 day | Thu 13-01-17 | Thu 13-01-17 | 5 | Miles | Complete |
| **3** | Phase C: Detailed Design | 77 days | Fri 13-01-18 | Mon 13-05-06 | | | Complete |
| **3.1** | Design Engineering/Flight Model | 6 wks | Fri 13-01-18 | Thu 13-02-28 | 3 | Miles | Complete |
| **3.2** | Manufacture and Test Engineering Model | 6 wks | Fri 13-03-01 | Thu 13-04-11 | 8 | Miles,Barona | Complete |
| **3.3** | Integration and Interface test (Andøya Rocket Range, Norway) | 10 days | Tue 13-04-23 | Mon 13-05-06 | 9 | Miles | Complete |
| **4** | Phase D: Build and Qualification | 129 days | Tue 13-05-07 | Fri 13-11-01 | | | Complete |
| **4.1** | Manufacture Flight Model Electronics and Sensor | 8 wks | Tue 13-05-07 | Mon 13-07-01 | 7 | Miles | Complete |
| **4.2** | Manufacture Flight Model Electronics Box and Sensor Mount | 6 wks | Tue 13-05-07 | Mon 13-06-17 | 7 | Barona | Complete |
| **4.3** | Test and Characterize Flight Model | 5 wks | Tue 13-07-02 | Mon 13-08-05 | 12,13 | Miles | Complete |
| **4.4** | Instrument Calibration (NRCan Geomagnetism Laboratory) | 1 wk | Tue 13-08-06 | Mon 13-08-12 | 14 | Miles | Complete |
| **4.5** | Vibration, shock, and vacuum test (David Florida Laboratory) | 1 wk | Tue 13-08-13 | Mon 13-08-19 | 15 | Miles | Complete |
| **4.6** | Sounding Rocket Integration (Andøya Rocket Range, Norway) | 5 days | Mon 13-08-26 | Fri 13-08-30 | 14,15,16 | Miles | Complete |
| **4.7** | Sounding Rocket Environmental Testing | 5 days | Mon 13-09-02 | Fri 13-09-06 | 17 | Miles | Complete |
| **4.8** | Launch Planning | 2 mons | Mon 13-09-09 | Fri 13-11-01 | 18 | Miles,Mann | Complete |
| **5** | Phase E: Launch and Operation | 145 days | Mon 14-08-04 | Sun 15-02-22 | | | |
| **5.1** | Shipping to Svalbard | 6 wks | Mon 14-08-04 | Fri 14-09-12 | 18 | Miles | N/A |
| * | Range Access at Svalbard | 0 days | Mon 15-01-26 | Mon 15-01-26 | | | |
| **5.2** | Launch Preparation | 8 days | Mon 15-01-26 | Wed 15-02-04 | 21,22,19 | Miles | Complete |
| * | Launch Window Opens | 0 days | Mon 15-02-09 | Mon 15-02-09 | | | Complete |
| **5.3** | Sounding Rocket Launch and Operation | 9 days | Mon 15-02-09 | Thu 15-02-19 | 23,24 | Miles | Complete |
| **5.4** | Quick look Data | 1 day | Fri 15-02-20 | Fri 15-02-20 | 25 | Miles | Complete |
| * | Launch Window Closes | 0 days | Sun 15-02-22 | Sun 15-02-22 | | | Complete |
| **6** | Phase F: Data Evaluation and Publication | 25 days | Mon 15-02-23 | Fri 15-03-27 | | | Complete |
| **6.1** | Instrument Analysis | 1 mon | Mon 15-02-23 | Fri 15-03-20 | 20 | Miles | Complete |
| **6.2** | Science Data Analysis | 1 wk | Mon 15-03-23 | Fri 15-03-27 | 29 | Miles,Mann | Complete |
| **6.3** | Dissemination of Results | 0 mons | Fri 15-03-27 | Fri 15-03-27 | 29,30 | Miles,Mann | Complete |
| **7** | Concept Study of Miniaturised FGM Sensor | 3 mons | Wed 14-01-01 | Tue 14-03-25 | | Barona,Ciurzynski,Miles | Complete |
| **8** | End of Contract | 0 mons | Mon 15-03-30 | Mon 15-03-30 | | | |

# 3 Project Financial Status

Overall, spending on the project is within the project envelope. Amendment #2, extended the grant until March 31, 2015 to support the revised February, 2015 launch date. The following summarizes the project's spends against the project's budget.

| Eligible Cost | Approved Budget | Actual Spend |
|---|---|---|
| **Access fees** | $0 | $0 |
| **Travel, accommodation, and meals** | $11,693 | $10,201.98 |
| **Acquisition or rental of equipment** | $17,333 | $20,580.02 |
| **Materials and Supplies** | $12,089 | $10,961.62 |
| **PST, HST, GST** | $326 | $75.41 |
| **Salaries and benefits** | $63,104 | $62,725.97 |
| **Overhead** | $10,455 | $10,455.00 |
| **TOTAL** | **$115,000** | **$115,000.00** |

Table 1: Actual vs. Budgeted project expenditures

# 4 Total Contributions Received

In compliance with Paragraph 9.2 of the contribution agreement, Table 2 shows total contributions received related to this project. PhD candidate Miles and undergraduate student Nokes applied to several student funding sources to secure additional travel funds to allow Nokes to participate in the ICI-4 launch campaign (beyond the scope of original proposal).

| Amount | Fiscal Year | Source | Comment |
|---|---|---|---|
| **$3,111** | 13-14 | U. Alberta | NGFM Engineering Model |
| **$105,000** | 13-14 | CSA | This contribution agreement. |
| **$10,000** | 14-15 | CSA | This contribution agreement. |
| **$300,000** | 14-15 | University of Oslo | In-kind. Pro-rated share of rocket and range fees. |
| **$1,983** | 14-15 | Shell Enhanced Learning Fund | Student travel funding. |
| **$3,300** | 14-15 | NTSP/CBAR Grant | Student travel funding. |
| **$1,500** | 14-15 | U. Alberta Green and Gold | Student travel funding. |
| **$400** | 14-15 | U. Alberta circumpolar institute | Student travel funding. |
| **$445** | 14-15 | U. Alberta Undergraduate Research Support Fund | Student travel funding. |

Table 2: Total contributions from all sources for activites related to the ICI-4 project.

# 5 Summary of the Initiative

The major activities in this initiative leading up to launch have been presented in the periodic status reports. These are summarised here for completeness before the ICI-4 launch campaign and its results are presented.

## 5.1 Engineering Hardware and First Integration

The prototype NGFM engineering model hardware was built using internal U. Alberta funding prior to the start of this contribution agreement. The engineering sensor was mocked-up using fast prototype 3D printing using magnetic cores provided by Narod Geophysics Ltd., and were wound by subcontractor Bennest Enterprises Ltd. The engineering model electronics were built using a commercial Actel FPGA development kit (AGLN-NANO-KIT) and a custom analog electronics card providing the magnetometer functions. The engineering electronics box was mocked-up using fast prototype 3D printing.

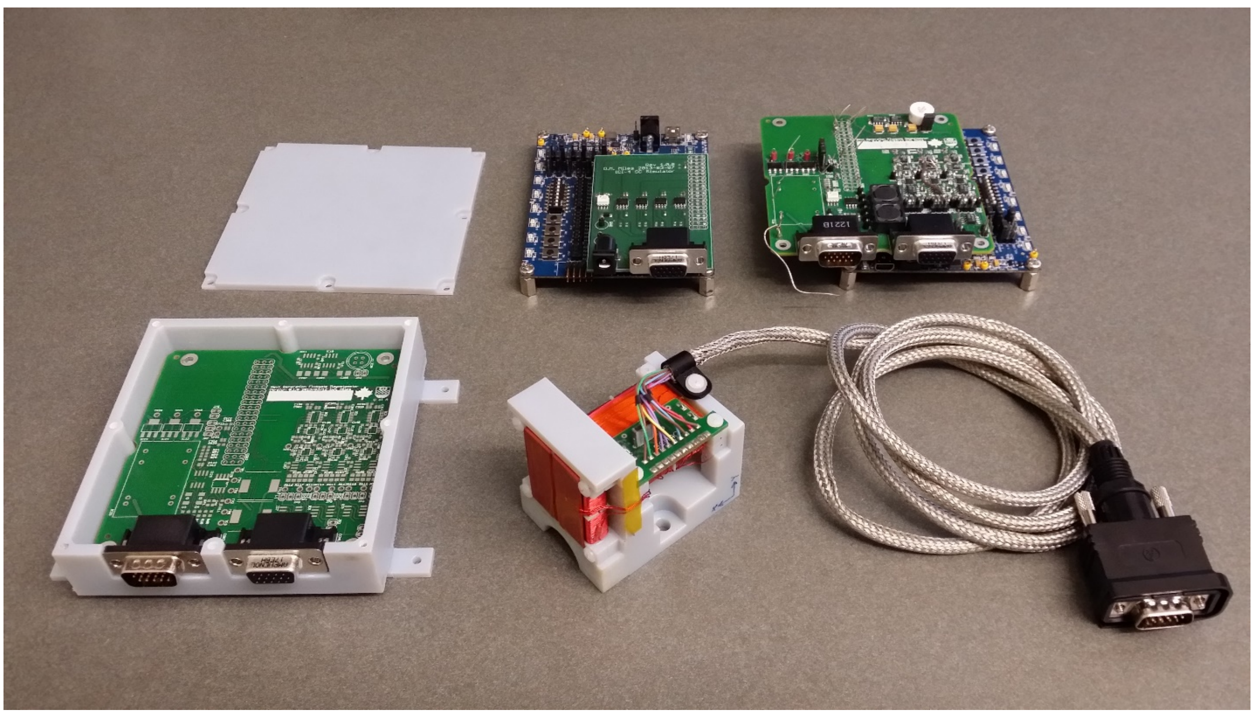


Figure 1: Early prototype hardware for the Next Generation Fluxgate Magnetometer

## 5.2 Manufacture of Flight Hardware

NGFM flight hardware for the ICI-4 sounding rocket program was designed and manufactured by the University of Alberta. Two identical electronics packages were manufactured and tested (flight hardware and flight spare). The NGFM requires only a single, highly integrated electronics card with dimensions equivalent to the PC-104 form factor typically used in nano-satellite (cube satellite) applications.

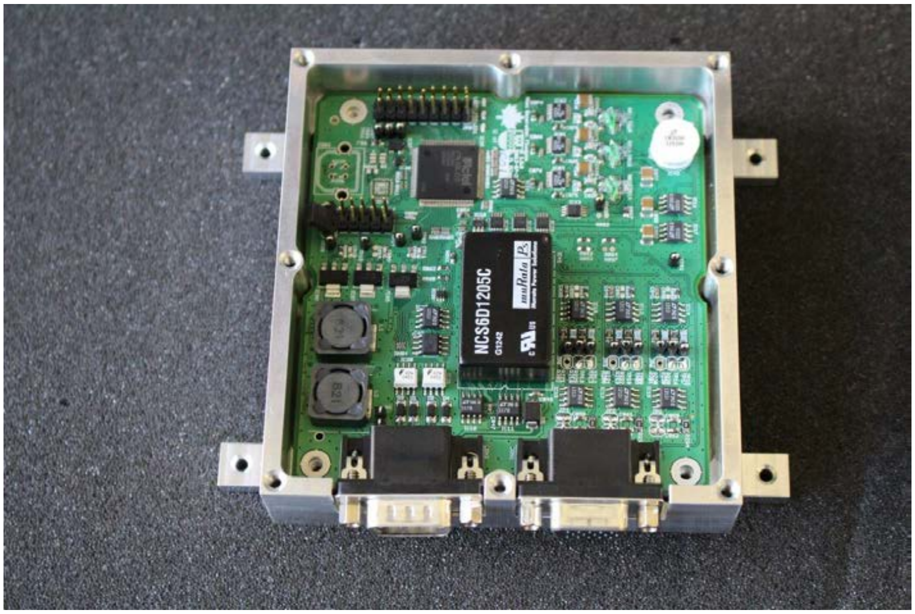



Figure 2: NGFM flight electronics and electronics box with cover removed for photograph.

The flight sensor was manufactured using magnetic rings from Narod Geophysics Ltd. The mount and bobbins were manufactured from the ultra-low temperature coefficient machinable ceramic Macor and were wound by contractor Bennest Enterprises Ltd.

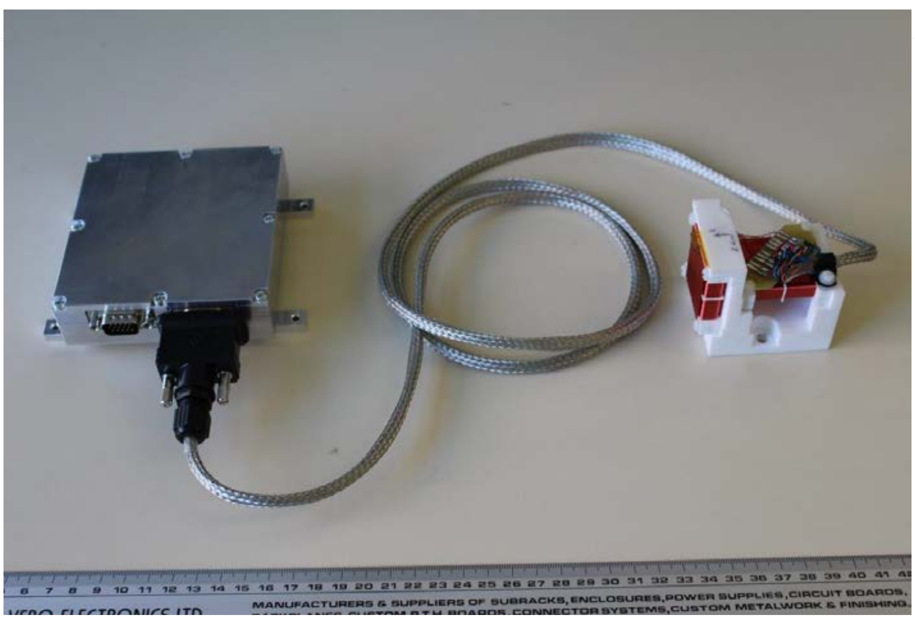



Figure 3: NGFM flight electronics package (left) and flight sensor (right). The black plastic connector is used for testing and was replaced during integration.

## 5.3 Characterisation of Flight Hardware

The engineering and flight sensors and both flight electronics cards were characterised on August 22 and 23, 2013 at the NRCan Geomagnetics laboratory using the Building 8 calibration facility with help from Dr. Don Wallis. All hardware operated nominally.

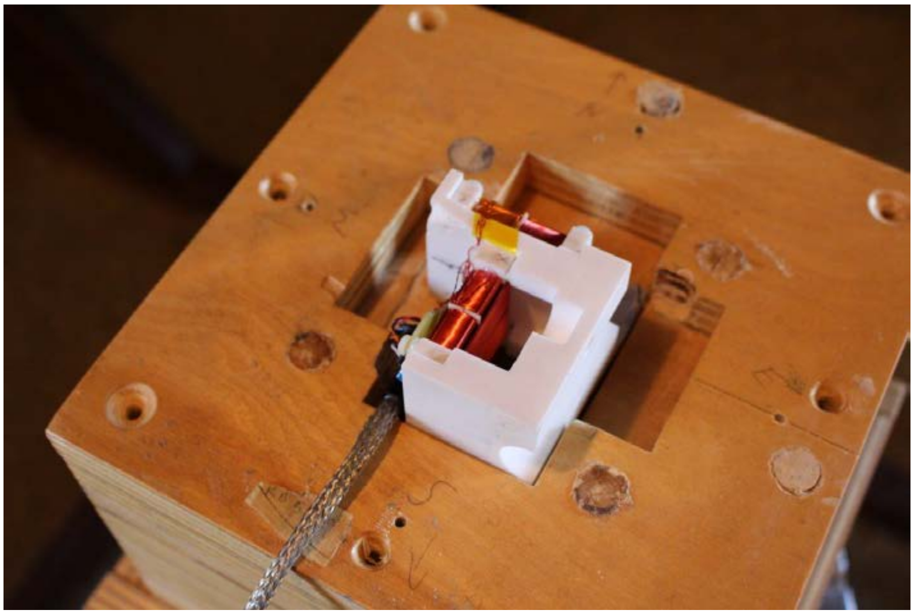


Figure 4: NGFM flight sensor in the NRCan Geomagnetics Laboratory Building 8 test fixture.

Figure 5: NGFM sensor and electronics under test at NRCan.

## 5.4 Integration of Flight Hardware

The NGFM flight hardware was integrated with the ICI-4 sounding rocket at the Andøya Rocket Range in Norway during the week of August 26-30, 2013.

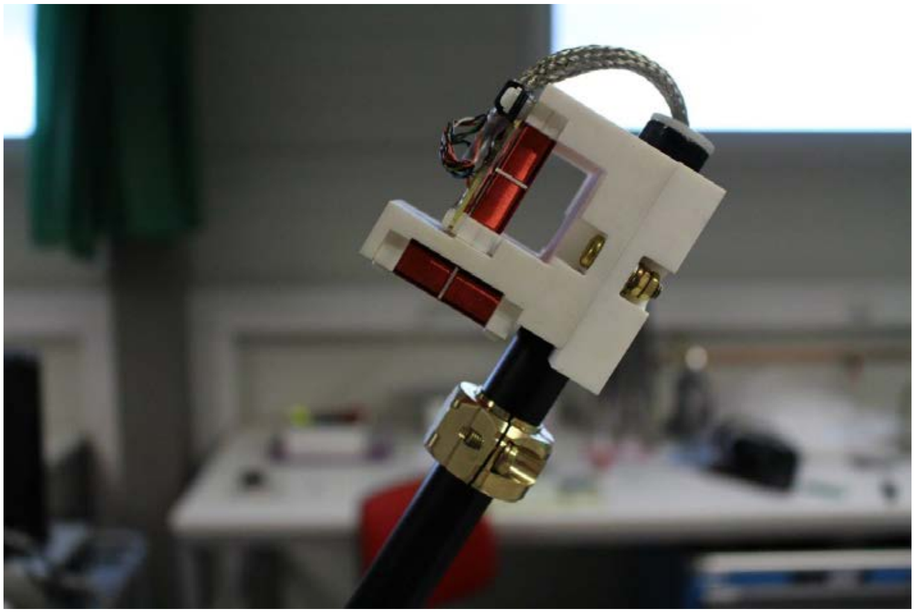


Figure 6: NGFM flight sensor integrated on the ICI-4 boom. A non-magnetic brass counterweight was installed for spin-balance.

Figure 7: U. Alberta NGFM flight sensor (left) and French LPP high frequency induction coil (right) installed on a custom deployable boom to isolate the magnetometer sensors from the magnetic noise of the rocket payload.

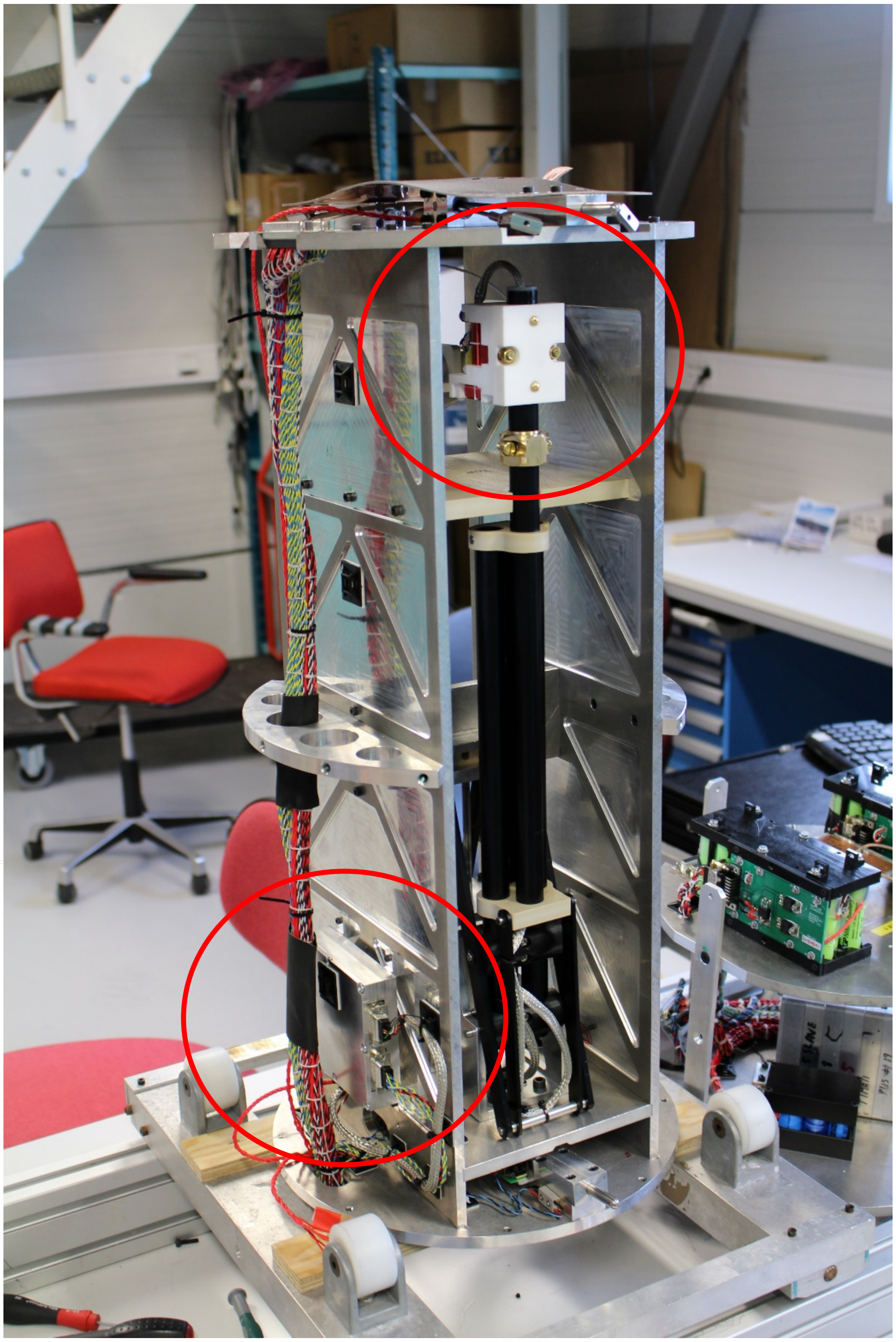


Figure 8: The NGFM sensor and the magnetometer boom fold up into the aft payload section and are deployed at altitude. The NGFM electronics package is mounted on the sidewall nearby.

## 5.5 Acceptance Testing

Environmental testing of the integrated rocket, including the NGFM payload, was completed by the Andøya Rocket Range at the Norwegian facility Habu Technology in Narvik during the week of September 2-6, 2013. The NGFM passed the integration review and environmental testing and was accepted for flight.

## 5.6 Design Optimisation to Simplify Data Processing

The Next Generation Fluxgate Magnetometer (NGFM) uses an offsetting design (based on the recently launched MGF payload in CSA's Cassiope/e-POP satellite) where digital feedback is used to null the majority of the magnetic field before digitising the residual. This approach has advantages compared to a conventional variable gain design as it allows the NGFM to achieve full resolution in large field strengths. However, in a moving reference frame, the dynamic behaviour of the instrument in response to changes in magnetic feedback can introduce transient effects which make the data difficult to process. For example, as the instrument rotates with respect to Earth's field the apparent strength in each component of the instrument changes and the digital feedback for each channel must be continuously varied. The transient behaviour of these updates must be carefully characterised and removed in data processing.

After the ICI-4 launch was delayed, the proponents re-optimised the offsetting design for the ICI-4 application. Specifically, the high nominal spin rate (4 rps) of the rocket imposed on the NGFM place significant demands on the digital offsetting feedback. An alternative open-loop mode was developed using a newly released 20 bit analog to digital converter which allowed the instrument to operate without digital feedback. The flight electronics were extracted from the ICI-4 rocket, reworked to implement this new design, and re-integrated with the rocket. This modification sacrifices some instrument resolution (although it meets the design requirement) but provides radically improved slew rate and bandwidth removing any risk that the fast rocket spin could saturate the instrument.

## 5.7 Concept study of miniaturized NGFM sensor for future small payload applications

The NGFM currently uses a sensor design based on a ground instrument developed by Narod Geophysics Ltd. This design is deployed throughout Canada as part of the CARISMA/GO Canada network and was modified slightly for the CSA Cassiope/e-POP satellite. Amendment #1 to the contribution agreement supported a concept study for a miniaturised version of this sensor to make the NGFM easily accommodated on future platforms such as nano-satellites (cube-satellites). A detailed report on this work was written by staff engineer Ciurzynski and submitted to the CSA. In short, Ciurzynski demonstrated a volume efficient design where a miniaturised sense winding is placed inside (rather than around) the ferromagnetic ring-core. This design may also allow the natural resonance of the sense winding to be matched to the ring-core drive frequency to increase the sensitivity of the sensor.

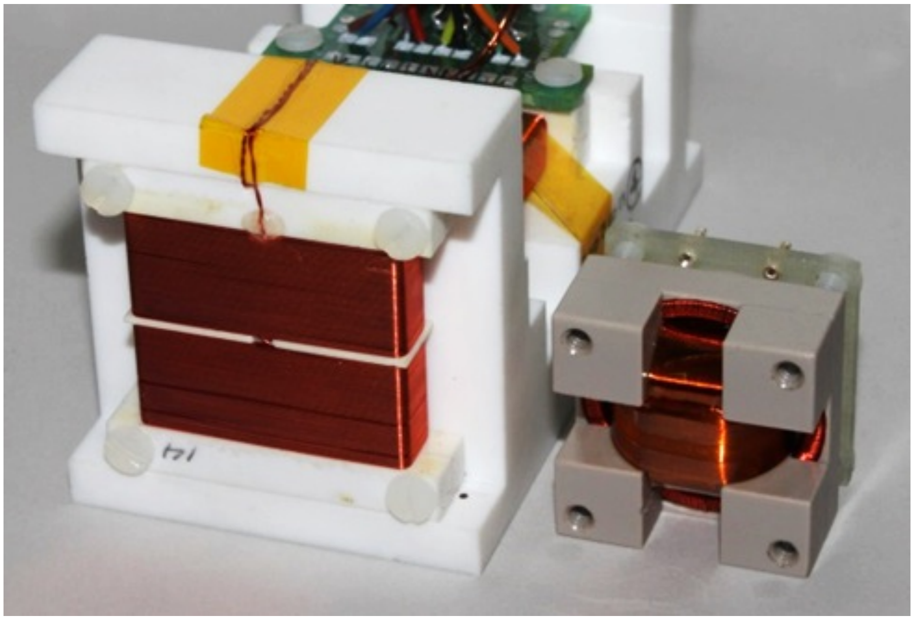


Figure 9: (Left) Three component fluxgate magnetometer identical to those deployed in the CARISMA ground array. (Right) Proof-of-concept two component miniaturised sensor prototype developed for small payload applications.

## 5.8 ICI-4 Launch Campaign

The ICI-4 sounding rocket campaign was carried out from January 26, 2015 to February 22, 2015. PhD student David Miles acted as the instrument PI for the U. Alberta NGFM payload, was present at the Andøya Rocket Range for the entire campaign and participated in all activities. Fourth year U. Alberta Engineering Physics student Charles Nokes was recruited to assist in the campaign. Nokes was present during the two week launch window, coordinated auroral imaging of the nominal ICI-4 trajectory each night using the CSA Cassiope/e-POP satellite, and assisted the Norwegian PI in deciding when to launch the ICI-4 rocket.


Figure 10: Mission badge for the ICI-4 sounding rocket campaign showing the rocket intercepting a GPS communication signal.

Each of the international science instruments was (re)integrated with the ICI-4 rocket and tested to validate its operation. The entire payload section was staked and secured to survive the shock and vibration of launch and pyrotechnics were installed to uncover and release the multiple deployable structures including the magnetometer booms.

Figure 11: U. Alberta PhD Candidate David Miles (top left) assists rocket range personnel during the final integration and closure of the ICI-4 payload.

Ballast was added to the complete payload section to ensure spin stability and minimal wobble/conning. Finally, the payload section was integrated with the first and second state rocket motors and mounted on the launch rail.

Figure 12: The ICI-4 sounding rocket mounted on its launch rail before the sacrificial weather housing is installed.

Despite excellent science conditions, gale force winds, cloud cover, and inclement weather prevented launch during the first week of the launch window. A lightning strike damaged the control circuitry for the launch rail, the second stage ignition unit on the rocket, and the University of Oslo needle Langmuir probe electronics. These systems were repaired or replaced in place and no lasting damage was done to the rocket or the instrument payloads was observed.

Figure 13: Despite excellent science conditions, inclement weather, high winds, and a lightning strike prevented launch during the first week of the launch window.

Figure 14: The ICI-4 sounding rocket raised into to launch position during the practice countdown.

Instrument PI and PhD Candidate David Miles and the other international instrument PI's monitored the state of health of each of the scientific payloads during the launch window. Instrument operation was checked several times each day during the launch window to ensure that the payload would be fully operational when the science and weather conditions permitted launch.

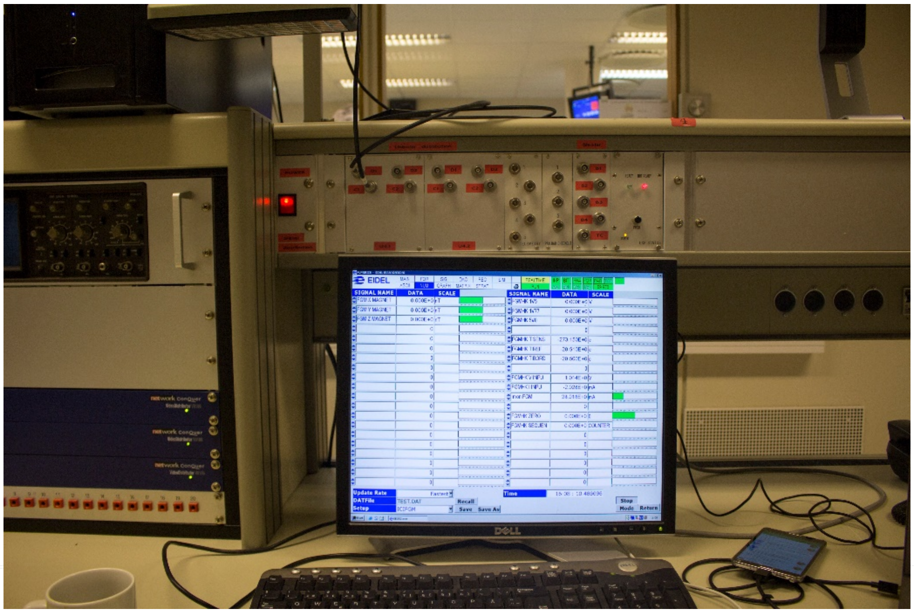


Figure 15: The NGFM payload was monitored remotely during the two week launch window to ensure that the instrument would be operational when the launch occurred.

Undergraduate student Charles Nokes and the international ICI-4 science team monitored a variety of geophysical conditions including GPS scintillation and Total Electron Content (TEC) in real-time to assess launch conditions.

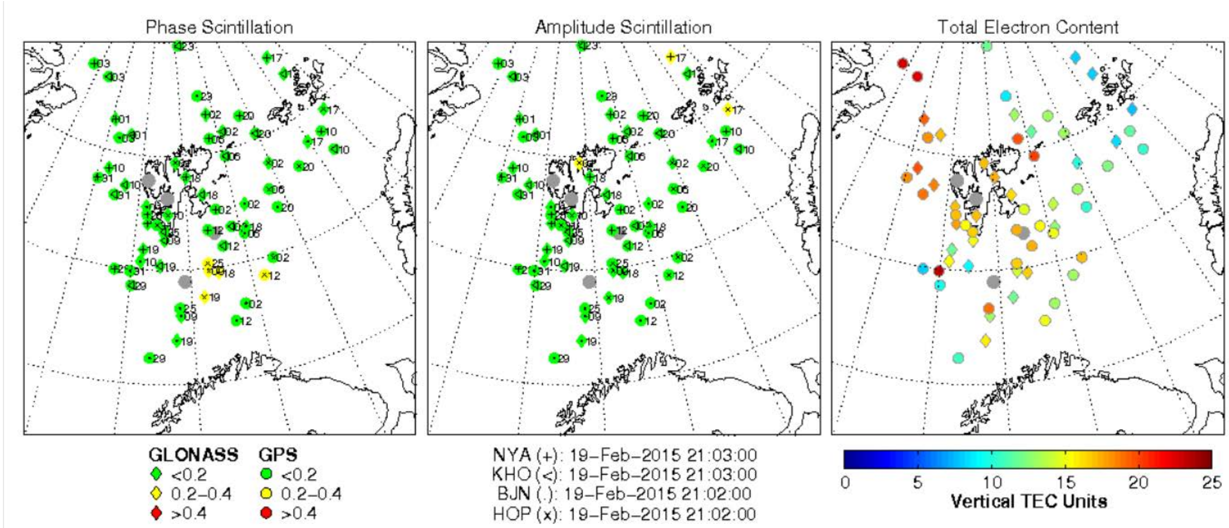



Figure 16: GPS scintillation and Total Electron Content (TEC) over the rockets flight path were monitored in real-time using receivers on Svalbard.

The ICI-4 rocket was launched on February 19, 2015 at 22:06:41 UT. ICI-4 successfully intersected a region of strong GPS scintillation providing an excellent dataset to study how this region was interfering with GPS signals. The Canadian NGFM payload survived launch and boom deployment and operated nominally throughout the flight. More than 99.9% of the measured science data was recovered via the real-time radio link.

Unfortunately, the French induction coil magnetometer built by the Laboratoire de Physique des Plasmas appears to have failed during boom deployment. This failure removes the possibility of cross-calibrating between the magnetometers. It also makes the NGFM critical to the scientific success of the mission as it now provides the only scientific grade measurement of magnetic field.

Figure 17: The ICI-4 sounding rocket was launched on February 19, 2015 at 22:06:41 UT and successfully intersected a region of active GPS scintillation. The U. Alberta NGFM payload operated nominally and captured scientific data for the duration of the flight.

The successful operation of the U. Alberta NGFM payload on the ICI-4 sounding rocket has demonstrated Technology Readiness Level 7 - "System prototype demonstration in a space environment" (TRL-7) providing significant credibility and risk-reduction for future satellite applications. The successful of the Canadian payload led the Norwegian PI, Jøran Moen, to offer a no-cost flight on the follow-on ICI-5 rocket. U. Alberta further negotiated space on the six daughter payloads which will be released at altitude to form a measurement constellation. This mission formed the basis of a successful FAST proposal and, if successful, will demonstrate a power and scalable tool to add multipoint measurements to future space science missions.

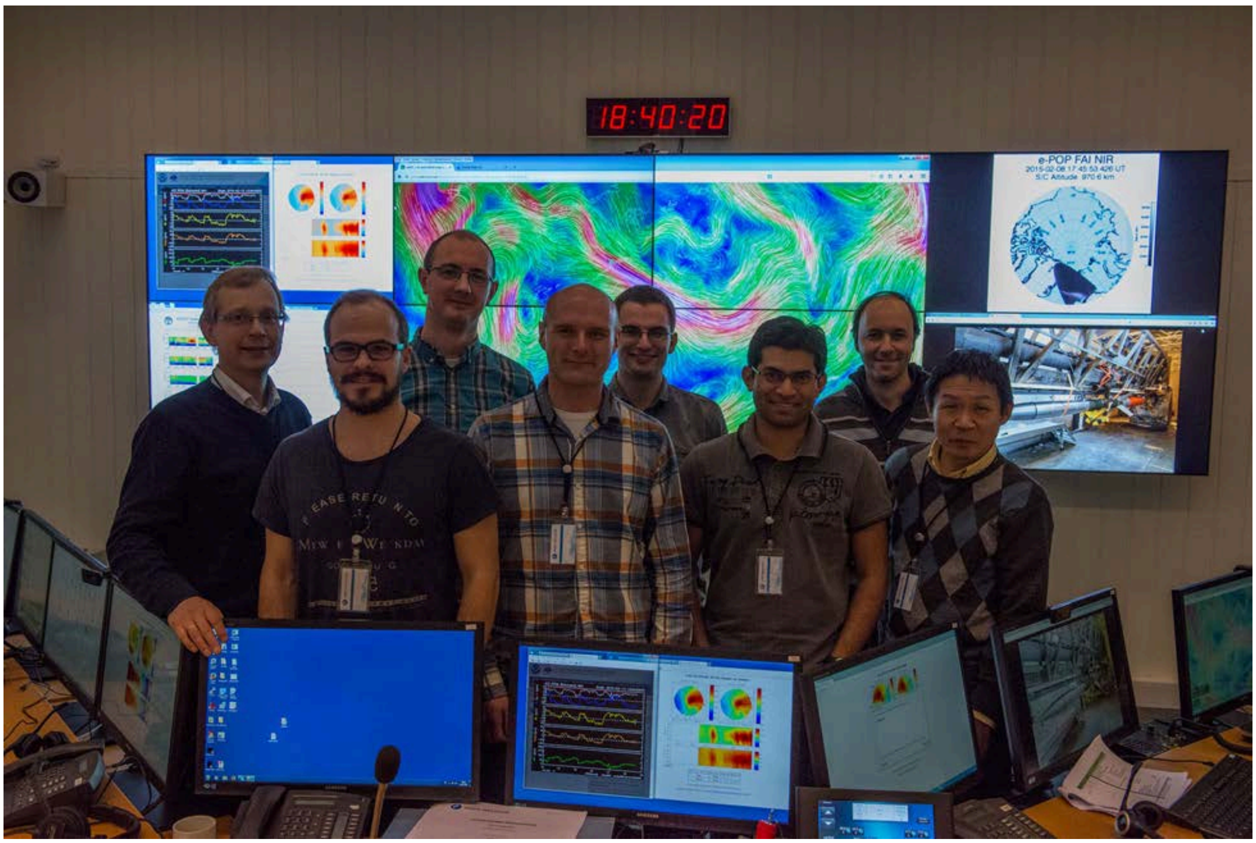



Figure 18: The international ICI-4 campaign science team left-to-right (top) Jøran Moen – University of Oslo, Norway; David Miles – University of Alberta, Canada; Charles Nokes – University of Alberta, Canada; Matthieu Berthomier, Laboratoire de Physique des Plasmas, France; (bottom) Andreas Spicher – University of Oslo, Norway; Espen Trondsen – University of Oslo, Norway, Swadesh Patra – University of Oslo, Norway, Takumi Abe – ISAS/JAXA, Japan.

## 5.9 Instrument Performance

Figure 19 shows a Quicklook plot of the measured magnetic data from the NGFM payload during the ICI-4 sounding rocket flight. Red, green, and blue show the three measured components of the field in the frame of the fluxgate sensor. Note the cylindrical spin-up of the rocket, the rotation of the field around 90 seconds as the magnetometer boom is released, and the subsequent wobble (coning) of the rocket for the duration of the flight. The bottom panel shows when the data was de-spiked to remove telemetry dropouts – more than 99.9% of the data was recovered.

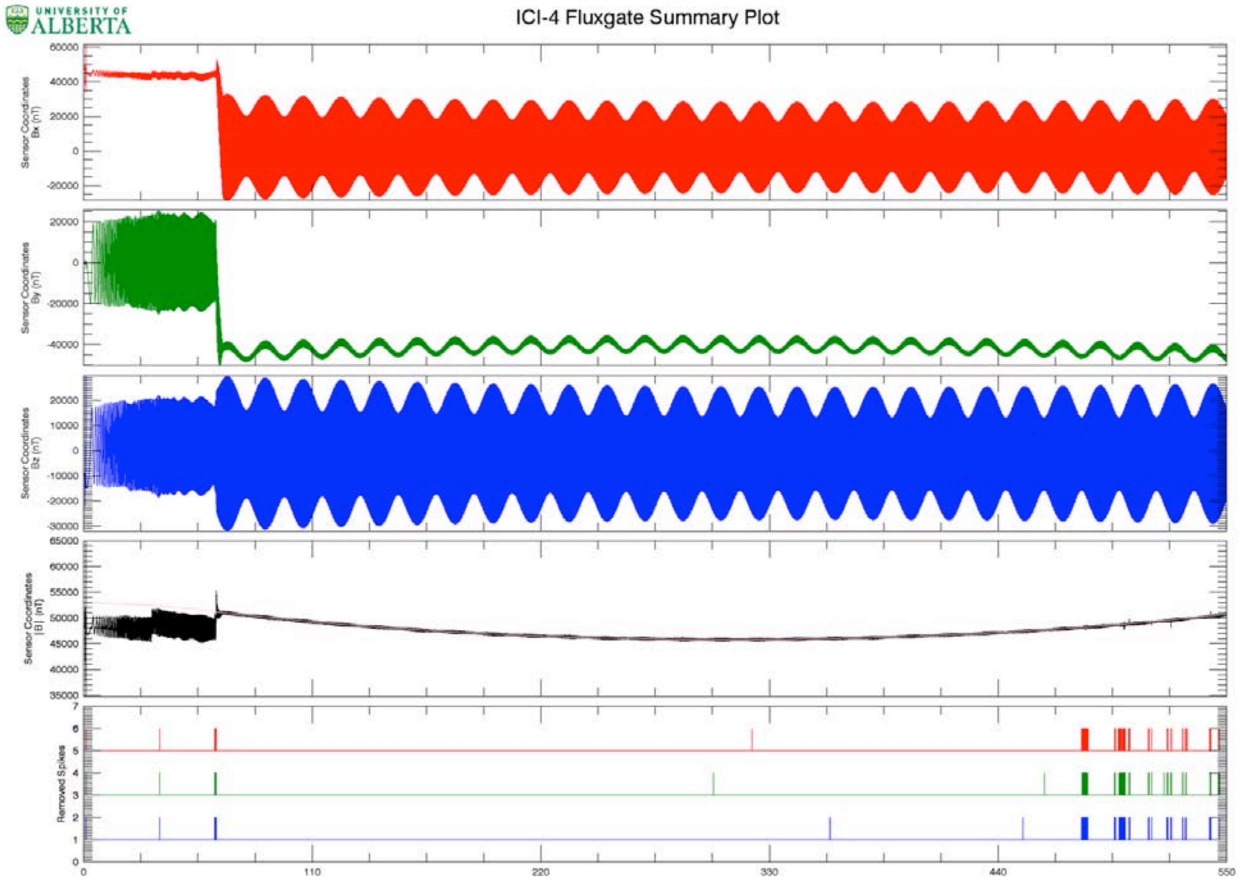



Figure 19: Quicklook data from the NGFM payload. Top three plots show the three components of the magnetic data. Note the boom deployment at 90 seconds and the spin and coning of the rocket. Black shows the match of the data to the IGRF model magnetic field. The bottom panel shows where data was interpreted to fill in telemetry losses.

The Quicklook plot highlights the challenge of interpreting vector magnetic field measurements on a rotating and coning platform with a non-negligible stray magnetic field. However, the instrument performed as designed and successfully captured the local magnetic field despite the challenges of the platform.

Figure 20 (credit: Lasse Clause, University of Oslo) shows an early attempt to de-convolve the ambient field from the magnetic measurements using minimum variance to track the rocket's spin and a band pass filter to show only the frequency range of the plasma waves of interest. The transient feature around 175 seconds corresponds to the powering on high-voltage on one of the particle instruments. The signatures of two potential plasma waves may be present in the Y component of the data around 250 and 375 seconds.

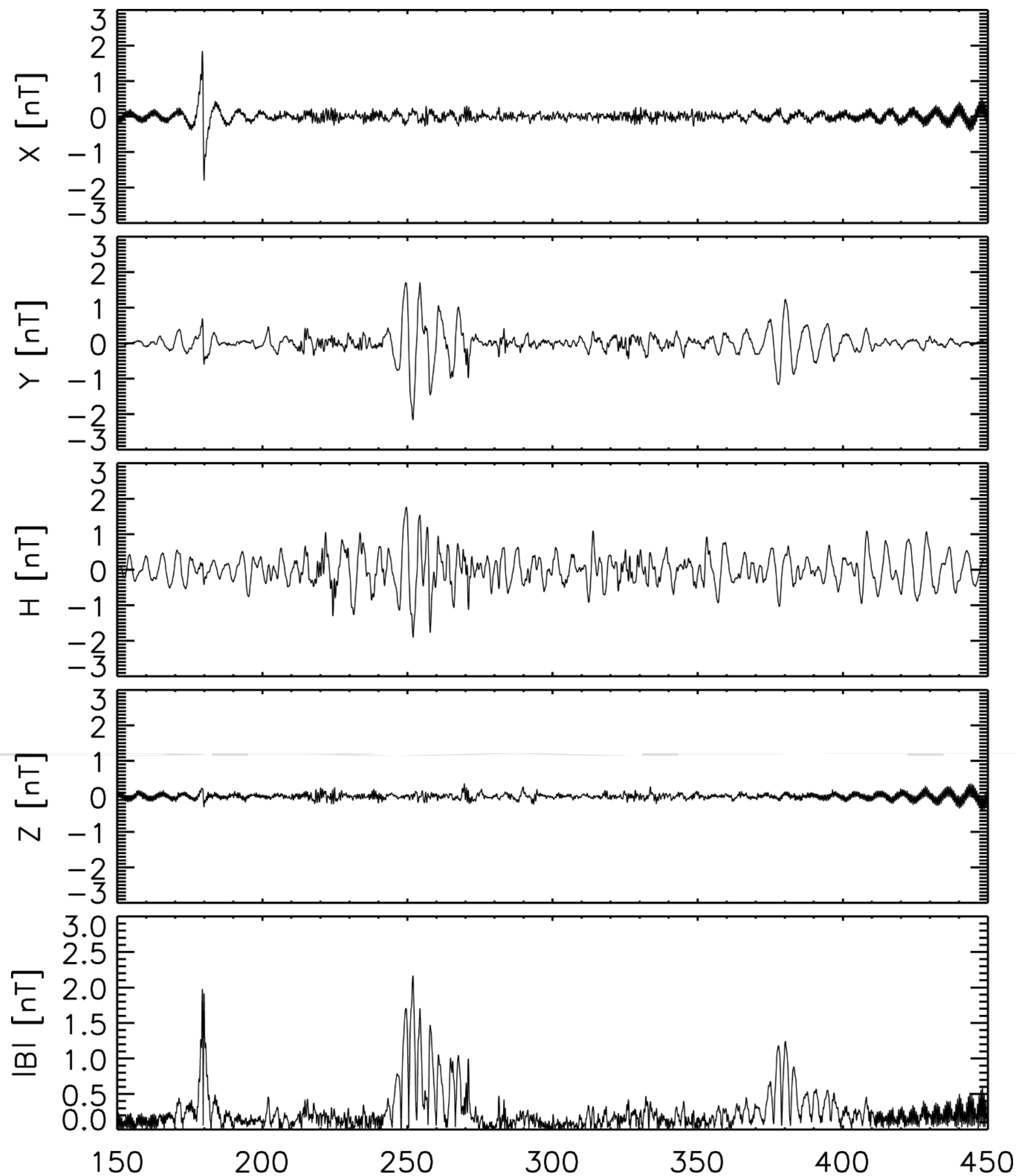



Figure 20: Preliminary processed NGFM data showing two possible wave processes around 250 and 400 seconds. The transient feature around 175 seconds corresponds to the powering on high-voltage on one of the particle instruments.

Detailed analysis and interpretation of this data will require significant staff time which is beyond the scope of this contribution agreement. The proponents submitted a proposal to the Canadian Space Agency titled “Analysis of Rocket data of Ionospheric Scintillation Event (ARISE)” and were awarded a grant to help support the exploitation of the NGFM / ICI-4 science data.

# 6 Performance Measures

1. The development and testing of a TRL-7 certified fluxgate magnetometer suitable as the basis for future ground, suborbital, and satellite missions.

   *The successful operation of the U. Alberta NGFM payload on the ICI-4 sounding rocket has demonstrated Technology Readiness Level 7 - "System prototype demonstration in a space environment" (TRL-7) providing significant credibility and risk-reduction for future satellite applications.*

2. Training of two HQP at the U. Alberta with cradle-to-grave space instrumentation experience.

   *U. Alberta HQP funded by this agreement successfully developed, integrated, ad operated the NGFM instrumentation on the ICI-4 sounding rocket. HQP involved were: David Miles (PhD candidate and research associate), Miroslaw Ciurzynski (Magnetometer Engineer) and David Barona (research associate/project management), and Charles Nokes (undergraduate student). Notably, PhD Candidate Miles led the development of the NGFM payload and served as the instrument PI for the entirety of the contribution agreement providing exceptional cradle-to-grave experience and credibility for future space missions.*

3. Low-cost solar-terrestrial science mission participation, leveraging international funding.

   *U. Alberta is a full partner in the ICI-4 sounding rocket campaign leveraging the no-cost launch opportunity provided by the University of Oslo and the payload contributions of the French and Japanese collaborators. U. Alberta attended and participated in the Science Team meeting and data workshop in October 2014 and will continue to participate in the science team under the funding from the successful ARISE science grant from the CSA. The success of the Canadian payload led the Norwegian PI, Jøran Moen, to offer a no-cost flight on the follow-on ICI-5 rocket. U. Alberta further negotiated space on the six daughter payloads which will be released at altitude to form a measurement constellation.*

4. (Subject to securing funds for scientific data analysis) High-impact science and active Canadian science team membership including participation in Phase F activities using ICI-4 science data focusing on the mechanism of space weather's impact on arctic communication.

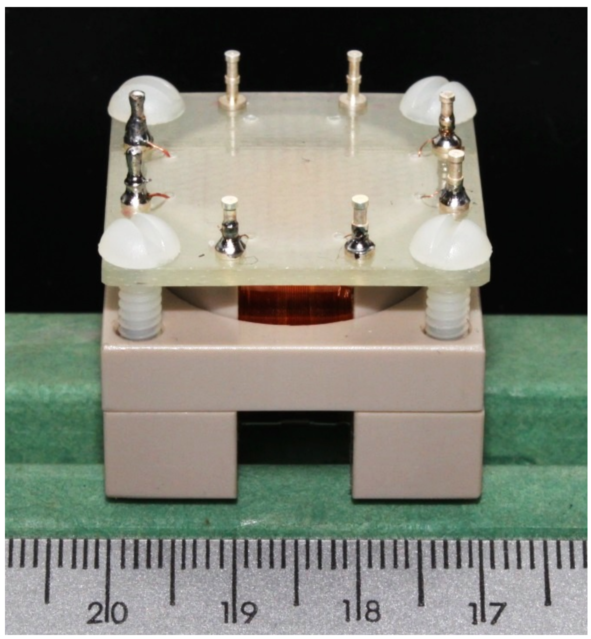
   *Full active participation in the space weather science activities resulting from the ICI-4 campaign is an exceptional opportunity for the U. Alberta and Canada. The proponents submitted a proposal to the Canadian Space Agency titled "Analysis of Rocket data of Ionospheric Scintillation Event (ARISE)" and were awarded a grant to help support the exploitation of the NGFM / ICI-4 science data. This work is currently in progress.*

# 7 Summary

Overall, the project has met all its objectives:

- The Next Generation Fluxgate Magnetometer has demonstrated TRL-7 through its successful flight and operation on the IC-4 sounding rocket.
- The mission provided cradle-to-grave experience to Canadian HQP including a PhD student instrument PI.
- Canada secured ongoing role in the international ICI science team.
- The NGFM data from ICI-4 appears robust and is anticipated to provide high-impact science return. A grant has been secured to fund more detailed analysis.
- The success of this project led to a no-cost flight on the follow-on ICI-5 rocket and payload space on six miniaturised daughter payloads.

# Concept Study of Miniaturized NGFM Sensor for Future Small Payload Applications




The project was carried out by the University of Alberta, Physics Department through funding received from the Canadian Space Agency

Miroslaw Ciurzynski

Magnetometer Engineer

March 31, 2014.

## Executive Summary

The University of Alberta (U of A) has successfully designed, built and tested a new miniature fluxgate sensor. The sensor size reduction was achieved by mounting the sense coils inside the ferromagnetic ring core rather than in the traditional and larger configuration where the sense coil surrounds the core. Test results from the fabricated prototype indicate that the U of A sensor matches or exceeds the sensitivity of a traditional fluxgate sensor with the same size of a ring core. The document describes the design and performance of the U of A sensor and compares it with a commercial Narod S100 fluxgate sensor. The new miniature sensor seems promising for small payload applications such as cube-satellites and sounding rockets. Future work has been identified that could lead to further and significant improvements in the design and performance of fluxgate sensors.

## 1. Introduction

This report describes the work completed under the *Concept study of miniaturized NGFM sensor for future small payload applications* work package, which is part of a Canadian Space Agency funded project entitled *Next Generation Fluxgate Magnetometer on the ICI-4 Sounding Rocket*. The scope of the work package was to develop a concept for a new miniature fluxgate sensor. Overall, the objective of the project was to develop a concept for a fluxgate sensor that would have similar performance to the much larger commercial fluxgate sensors made by Narod Geophysics Ltd, such as the S100, but to be small enough for use on sounding rockets and nanosatellites.

As appropriate to the development of an initial bench prototype miniature sensor, and due to the short duration of the project, the new sensor design utilized ring cores with the same geometry as those used very successfully in larger fluxgate sensors like the Narod S100.

Because accurate modeling of fluxgate sensor performance from purely theoretical concepts is difficult and unreliable, the U of A decided to design, construct and test a miniature sensor concept. The resulting prototype sensor could was then compared to a traditional sensors for several key performance indicators. . The document describes the design of the fabricated prototype and its performance results. The project was carried out between Jan. 15 and March 31, 2014.

## Document Approval

| | | | |
|---|---|---|---|
| Prepared by: | M. Ciurzynski | | 2014/03/31 |
| | Miroslaw Ciurzynski<br>Magnetometer Engineer | | Date |
| Recommended by: | | | 2014/07/02 |
| | David Miles<br>PhD Student | | Date |
| Recommended by: | | | 2014/07/02 |
| | David Barona<br>Project Manager | | Date |
| Approved by: | I. Mann | | 2014/07/02 |
| | Ian Mann<br>Principal Investigator | | Date |

## 2. Functional Principle of a Ring-Core Fluxgate Sensor

The following text and figures explain the functional of ferromagnetic ring cores in fluxgate sensors. The principle is utilized in all ring-core fluxgate sensors regardless of their size and sense-coil design or mounting. A magnetically unsaturated ferromagnetic material concentrates ambient magnetic flux because it has much higher magnetic permeability than air or vacuum. A saturated ferromagnetic material has negligible effect on ambient magnetic flux because it has nearly the same magnetic permeability as air. Figure 1 illustrates how an unsaturated and saturated ferromagnetic ring would ideally affect ambient magnetic flux lines in the plane of the core. The flux concentration patterns would be somewhat similar in the perpendicular top-to-bottom plane of the core.

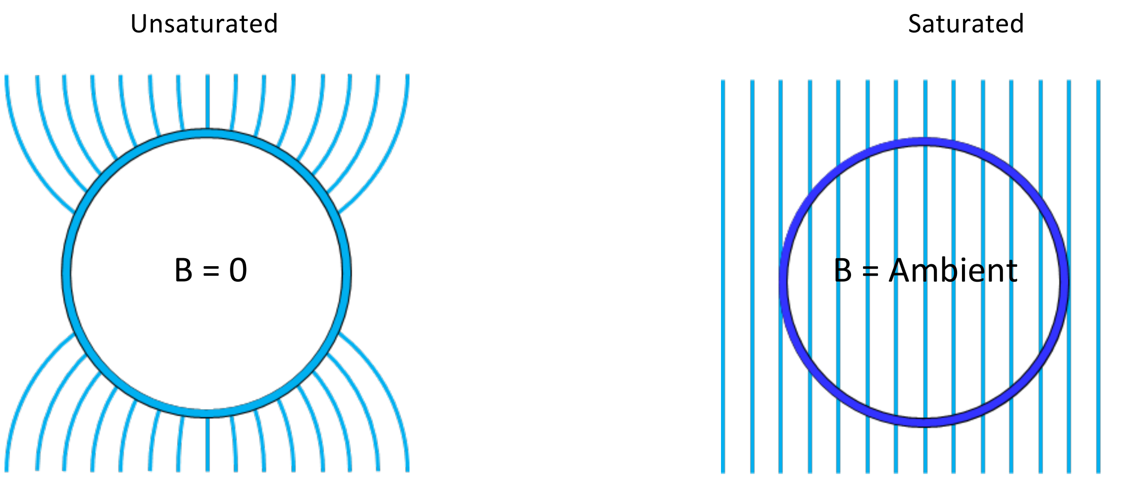



Figure 1. The effect of an unsaturated and saturated ferromagnetic ring core on magnetic flux lines.

Fluxgate magnetometers take their name from the flux-gating effect where cyclically saturated and unsaturated ferromagnetic cores modulate the density of magnetic fluxes near the cores. An induction coil placed in such a field will generate a voltage whose amplitude will be proportional to the strength of the ambient magnetic field (at constant core saturation/unsaturation rate).

Traditionally, including in the prior Narod S100 design, the “sense” induction coil is wrapped solenoidally ***externally*** around the magnetic core (Figure 2 left). The external sense coil experiences flux densities ranging from the ambient field to several times the ambient field (the magnetic concentration or gain depends on core size and geometry). In the course of this Concept Study the U of A considered the benefits of an alternative design (Figure 2 right), in which an ***internal*** sense coil is exposed to flux density variations ranging from near zero to ambient - regardless of the core size. Core sizes in both designs determine the sizes of sense coils and subsequently their performance. Sensor cores with an internal diameter greater than 15 mm can readily accommodate an internal sense-coil mounting, and as we have discovered in the course of this Concept Study, such mounting can provide very significant design and performance advantages over the traditional approach (c.f., Figure 3).

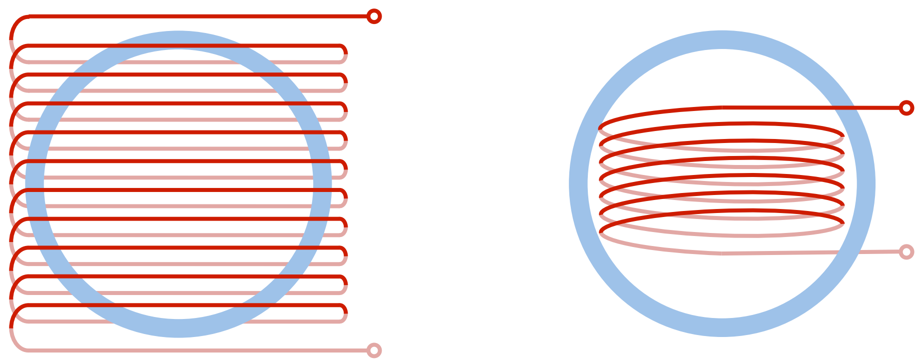



Figure 2. External (left) and internal (right) mounting of sense coils on ring cores in fluxgate sensors.

The ferromagnetic cores are saturated by electric currents passed through magnetization windings wrapped around the cores (not illustrated in Figure 2). Two orthogonal sense coils are usually mounted on each core for sensing two perpendicular vector components of flux density variations.

The size of a ferromagnetic core determines the amount of ambient magnetic flux affected by the core, and the size of a sense coil determines (to a large degree) how much of the affected flux is sensed. Consequently, larger fluxgate sensors are able to produce stronger signals than smaller ones, and sensors with 25 mm ring cores are large enough for detecting flux density variations as small as several pT – which is sufficient for most Earth applications. For 25-mm cores, sensitivity is practically limited by Barkhausen noise of the core material. Mounting sense coils inside ring cores produces more compact sensors than mounting them outside. The prototype miniature U of A fluxgate sensor was built to quantify the performance of this design..

## 3. The Miniature U of A Fluxgate Sensor Prototype Design

Following the fundamental principles mentioned earlier, the U of A has developed and built a bench prototype of a new fluxgate sensor in which two orthogonal sense coils were mounted inside a ferromagnetic ring core. A photograph of the sensor prototype is shown on Figure 3.

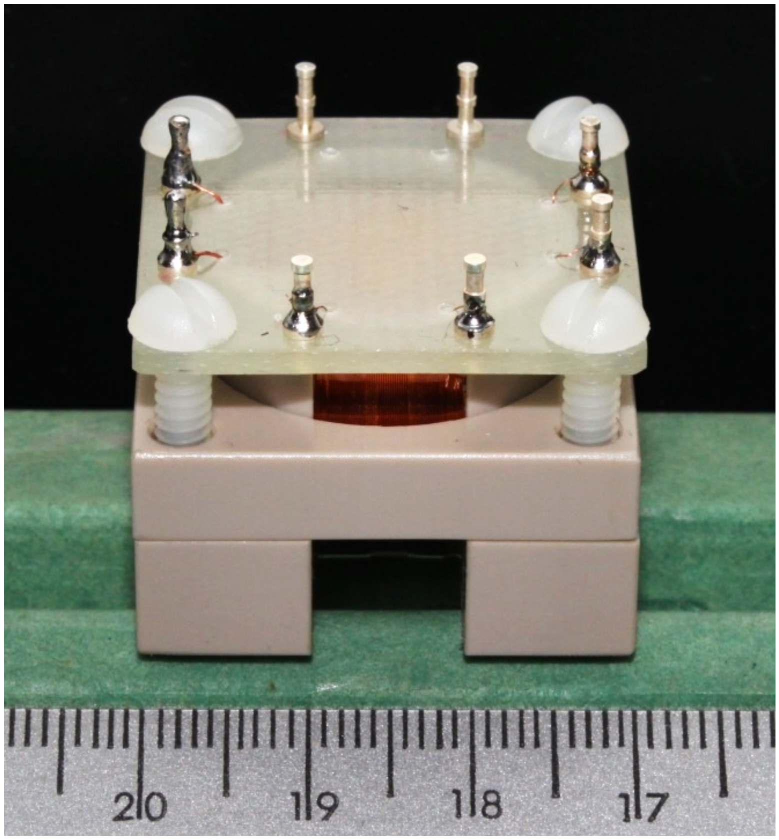



Figure 3. A photograph of a 2-axis fluxgate sensor prototype designed and fabricated by the U of A.

The sensor holder was machined from a thermoplastic material called polyether ether ketone (PEEK). It contains one ferromagnetic ring core and two sense coils, all concentric and orthogonal. The termination board on top of the sensor is made from Garolite, a fiber-glass reinforced epoxy commonly used in printed circuit boards. Coils are made from copper wire with polyimide insulation. All materials used in the sensor are used in aerospace applications. The highly symmetrical design of the sensor holder is designed to maintain the alignment of its components when the holder expands or contracts due to temperature changes.

Figure 4 illustrates a cross-section of this 2-axis fluxgate sensor which was designed and built by the U of A. The ring core (including its bobbin and a magnetization winding) has internal diameter of about 22 mm.

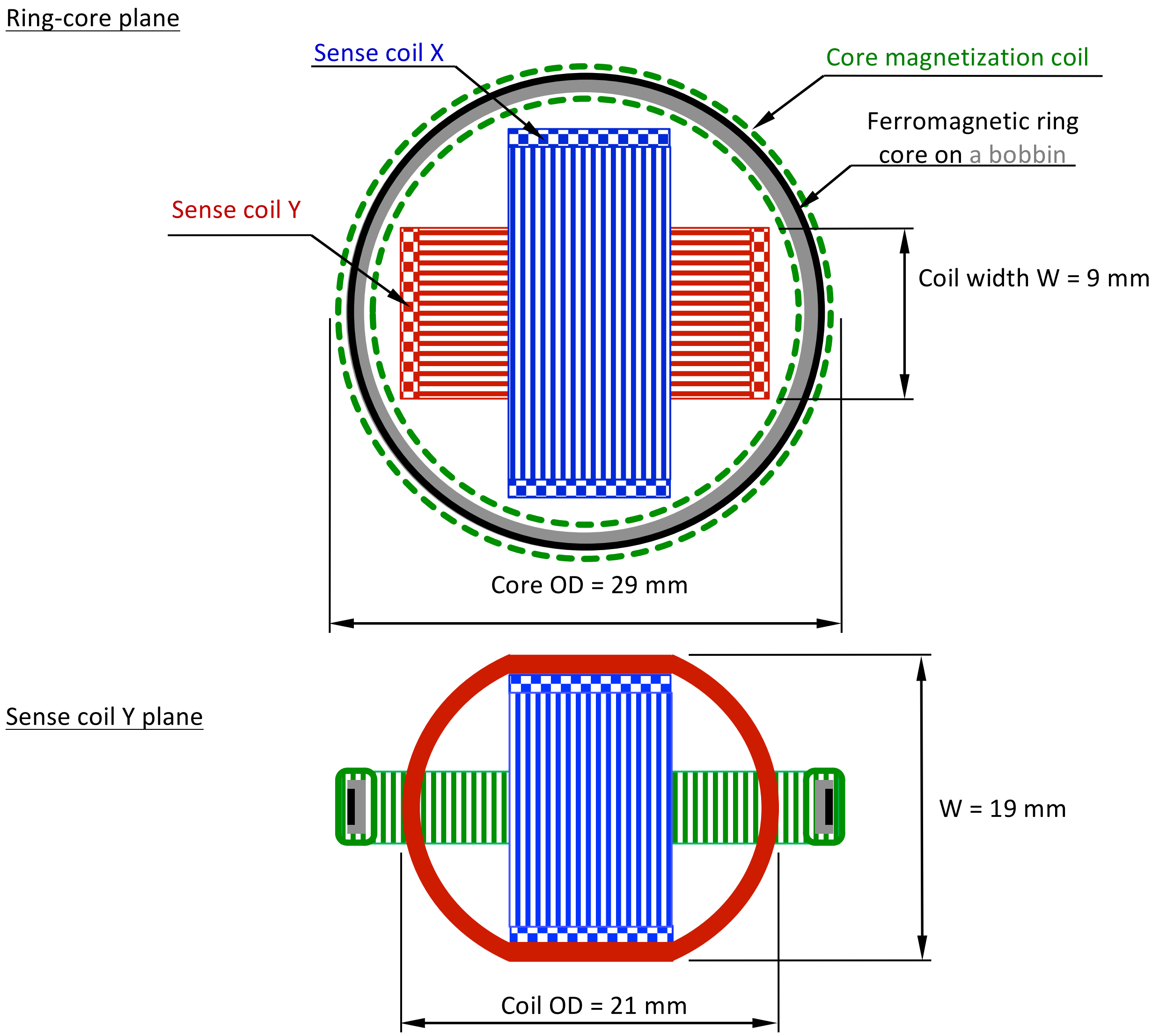



Figure 4. Cross-section of a 2-axis fluxgate sensor designed and built by the U of A.

## 4. Sensor Characteristics: Comparison with Narod S100 Sensor

The photographs in Figure 5 show the standard 3-axis Narod S100 fluxgate sensor (white base), and the new miniature 2-axis fluxgate sensor prototype designed and built by the U of A (beige base). Both sensors use the same size and type of a ring core made by Narod. The ring core with its magnetization winding has the following dimensions: OD = 29 mm, ID = 22 mm, W = 4 mm.

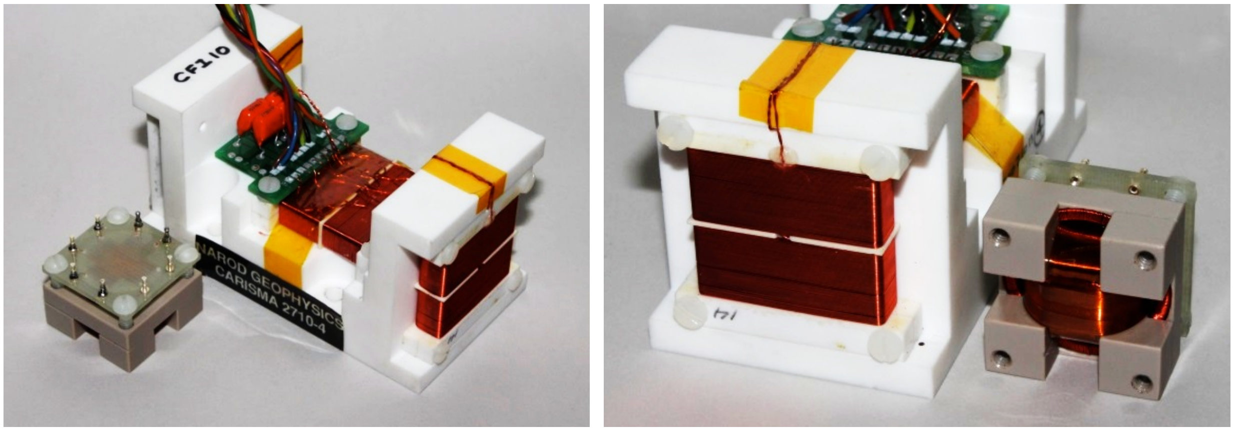



Figure 5. Photographs of fluxgate sensors made by Narod Geophysics Ltd. (white base) and the U of A (beige base).

The following table lists the basic physical properties of a standard Narod S100 fluxgate sensor and the new miniature fluxgate sensor prototype made by the U of A.

| | Narod | U of A |
|---|---|---|
| Sense coil mounting on a ring core | External | Internal |
| Sense coil cross-section | Rectangular | Quasi circular |
| Mean cross-section area of a sense coil | 260 $mm^2$ | 260 $mm^2$ |
| Wire size in sense coils | AWG 32 (d = 0.22 mm) | AWG 37 (d = 0.14 mm) |
| Number of wire-turns in a sense coil | 360 | 715 |
| Resistance of a sense coil | 18 ohm | 81 ohm |
| Envelope dimensions of 2-axis sensor | 41 x 41 x 10 mm | 30 x 30 x 20 mm |
| Envelope dimensions of 3-axis sensor | 64 x 46 x 48 mm[1] | 50 x 30 x 30 mm |
| Structural material | Macor | PEEK |
| Mass of a 2-core 3-axis sensor | 240 g [1)] | 2 x 26 g |

Table 1. Properties comparison of fluxgate sensors made by Narod Geophysics Ltd. and the U of A.

## 5. The U of A Miniature Fluxgate Sensor Performance

The performance of the U of A fluxgate sensor prototype was tested in a lab using commercial test equipment. Signal generators (Agilent 33220A and Stanford DS360) were used for supplying core magnetization waves, and Tektronix MSO3034 oscilloscope was used for capturing the input and output signals from the fluxgate sensor. The plots in Figure 6 show the voltages induced in the sense coils of both the Narod S100 sensor and the new miniature U of A sensor. The ring cores of the two fluxgate sensors were cyclically re-polarized and saturated by applying a square voltage wave (9 Vp-p) to the core magnetization windings. The magnetization frequency was set to 33 kHz, which was the maximum at

[1] The dimensions and mass apply to a more compact Narod sensor built for a satellite mission. That sensor had two ring cores instead of the three as shown on Figure 5.

which the cores could be repolarized and deeply saturated. A resistance of 9.1 kohms was connected to each coil to suppress excessive ringing. The sensors were in 50 µT field during these tests.

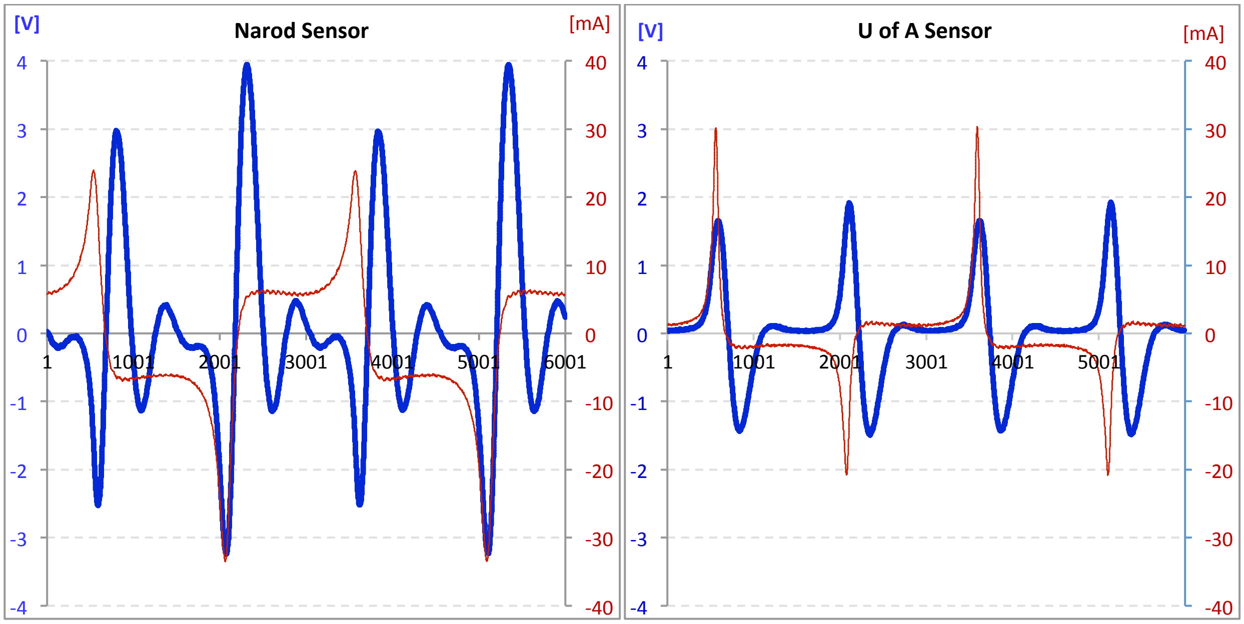



Figure 6. Signals from Narod and U of A fluxgate sensors whose cores were cyclically re-polarized and saturated by voltage square-waves applied to their magnetization windings. Blue/thick traces = voltages induced in sense coils, red/thin traces = core magnetization currents.

Observations arising from the tests:

a) In both sensors the signals arising from cores when magnetized clockwise are considerably different from those when magnetized counter-clockwise. This raises doubts about the usefulness of deep repolarized magnetizations and could have implications for future design optimizations of fluxgate sensors. Using only a portion of the core magnetization loop may have significant benefits;

b) In each re-magnetization cycle, only the voltages induced during short transitions from core saturation to unsaturation (and vice-versa) are useful. The remaining part of each cycle is wasted time and energy, - which again questions the usefulness of deep repolarized magnetizations;

c) The signal induced in the Narod sense coil has significantly more ringing than the signal from the U of A sense coil, - which may be the reason for its higher amplitude;

d) The Narod sensor has significantly higher average core magnetization current than the U of A sensor, which may be due to its close proximity to a second idling ferromagnetic core which is also present in the Narod sensor housing and is adjacent to the core being tested.

The plots in Figure 7 show the voltages induced in the sense coils of the Narod and U of A miniature fluxgate sensors whose ring cores were cyclically saturated and unsaturated (without repolarizations) by applying sinusoidal voltage waves to core magnetization windings. Frequencies of these waves matched the resonance frequencies of the sense coils (223 kHz for the Narod sensor, 179 kHz for the U of A sensor). Amplitudes and offsets of these waves were set to produce near maximum amplitudes in the coil-induced voltages. The voltages were captured on open-ended coils. (The signals were not ringing, and therefore the coils did not need to be loaded with resistances.) The sensors were in 50 µT field during the tests.

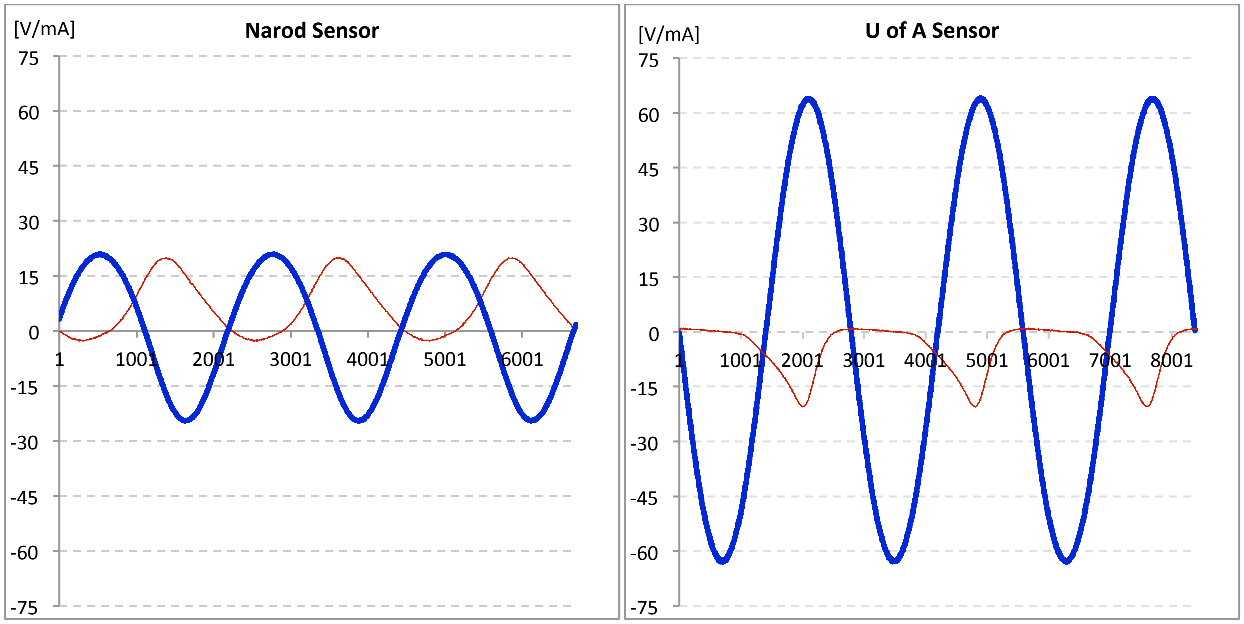



Figure 7. Signals from Narod and U of A fluxgate sensors whose cores were cyclically saturated and unsaturated by sine waves at resonance frequencies of sense coils. Blue/thick traces = voltages induced in sense coils, red/thin traces = core magnetization currents.

Observations arising from the tests:

a) The sense coil of the U of A sensor had its resonance frequency lower than the sense coil of the Narod sensor by about 20% (179 kHz vs. 223 kHz), which would result in less power consumed by a fluxgate magnetometer if the sensors were operated at their resonance frequencies.

b) The U of A sensor produced a less distorted and 2.8 times stronger signal than the Narod sensor (127.2 vs. 45.7 Vp-p);

c) The average core-magnetization current of the U of A sensor was about 24% lower than that of the Narod sensor (5.2 mA vs. 6.8 mA).

## 6. Conclusions

Placing sense coils inside a ferromagnetic ring of a fluxgate sensor represents a very promising solution to the challenge of miniaturizing fluxgate sensors. Results from testing the U of A fluxgate sensor prototype indicate that the novel design can match and possibly exceed the sensitivity of traditional and larger fluxgate sensors; however, this needs to be verified in the context of signal to noise ratio and sensor noise floor. Moreover, a design modification to saturating and unsaturating the ferromagnetic core with a sine wave instead of a square wave eliminated harmonics and problems associated with them. Magnetizing the core at the resonance frequency of a sense coil also allowed the performance of the sensor to be maximized – and this is an additional significant new design modification. Magnetizing the core without repolarizations allowed us to operate the senor at a frequency high enough for measuring magnetic field variations up to at least 50 kHz - which is higher than the upper frequency range of most search coil magnetometers and which may also have additional design advantages for designs incorporating combined fluxgate and induction coil frequency responses in a single instrument.

## 7. Perspectives for Future work

The new miniature bench prototype fluxgate sensor designed and built by the U of A differs considerably from the design of the Narod sensor and that of other typical fluxgate sensors built by others. Our initial tests have indicated that the small U of A sensor has the potential to outperform the good but much larger Narod sensor. Below we list items and perspectives for potential further work:

a) Determine the advantages and disadvantages of magnetizing the ring core without complete repolarizations and saturations. (Eliminating complete repolarizations would allow one to increase the operating frequency of a fluxgate sensor by an order of magnitude.)

b) Determine the advantages and disadvantages of magnetizing the ring core with a sine wave instead of a square wave. (Using sine wave would significantly improve signal quality by eliminating harmonics and problems associated with them.)

c) Determine the advantages and disadvantages of magnetizing the core at the resonance frequency of sense coils. (Operating sense coils at their resonance frequency would take advantage of their maximum sensitivity.)

d) Determine the advantages and disadvantages of almost-full vs. deep saturation of the core on sensor performance. (Magnetizing the core to almost-full instead of deep saturation could reduce the peak magnetization current by an order of magnitude.)

e) Optimize the waveform of the voltage signal applied to the magnetization winding for the best performance of the fluxgate sensor. (The optimal waveform may resemble a stretched sine wave which could be produced by an arbitrary waveform generator.)

f) Optimize the parameters of magnetization and sense windings (geometry, wire size, number of turns).

g) Explore the advantages and disadvantages of adding a winding on the ring core for magnetic biasing of the core to reduce Barkhausen noise. (This may reduce Barkhausen noise by an order of magnitude.)

h) Determine how the distance between ring cores affects the mutual interference of two sensors. (Mounting ring cores close to each other may limit sensor performance.)

i) Explore the feasibility for adding a reference-magnetic-field generation method to the fluxgate sensor for on-demand or self-calibrations. (This would be highly desired in space applications.)

j) Explore the feasibility of making a tri-axial fluxgate sensor consisting of two orthogonal ring cores (one inside the other) and three internal orthogonal sense coils, - all concentric. (This would allow miniaturizing the sensor even further.)

k) Determine the performance of a fluxgate sensor at ambient temperature ranging from -70 $^{o}$C to +70 $^{o}$C. (Knowing and applying the temperature coefficient in data processing may be easier than trying to design a fluxgate sensor having near-zero temperature coefficient.)