2023 Technology Showcase for Future NASA Planetary Science Missions

NGFM

Next-Generation Fluxgate Magnetometers

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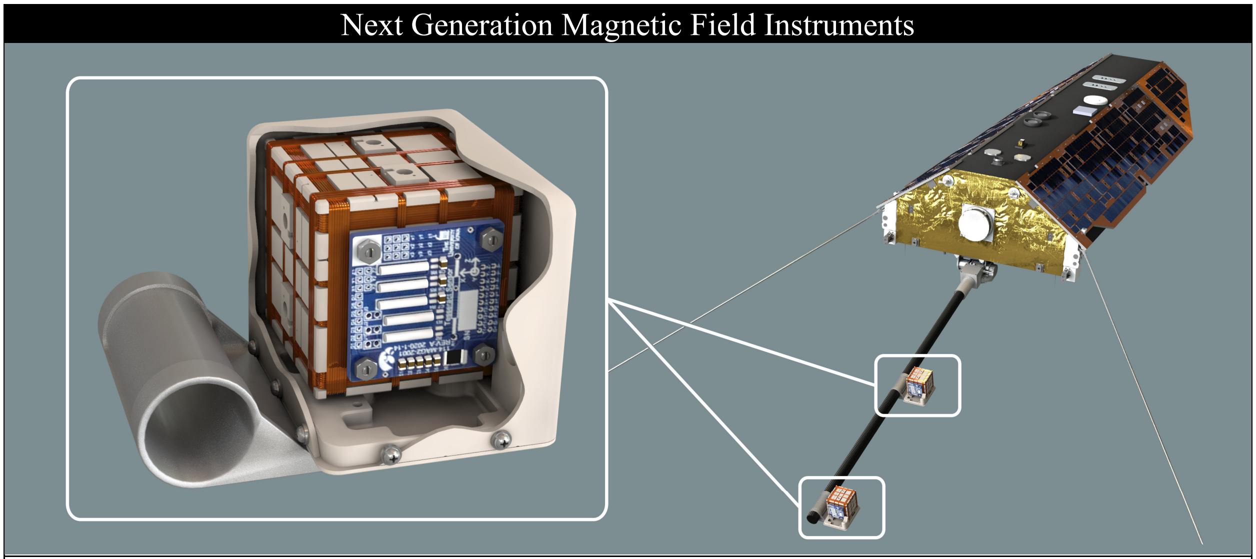
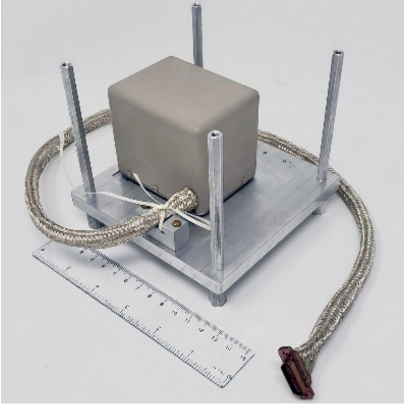
Next Generation Magnetic Field Instruments

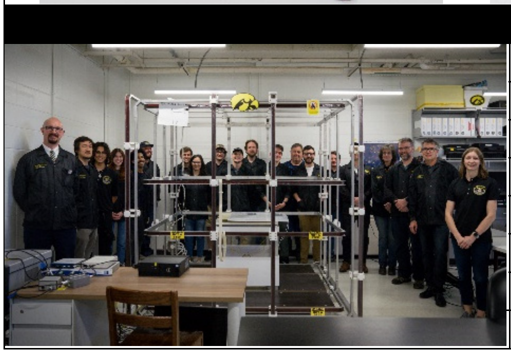


The Miles Research Group at the University of Iowa has developed a range of next-generation magnetic field instruments that are built and tested in-house by an experienced science and engineering team. The designs have been refined through heritage from a series of spaceflight missions including the MAGIC payload on the Heliophysics TRACERS SMEX mission. Uniquely, we manufacture our own low-noise fluxgate cores from scratch rather than depending on the depleting supply of legacy cores used historically. This enables innovations like the Tesseract high-stability sensor and our compact nanosatellite sensor. Typically, two sensors mount at different distances from the spacecraft. Both experience a common geophysical field, but the spacecraft's stray fields diminish with distance enabling modern adaptive filter and interference cancellation techniques to mitigate time-varying local spacecraft magnetic noise.

Example Instrument Package (TRACERS/MAGIC)



Instrument Team



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Need for Magnetic Field Measurements

Magnetic field measurements are essential for future planetary science targets including planetary magnetospheres, planetoid formation and composition, and electromagnetic imaging of water- and ice-bearing bodies. Fluxgate magnetometers provide measurements of the local DC and low-frequency AC magnetic field and are a robust work-horse instrument that can survive and operate in extreme conditions. At least seven of the science mission abstracts submitted to the 2023 Technology Showcase for Future NASA Planetary Science require magnetic field measurements (Table 1).

Instrument Overview

The Miles Research Group at the University of Iowa develops and builds a range of Next-Generation Fluxgate Magnetometers (NGFM). Instruments are built and tested in-house by an experienced science and engineering team. The design has been refined through heritage from a series of spaceflight missions including the current MAGIC payload on the Heliophysics TRACERS SMEX mission. Uniquely, we manufacture low-noise fluxgate cores from scratch rather than depending on the depleting supply of legacy cores used historically. This allows us to innovate on the traditional fluxgate through improvements like the Tesseract high-stability sensor and our nanosatellite sensor.

Pairs of instruments are typically flown in a gradiometer configuration (two sensors and different differences from the platform) enabling modern signal-processing techniques to separate the target geophysical fields from local magnetic noise from the platform.

NGFM measures the in-situ DC and low-frequency magnetic field experienced by a spacecraft throughout its orbit. The fluxgate sensor and the electronics package are both built at U. Iowa under PI Miles. NGFM is based on the MAGIC Technology Demonstration for the TRACERS SMEX mission, which has passed its confirmation review and is in flight build. Uniquely, NGFM uses purpose built low-noise (~5 pT) cores manufactured in-house, rather than depending on the dwindling supply of often higher noise legacy cores. NGFM is typically deployed as a gradiometer of two sensors along a spacecraft boom (Figure 1) with modern sensor fusion to mitigate static and time-varying magnetic platform noise.

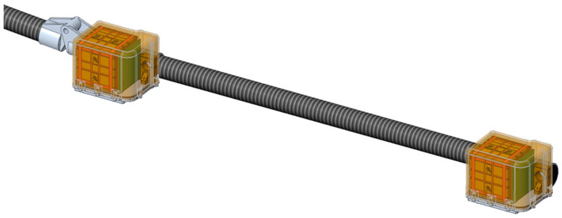


Figure 1: NGFM uses two fluxgate sensors mounted on a common boom.

Next Generation Sensors

Fluxgate magnetometers (e.g., Primdahl, 1979; Snare, 1998) sense the magnetic field through the electromagnetic force (EMF) induced by changing magnetic flux. Voltage is induced in a sense winding by the changing relative permeability of a ferromagnetic core that is

Potentially Relevant Mission Abstracts	Instrument Size	Gradiometer?
Astrolab Venturi	TBD	TBD
Ceres Sample Return Mission	TBD	TBD
Coral: Centaur lander	Standard	No – 1 sensor (TBC)
Extending Small Mission Opportunities to the Outer Solar System Through Rideshare	Standard/Nanosat	TBD
Prometheus	TBD	TBD
Triton Ocean World Surveyor	Standard	Yes – 2 sensors
Uranus Orbiter	Standard	No – 1 sensor (TBC)

Table 1: Potentially relevant Future NASA Planetary Science Missions Science Mission Abstracts.

periodically driven into magnetic saturation using a drive winding. Fluxgates performance is typically limited by the intrinsic magnetic noise of the core entering magnetic saturation. NGFM uses purpose-built low-noise cores, manufactured at U. Iowa (Figure 2).

These cores reproduce the performance of the legacy Infinetics S-1000 ring-cores dating from the 1960s that have been used historically. The manufacturing process for these cores is now well documented (Miles et al., 2019b) and has completed a first detailed optimization for noise (Miles et al., 2022) resulting in a ~90% yield for cores noise better than 10 pT/√Hz at 1 Hz. Consequently, U. Iowa can reliably mass-produced cores for future missions.

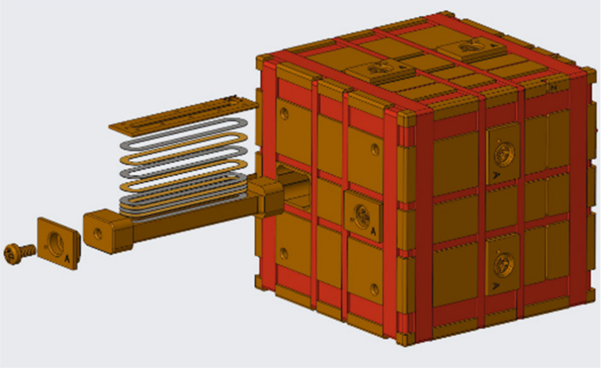


Figure 2: The Tesseract sensor uses purpose-built highly-repeatable racetrack cores.

The NGFM Tesseract sensor provides magnetic feedback using a triple-wound Merritt coil (Figure 2) that creates a three-axis magnetic null inside the sensor where the racetrack fluxgate cores are held in near-zero field. This ensures that the cores are not subject to un-compensated cross axis magnetic fields regardless of the magnitude of the ambient magnetic field (Primdahl and Jensen, 1982).

Retaining the cores in a magnetically homogeneous region, where the magnetic field can be uniformly nulled, ensures a reproduceable magnetization of the ferromagnetic cores, thus improving the sensor's measurement stability and linearity (Ripka, 1992). The NGFM Tesseract sensor's triple-wound Merritt coil feedback design has been optimized to generate a highly homogeneous field using a Biot-Savart model (Figure 3 that simulates the magnetic field generated by the feedback coil on a 3D grid. This holds the ferromagnetic cores in a region that is magnetically uniform within 0.5%, making their magnetization more repeatable and thereby improving sensor stability from the traditional single- or double-wound sensor topology (Acuña and Pellerin, 1969; Wallis et al., 2015) that achieves a uniform field to within 5.6% (Greene et al., 2022). The base of the sensor presents a mounting interface to a U. Iowa provided bracket that is bonded to the spacecraft provided boom.

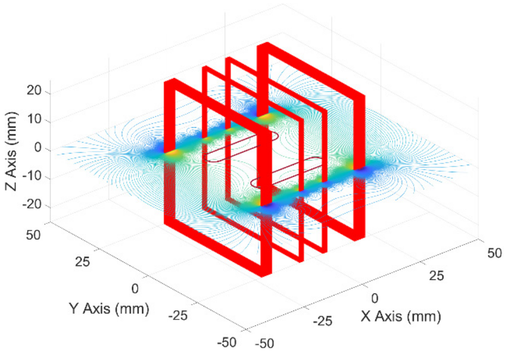


Figure 3: Biot-Savart modelling optimized a large, homogeneous 3D magnetic null for all six cores (Greene et al., 2022).

A variation of this geometry enables a new nanosatellite sensor (Figure 4) that will provide < 10 pT/√Hz at 1 Hz performance and is currently in laboratory testing.

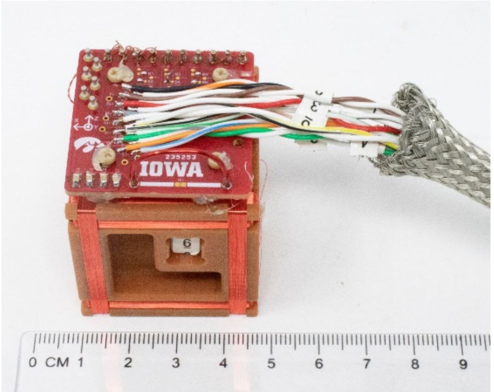


Figure 4: Nanosatellite-scale fluxgate sensor

Spacecraft Magnetic Noise Mitigation

Boom deployment is an essential, but typically insufficient, step towards magnetically clean measurements. Stray magnetic field from the spacecraft generally falls into two categories. DC field from ferromagnetic spacecraft materials create a nominally constant offset at the sensor that can usually be removed by careful in-situ calibration. Time-varying fields resulting from active spacecraft subsystems are typically much harder to mitigate.

The optional two-sensor gradiometer requires additional cost and resources compared to a single instrument on each spacecraft. However, it simplifies mission formulation and reduces risk by allowing clean magnetic field measurements even in the presence of non-trivial stray fields. Instruments can be selected without as rigorous magnetic cleanliness, and, if issues arise with magnetic cleanliness during flight build, the gradiometer allows the possibility for the mission to simply waiver the unplanned magnetic source rather than triggering redesign or reworked mitigation.

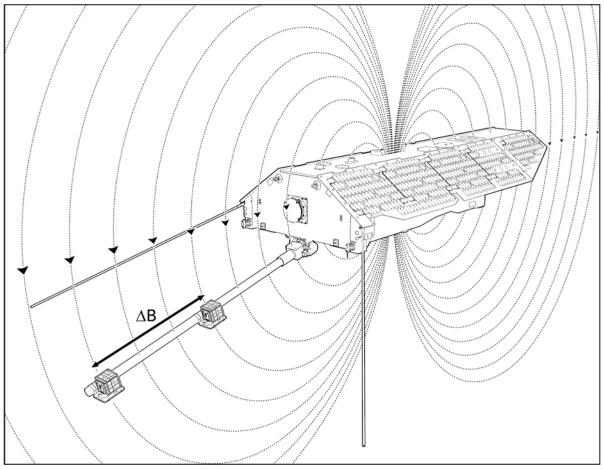


Figure 5: The two sensors experience a common geophysical field but different stray magnetic fields from the spacecraft.

Two sensors mounted at different distances from the spacecraft, as shown in Figure 5, both experience a common geophysical field. However, stray fields from the spacecraft will diminish with distance and be measured with different amplitudes (the exact drop-off rates vary with the order of the local magnetic field source). This dual-sensor technique has long been used to estimate the stray DC spacecraft field (e.g., Ness et al., 1971; Neubauer, 1975); however, modern adaptive filter and sensor fusion techniques (e.g., Constantinescu et al., 2020) show promise for additionally mitigating time-varying noise sources. Recent work by the Miles Research Group (Finley et al., 2022) show how Multichannel Singular Spectrum Analysis (MSSA) can be used to decompose measurements from two fluxgates, correlate the decomposed signals against the simple difference of the two sensors to identify local noise, and then exclude those terms from the reconstruction. Figure 6 shows this using Swarm-Echo data, which has significant magnetic interference from multiple reaction wheels (Black, 1.77 nT_{rms} noise) that is significantly mitigated (Figure 6, Blue, 0.68 nT_{rms} noise) using MSSA. Additionally, this data can also be used successfully to train a neural net that can classify the decomposed signals from a single sensor albeit with reduced effect (Figure 6, Orange, 0.76 nT_{rms} noise).

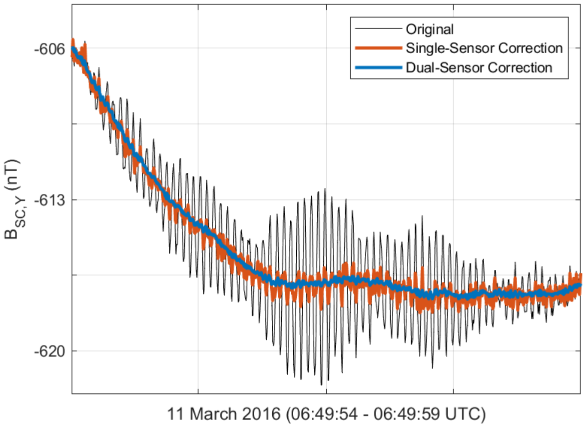


Figure 6: Reaction wheel noise removal using one sensor, Singular Spectrum Analysis, and machine learning trained on gradiometer data.

This technique has been provisionally demonstrated using both Swarm-Echo and Parker Solar Probe data and significantly mitigates stray fields such as reaction wheels and solar panel currents.

Heritage

The NGFM payload leverages the flight-proven design from the MGF instrument (Wallis et al., 2015; Miles et al., 2019a) on the e-POP/Swarm-Echo (Yau and James, 2015) that has operated on-orbit since 2013. The electronics design was updated with a radiation tolerant route to flight (Miles et al., 2013). Updates and improvements to the electronics and firmware have been tested on the ICI-4 (2015), Maxidusty-1b (2016), and ICI-5 (2019) sounding rockets. The design was miniaturized for the Ex-Alta 1 cube-satellite mission (Miles et al., 2016) that deployed from the International Space Station in May 2017 and operated until re-entry in November 2018.

PI Miles has developed new low-noise cores to replace the legacy Infinetics ring-cores used in most missions, which went out of production in 1996. The new cores are manufactured under a process which produces comparable magnetic noise and has passed vibration, thermal, and vacuum testing (Miles et al., 2019b).

More recently, NASA funded PI Miles' Magnetometers for Innovation and Capability (MAGIC) Technology Demonstration on the TRACERS SMEX mission. Engineering model equivalents of MAGIC were successfully flown on the two ACES-II rockets in Nov 2022. We assess the technical readiness level of the payload to be TRL-6 based on flight heritage and the system and subsystem level testing of subsequent changes. As needed, we can conduct appropriate differential analysis for the unique needs of future missions.

U. Iowa has extensive specialized expertise in the design and fabrication of spaceflight instrumentation. The MAGIC instrument team are currently completing the flight hardware for the TRACERS satellite mission. Consequently, U. Iowa can provide a heritage design, built by the same people, at the same institution, and using the same facilities for future applications.

Availability of Fluxgate Cores

Most spaceflight fluxgate magnetometers providers worldwide rely on legacy Infinetics S1000 fluxgate cores which have been out of production since 1996. The known stockpiles of these legacy cores, maintained by individual institutions, have been critically depleted with some providers now exploring destroying flight-spares from previous missions to recover and refurbish the cores to produce new instruments. In contrast, U. Iowa has no dependency on legacy cores and can manufacture purpose-built fluxgate cores on-demand and tailor them to mission needs. U. Iowa produces fluxgate cores starting with base metal powders, manufactures the permalloy foils in-house, and has a customized process furnace to heat-treat fluxgate cores for low magnetic noise (Figure 7).

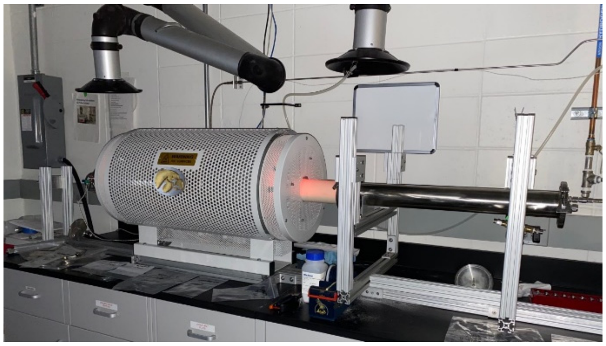


Figure 7: Customized process furnace for heat-treating fluxgate cores for low magnetic noise.

U. Iowa can manufacture and heat-treat fluxgate cores in bulk (Figure 8). We have built and tested more than a hundred cores in the last twelve months as part of the MAGIC Technology Demonstration program.

Figure 8: Bulk heat-treatment of ferromagnetic foils for fluxgate cores.

U. Iowa has a reliable manufacturing process and robust process control. For example, Figure 9 show the noise performance of twenty notionally identical racetrack cores to test the noise variability of the manufacturing process. The histogram of the noise floor distributions shows a narrow noise peak at 9 pT/√Hz at 1 Hz which is sufficient for most applications. Lower noise can be achieved in the current process by simply adding additional foil layers at the expense of a modest increase in power. Ongoing optimization work has already improved the noise versus power yield compared to these results.

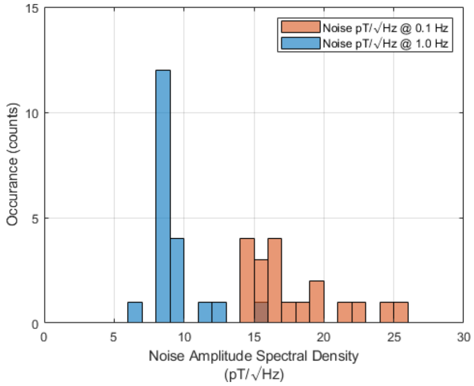


Figure 9: Noise histogram for twenty notionally identical fluxgate cores. Note the narrow noise cluster at the 9 pT/√Hz at 1 Hz which is sufficient for most applications.

Production Capability and Infrastructure

The U. Iowa Department of Physics and Astronomy has been developing successful space-flight instruments since James Van Allen's pioneering discovery of Earth's radiation belt in 1958. Significant recent investments have been made to hire spaceflight experimental faculty, update the facilities, and hire new engineering and technical staff. U. Iowa has recently made several significant infrastructure advancements including a thermal vacuum chamber, a vibration table, 5-axis CNC machining, a CNC coil winder, pick-and-place electronics assembly, vapor-phase reflow soldering, and establishing a Quality Management System (QMS) to comply with the ISO9001 standard as it applies to our development of spaceflight scientific instrumentation. U. Iowa is well positioned to provide long-term support for future flagship planetary missions.

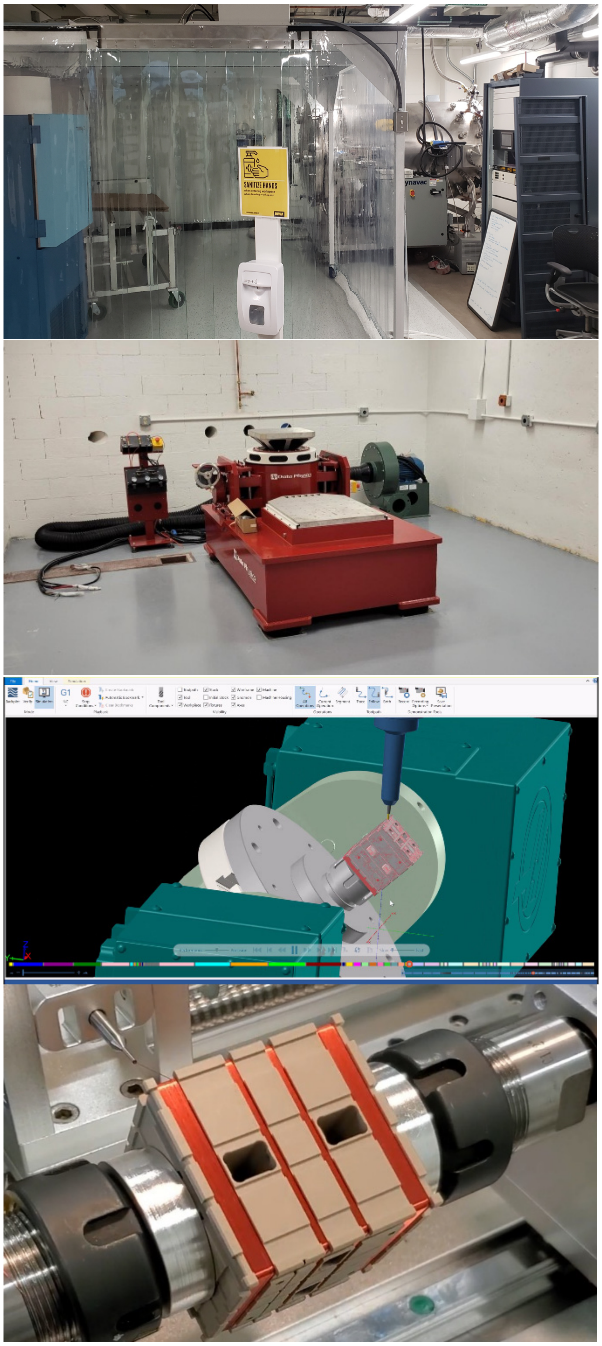
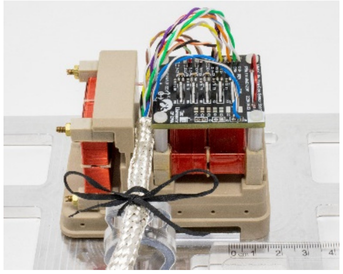
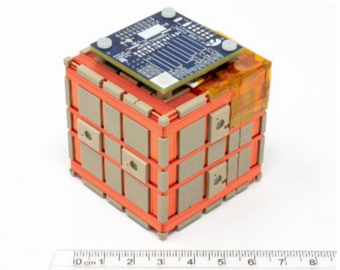
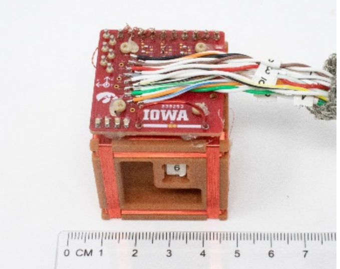
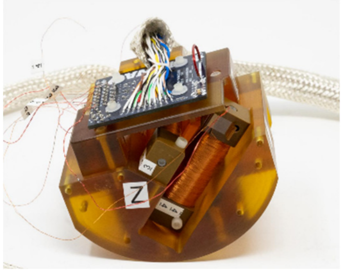
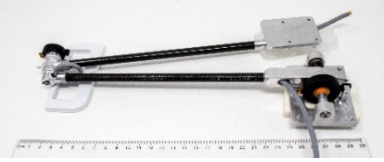


Figure 10: (Top-to-Bottom) Thermal vacuum qualification chamber, vibration table, 5-axis CNC machining, and CNC coil winder.

Iowa Next Generation Fluxgate Magnetometer Options

Classic 1" Ring-core		Purpose:	Compatible with heritage designs
		Heritage:	TRACERS SMEX (2 satellites) in 2024 ACES-II (2 rockets) in 2022
		Frequency:	DC – 50 Hz (configurable)
		Noise:	~6 pT / √Hz @ 1 Hz
		Mass:	~350 g
		Volume:	86.9 x 55.7 x 64.2 mm
		Features:	S1000 core compatible, thermistor, heater
High Stability		Purpose:	Higher stability to minimize calibration
		Heritage:	TRACERS SMEX (2 satellites) in 2024 ACES-II (1 rocket) in 2022
		Frequency:	DC – 50 Hz (configurable)
		Noise:	~4 pT / √Hz @ 1 Hz
		Mass:	~370 g
		Volume:	80.4 x 63.4 x 65.2 mm
		Features:	Thermistor, heater
Nanosat Sensor		Purpose:	Nanosatellites, quantity production, lower cost
		Heritage:	Lab prototype ICI-5b (sounding rocket) in 2024
		Frequency:	DC – 50 Hz (configurable)
		Noise:	~10 pT / √Hz @ 1 Hz (TBC)
		Mass:	~80 g
		Volume:	40 x 40 x 45 mm
		Features	Thermistor, small, low mass
Chimera Hybrid AC/DC		Purpose:	Hybrid AC/DC (Searchcoil/Fluxgate) Instrument
		Heritage	ACES-II (1 rocket) in 2022
		Frequency:	DC – 50 Hz Fluxgate (configurable) 10 to 5000 Hz Searchcoil (configurable)
		Noise:	~25 pT / √Hz @ 1 Hz (Fluxgate) ~5x10^{-7} nT^2/Hz @ 1000 Hz (Searchcoil)
		Mass:	~250 g
		Volume:	~60 x 60 x 60 mm
		Features:	Thermistor, replaces fluxgate and searchcoil
Nanosat Boom		Purpose:	Nanosat magnetically clean magnetometer boom.
		Heritage	BLAZE (parabolic flights) in 2021 and 2022
		Mass:	~150 g
		Volume:	312 x 86 x 32 mm
		Features:	Non-magnetic from shoulder forward, locking, embedded wiring, integrated potentiometers
Electronics		Purpose:	Scalable fluxgate electronics package
		Heritage:	TRACERS SMEX (2 satellites) in 2024 ACES-II (2 rockets) in 2022
		Supply:	28±6 Vdc
		Interface	LVDS/RS-422 asynchronous serial, 1 PPS timing
		Power:	1.5 W / 3-axis magnetometer
		Mass:	1200 g (two 3-axis magnetometers)
		Volume:	213 x 129 x 61 mm

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