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AN UPDATE ON THE ROCK AND PALEOMAGNETIC INSTRUMENT DEVELOPMENT CONSORTIUM (RAPID)

Invited

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Abstract

Although superconducting magnetometers were introduced to paleomagnetism over 40 years ago, very few laboratories have been able to exploit their rapid measurement capabilities, their wide dynamic range, and intrinsic sensitivity. The RAPID consortium was formed about 6 years ago to provide a common user-driven platform to allow advances made by one lab to be used by others, within a common and flexible instrument and software framework. In the process, we have expanded the systems to include control of Af demagnetization, ARM, IRM, and susceptibility measurements, which enable a huge range of rock-magnetic experiments to be done automatically. The use of acid-washed quartz-glass tubes, along with a computer-controlled vacuum system for supporting specimens, allows us to do paleomagnetic measurements on samples with NRM intensities as weak as 10^{-11} Am^2 (NRM intensities starting at 10^{-8} emu). Current projects include replacing the ‘snake-chain’ belt for holding samples with a simple XY stage assembly, designing a liquid-helium free pulse-tube cryocooler link to replace the Sterling-cycle cold heads on existing 2G magnetometers, using a Digital/Analogue converter to dynamically control the Af demagnetization process, and using a pulse-tube system to run a scanning SQUID magnetic microscope. I will give a broad update on how these have been implement in the present RAPID consortium laboratories (Caltech, Vanderbilt, Occidental, MIT, Yale, USGS Menlo, UT Austin, Johannesburg, Baylor College, and Edinburgh). Although we have not solved the sample-changing problem for horizontal magnetometer systems, the RAPID system with all of the rock-magnetic ‘bells & whistles’ can be used in single-sample mode on them.

Introduction

Although the twin fields of Paleomagnetism and Rock Magnetism are intellectually rich and deep, capable of providing unique discoveries about the nature of Earth and Planetary materials, there has been a long standing problem of the best and brightest students abandoning the trade for other disciplines they view as intellectually more stimulating (e.g., geochemistry). From my perspective, this is most often driven by the large numbers of mind-numbing, repetitive measurements that are required to pull apart the nature and vector characteristics of natural remanent magnetizations in geological samples, and students are simply migrating to the shiny clean-labs that let them write papers or watch movies while an instrument somewhere does the mind-numbing repetitive measurements. This leads to what I refer to as the “brain-dead student syndrome”, which is clearly a factor in the decision of many universities to terminate their programs in paleomagnetics after the retirement or departure of faculty. We need to compete with the other disciplines in the Earth Sciences not just with the intellectual merit of the problems to be addressed (which is seemingly endless), but by attracting and retaining the top students in the field.

In 1981, we were in the initial discovery phase of magnetite biomineralization in animal tissues, which necessitated setting up a superconducting rock magnetometer in a dust-and-particle-free clean lab system, and pretending that frozen bits of animal tissues were actually rocks. These samples were so weakly magnetized that conventional sample holders would not work, and the issue of contamination during the measurement process forced the development of techniques that minimized both the intrinsic moment of the sample holders and the number of times that specimens needed to be handled. Automation was the obvious solution. It quickly became apparent that acid-washed quartz-glass fibers could have sIRM values below the instrument noise levels, and that, when suspended on thin, monofilament fishing lines, this would allow rock-magnetic measurements to be made semi-automatically (Kirschvink et al., 1985).

These developments gradually paved the way of automating the use of superconducting moment magnetometers. In 1981 I had the great fun of re-wiring a one-axis Schonstedt Af demagnetizing system that I had inherited from Eugene M. Shoemaker, to bring it under the control of an early Apple-II microcomputer and arranging it to do 3-axis demagnetization in-line with the sample path. This was similar to that done by Alan Cox at Stanford (in collaboration with Goree and Goodman of 2G Enterprises, then Superconducting Technology), but avoided placing the Af coils inside the superconducting shields. About the same time I got the idea of using a capacitive discharge circuit through a coil for producing controlled, unidirectional magnetic pulses for IRM acquisition, based on the use of a similar circuits in spot-welders and for re-magnetizing magnetotactic bacteria (Kalmijn and Blakemore, 1978; Kirschvink, 1983). I found it rather easy to attract top-notch undergraduate engineering students to work on these systems, and many of these open-source developments we made were later improved and marketed commercially (by both 2G Enterprises and ASC Scientific). I never asked for, nor received, royalties on these concepts, although they did occasionally give me a discount on the purchase price for such systems!

By mid-1995 we had the automatic rock-magnetic capabilities nicely under control, in which a single sample could be cemented to the end of a quartz-glass fiber, moved into position by stepping motors, and subjected to automatic Af demagnetization, and both IRM and ARM acquisition. It was amazingly useful (Kirschvink et al., 1997). However, all of our attempts at implementing automation for discrete paleomagnetic samples ran into the problem of how to pick them up, support them during the measurement process, and drop them off, all without adding more magnetic ‘junk’ from the sample support system into the measurement area of the magnetometers. As an undergraduate in molecular biology at Caltech I had used Beckman radiation counters that changed samples using a chain of 1” diameter plastic rings, and I was intrigued with the thought of adapting them to the problem of queuing up paleomag samples for measurement. We eventually obtained one of the old Beckman systems, ripped it apart, connected it to the stepper motor systems, and adapted it to hold the standard paleomagnetic samples.

At that point the major problem was how to pick up and hold the sample during the measurement process. We experimented with a complex ‘alligator-jaw’ system, activated by pulling a string, but the thing was more magnetic than most of our paleomagnetic samples and usually jammed. It was also not easy to bring under reliable computer control. Finally, one day I was using a vacuum cleaner in the lab and accidently grabbed a book with it, and was amazed at how tightly it was held. It struck me then that a thin-walled quartz-glass tube with a vacuum could do the same thing with paleomagnetic samples (typically cylinders 2.54 cm in diameter with flat ends), minimizing the holder noise and mechanical problems simultaneously. That concept has worked amazingly well, leading to the first prototype sample changer for what we now call the ‘Rock And Paleomagnetism Instrument Development’ (RAPID) consortium, which is described more completely in Kirschvink et al. (2008), with current plans and documentation updated periodically in the RAPID www site, http://rapid.gps.caltech.edu .

Post-2008 RAPID Innovations:

In the past 3 years, we have added a new system at the University of Johannesburg (with Nic Beukes and Michiel de Kock), and are part-way through completing them at Baylor University (for Dan Peppe), and the University of Edinburgh (for Jenny Tait & Ken Creer); all of these new units are built around the new vertical 2G Enterprises helium-free systems. In the process, we have made several substantial improvements beyond those reported in 2008, reducing the costs and increasing the speed and utility. These are described next.

Alternating-field demagnetization. As described by Kirschvink et al. (2008), the first 7 systems used the older Applied Physics Systems (APS) units for controlling the Af ramp cycles, but we discovered numerous bugs with them, including a digital to analogue (D/A) conversion system that is antique (introducing zig-zags in the calibration curves), and a tendency to throw off IRM spikes about 0.1% of the time. At the suggestion of Stu Gilder (of LMU, Munich), we have successfully modified a commercial, high-speed 24-bit D/A converter (AdWin Gold Lite™) to give us flexible control of the Af ramp cycle – it has the ability to control the output waveform at several hundred kHz, or hundreds of times per cycle, at the typical resonance frequencies of 300 to 1000 Hz. The system is fast enough to record the waveforms via their A/D voltage monitoring, and can do Fast Fourier Transforms (FFTs) rapidly enough to monitor waveform distortions. We modify the APS capacitor/relay boxes so that the high-current relays are controlled directly by solid-state relays activated by TTL signals from the AdWin units, the current is driven by the same Crest™ audio amplifiers operating in bridge mode, and the current is monitored passively with the same Pearson Electronics ‘green doughnut’ used in the APS system. However, we remove a small amplifier that the APS system uses to boost their monitor voltage, replacing it by a direct link to a differential voltmeter channel on the AdWin card. The RAPID software now allows each coil to be tuned to its peak resonance semi-automatically, and can also (via the FFT routines) determine the peak current flow before the waveform distorts or clips. As of this writing, it costs only about $6k (US) to convert an existing APS to run with this AdWin controlling unit, compared with over $30k (US) for one of the commercial controllers, and an entire Af system can be assembled (box, relays, amplifier, controller and all) for under $10K (US). Our former student, Isaac Hilburn, is almost solely responsible for bringing this under control and incorporating it flexibly into the RAPID software.

This Af system is now on-line at 4 of the RAPID magnetometer systems (one each at Caltech, University of Johannesburg, Baylor University, and the University of Edinburgh). The axial solenoid and transverse Helmholtz coil pair resonate at about 900 and 300 Hz, respectively, and can reach their non-distorting peak field levels in less than 0.1 second. The ramp-down rates can be controlled to produce approximately equal numbers of oscillations on both axes, and a total ramp cycle time of a few seconds is adequate to divide the coercivity spectrum up into thousands of slices. This rapid cycle time, coupled with less harmonic distortion of the main waveform, has drastically reduced problems with the coils overheating. Peak fields tend to be between 350 to 400 mT on the axial solenoid, and 100 to 120 mT on the transverse Helmholtz pair. Progressive demagnetization data from these systems is remarkably clean and linear compared with that produced by the previous systems.

The MIT group has implemented a simple thermal sensor pause intensive Af demagnetization cycles if the coils warm up too much; we have installed it on one of the Caltech systems and it is functioning nicely, although the batteries need replacing often if we forget to turn off the power switch.

Control of the IRM and ARM systems. The first of the RAPID systems used custom-made controlling circuits for IRM and ARM experiments that were designed and built by Caltech’s former electrical engineering technicians, Victor Nenow and Chris Baumgartner. Their circuits took computer-generated control voltages from 0-10V, and converted them to charging voltages of 0-450 V (for the IRM capacitors), or currents generating 0-2 mT fields in the ARM circuits (e.g., Kirschvink et al., 2008). With the retirement and departure of these technicians, however, we were forced to find suitable replacements. After an intensive search, I found a Japanese firm, Matsusada Electric Co. (www.matsusada.com), that makes small programmable power supplies for both, at a cost that was half that of having the EE technicians build them from scratch. (These are the Matsusada W3-0.5 P, with a 0-500 V output for the

IRM circuit, and the RK-80L, opt. -LRmf, for the ARM bias current; at the present time these cost about (US) $1300 and $800, respectively.) Recently, ASC Scientific Co. has incorporated the Matsusada 500 V supply in their impulse magnetizers (the ASC IM-100 unit), with a compatible interface connection for the RAPID consortium interface and software.

Automatic Hall-probe calibration of Af and IRM peak field values. One of the most important aspects of the RAPID system is to ensure that all of the coils and solenoids are properly calibrated relative to each other, and to absolute standards. For this, we have found that the Magnetic Instruments 908A Hall probe, with the axial and transverse sensors, is ideal. It communicates with the RAPID software via a USB connection, changing range and setting function automatically as needed. By folding the cable back along the axis of the probes, they can be positioned inside the 19 mm diameter quartz tube of the sample handler, with the Hall probe sensor positioned at the tube opening. Calibration values are written into a CSV-formatted ASCII file that can be viewed with Excel, and uploaded into the master initialization file for the RAPID system.

MatLab routines for analyzing data. Intensive rock-magnetic analyses (‘the Works’) can produce hundreds to thousands of data points per sample, depending on the number of experiments conducted and the patience of the user. Although these data are written in simple CSV-ASCII formatted files (*.rmg) that can be easily handled in data-base programs like Excel, we have found it much easier to handle data from large numbers of samples with a series of MatLab scripts. These (as well as the RAPID operating software) are available from links on the RAPID www site given above. Many thanks to Bob Kopp (now at Rutgers University) and others for continually improving these.

Status of Ongoing projects:

XY stage design. At the Fall 2010 meeting in San Francisco, members of the RAPID consortium had our annual working lunch to compare notes on the system, and make suggestions for improvements. Bob Kopp asked why we used a snake-chain, rather than a simple X-Y stage, to move the samples around (this had been suggested to him earlier by Brent Turrin at Rutgers). I was stunned. One of the most frustrating things about making the snake chain system is getting our machine shop to produce the hundreds of little plastic cups, the gears, and such, as it seems to always fall to the bottom of their interest list. The XY stage, on the other hand, is conceptually simple, and more compact. Samples trays can be made from ~30 x 30 cm square plastic sheets (or any other shape), can easily have 100 depressions machined into them, with a hole in the middle to allow access to the underlying rock magnetometer. The sample trays could be removed easily, so one can be loaded up separately while another is being used in the measurement process. These would need to be mounted on two orthogonal pairs of non-magnetic glides, positioned by two screw drives that are driven by small DC servo motors located a meter or so away. The software would simply need to know the location of each sample slot, and the central hole. Adding one additional servo motor to the systems is cheap and easy, given that we have already tamed the software to control them. The Baylor University and University of Edinburgh systems will have the first versions of these, and if they work well I may swap out the two at Caltech.

Horizontal sample changers. Although the RAPID software, with all of the automatic rock-magnetic and Af demagnetization functions, would work well in single-sample mode on horizontal systems, we have not solved the problem of how to change samples on them. This is important, as most of the superconducting magnetometers built by 2G Enterprises are horizontal systems, designed for running both single-samples and long-core measurements. Although some of the older instruments using the Sterling-cycle cryocoolers can be run either horizontally or vertically, the new pulse-tube instruments can only be run in one orientation. (The 2G-755 system at UT Austin was originally horizontal, and has worked very well in the vertical orientation.)

To achieve the low holder-noise, the horizontal sample changing systems will also need to have the vacuum support with quartz-glass tubes, and that means that the cylindrical samples must be held horizontally when being attached to the vacuum system. Unfortunately, I don't know how to do that. I am thinking that we might design a second vacuum system to grab the top of a vertical core and rotate it into a horizontal position, from which the quartz tube can home to the bottom of the sample, switch the vacuum attachment, retract the first vacuum assembly, do the measurement, transfer back to the top vacuum, and re-position the sample. Rube Goldberg would love it, but it makes me nervous.

Pulse-tube conversion of SRMs to replace the Sterling-cycle cryocoolers. Over the past decade, pulse-tube cryocoolers have been developed that – at least on paper – far exceed the cooling capacity of the Sterling-cycle cryocoolers that have been used on our superconducting magnetometers for the past 35 years. Indeed, 2G now only markets new instruments that are cooled with the pulse tube units, allowing them to operate entirely without liquid helium. They are virtually maintenance-free, with no moving parts in the cryogenic area. We have successfully modified the scanning SQUID microscope here at Caltech to run on one of these systems, and so have first-hand experience with their use.

Unfortunately, there are over 100 older superconducting rock magnetometers that the community still depends upon that use the old Sterling-cycle cryocoolers, and have periodic maintenance problems like cold-head swap-outs. My dream, after 35 years of dealing with this on 3 separate magnetometers, is to be able to simply retro-fit a pulse-tube system to the access port on a SRM and have it function at least as well as the old system does. On paper this ought to work – the entire heat leak into one of 2G helium reservoirs is only a few mW (W. Goree, personal communication), whereas the cooling capability at 4.2 K for commercial pulse-tube systems (e.g., the CryoMech PT-403) is measured in several hundred mW. I have tried this so far with no success, on our old 2G 760 unit (serial #001). My approach is to make high-conductivity thermal links from the first and second stages of the Cryomech PT-403 system, to the corresponding first and second stage thermal contacts of the CTI stainless-steel Sterling-cycle ports that are built into the 2G magnetometers. The second stage only needs to reach 10 K to equal the hold time on the normal units, but I have failed miserably with this on my first two cryogenic engineering attempts. Any advice is welcome!

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