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Ice Dynamics and Surface Glaciology along US ITASE Traverse Routes in East Antarctica

Gordon Hamilton
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Final Report for Period: 09/2010 - 08/2011

Submitted on: 06/27/2012

Principal Investigator: Hamilton, Gordon S.

Award ID: 0440792

Organization: University of Maine

Submitted By:

Hamilton, Gordon - Principal Investigator

Title:

Ice Dynamics and Surface Glaciology along US ITASE Traverse Routes in East Antarctica

Project Participants

Senior Personnel

Name: Hamilton, Gordon

Worked for more than 160 Hours: Yes

Contribution to Project:

Dr Hamilton managed the UMaine component of this multi-institutional project. His major activities included planning field campaigns, participating in all field seasons, and coordinating data analysis and interpretion in conjunction with other US ITASE Principal Investigators. He served as the primary supervisor of a PhD student (Daniel Breton) who worked on this project. Dr Hamilton prepared results for publication and presentation at scientific meetings.

Name: Hughes, Terence

Worked for more than 160 Hours: No

Contribution to Project:

Dr Hughes participated in the preliminary interpretation of data collected during the first field season, and was involved in planning discussions for the second field season. Due to health and family reasons, he did not participate in field work as originally planned. Following completion of field activities, Dr Hughes continued to collaborate with US ITASE investigators on data interpretation.

Post-doc

Graduate Student

Name: Breton, Daniel

Worked for more than 160 Hours: Yes

Contribution to Project:

Dan Breton was a candidate for the PhD degree in Physics during the course of this project. Dr Hamilton was his primary adviser. The topic of Breton's thesis was firn properties across the Antarctic ice sheet. Part of this work included a detailed understanding of the physical causes leading to stratigraphic layering in observed in GPR profiles. He pursued his work with a detailed examination of firn depth-density profiles, derived from a high-resolution gamma attentuation profiling tool which he developed specifically for this project. Breton designed, fabricated, tested, and deployed two instruments during the ITASE field seasons (MADGE -- Maine Automated Density Gauge Experiment; and MABLE -- Mostly Automated Borehole Logging Experiment). He also published scientific papers and presented his results at scientific meetings. Dr Breton is now a postdoctoral research fellow at the Thayer School of Engineering at Dartmouth College.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

US Army Cold Region Researach and Engineering Laboratory

We collaborated extensively with Dr Arcone (US Army CRREL) in the analysis of high-resolution density data as it relates to radar profiling of firn stratigraphy. The collaboration included data processing and analysis. The UMaine field team (Breton, Hamilton) took the lead in field deployment of the CRREL ground-penetrating radar, and was involved in data analysis of the GPR data, and the extraction of snow accumulation rates. We also collaborated with Dr Arcone on the interpretation of firn stratigraphy. Dr Arcone was a member of Dan Breton's PhD thesis committee.

Other Collaborators or Contacts

We collaborated with other US ITASE principal investigators in the design of field experiments, as well as the joint analysis of data collected during the field campaigns.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Our principal research activities were the analyses and interpretation of high-resolution density and ground-penetrating radar data collected during two overland field traverses in East Antarctica. The design and operational deployment of our gamma-attenuating device was published in Journal of Glaciology. A two-part series of papers describing internal stratigraphy and pointing to the widespread occurrence of glaze surfaces (regions of zero accumulation) was also published in Journal of Glaciology. A manuscipt describing our design, development and operation of a novel ice-core melter system was recently submitted to Environmental Science and Technology. We also performed high resolution density scans of the top 150 m of the Inland WAIS Divide deep core, on the basis that accumulation rates at the WAIS divide are 3-4 times larger than along our EAIS traverse routes, which allowed us to assess depth-density evolution in different accumulation regimes.

Our primary educational activity was the advising of a PhD student working fulltime on the project (Breton). An undergraduate research assistant was also employed by the project. Hamilton incorporated ITASE research into his university-level courses, as well as into educational outreach activities.

Findings: (See PDF version submitted by PI at the end of the report)

See attached.

Training and Development:

The project provided Dr Hamilton with new experience in nuclear measurements of geophysical processes and materials, as well as the design and fabrication of field instrumentation. This experience included the advising of a PhD student in Physics.

Outreach Activities:

We made regular visits to local K-12 classrooms to describe our field activities and science investigations. Hamilton also gave numerous outreach talks on polar climate change to community groups across the northeastern US, and incorporated ITASE research into climate workshops organized for high school science teachers (hosted by the Climate Change Institute in spring semesters or 2009, 2010 and 2011, and the School of Marine Sciences in May 2010).

Journal Publications

Breton, D.J.; Hamilton, G.S., "Design, optimization and calibration of an automated density gauge for firn and ice cores", Journal of Glaciology, p. 1092, vol. 55(194), (2009). Published,

Spaulding, N.E., D.A. Meese, I. Baker, P.A. Mayewski & G.S. Hamilton, "A new technique for firn grain size measurements", Journal of Glaciology, p. 12, vol. 56, (2010). Published,

Arcone, S.A., R. Jacobel & G.S. Hamilton, "Unconformable stratigraphy in East Antarctica, Part I: Large firn cosets, recrystallized growth, and model evidence for intensified accumulation", Journal of Glaciology, p. 240, vol. 58, (2012). Published, 10.3189/2012JoG11J044

Arcone, S.A., R. Jacobel & G.S. Hamilton, "Unconformable stratigraphy in East Antarctica, Part II: Englacial cosets and recrystallized layers", Journal of Glaciology, p. 253, vol. 58, (2012). Published, 10.3189/2012JoG11J045

Breton, D.J., B. Koffman, A.V. Kurbatov, K. Kreutz & G.S. Hamilton, "Quantifying Signal Dispersion in a Hybrid Ice Core Melting System for Geochemical and Microparticle Analysis", Environmental Science & Technology, p. , vol. , (2012). Submitted,

Books or Other One-time Publications

Breton, D.J. & G.S. Hamilton, "Accumulation Rate Effects on High Precision Density Profiles of Antarctic Firn Cores", (2009). Conference Proceedings, Published
Bibliography: Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract C52A-06

Breton, D.J., "Investigation of Micro-mechanical Causes of Density Inversion in Polar Firn", (2011). Abstract Volume, Published
Bibliography: Eos, Abstract C33C-0660 presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec.

Web/Internet Site

URL(s):
http://gcmd.nasa.gov/getdif.htm?hamilton_0440792
Description:

Other Specific Products

Contributions

Contributions within Discipline:

We completed the design, fabrication, deployment, and documentation of a new gamma density probe. The new instrument offers several important advances over existing instruments, namely in improved vertical measurement resolution and faster sampling speeds. We expect the instrument will be of wide interest to polar glaciologists. Our second instrument for in situ logging is a relatively low-cost method for examining the physical characteristics of boreholes, and should have great utility among ice core researchers.

Contributions to Other Disciplines:

The design of our instrument led to some improvements in radiation shield design for containing radio-isotopes in extremely cold environments.

Contributions to Human Resource Development:

This project provided advanced research and training opportunities for a PhD student in Physics.

Contributions to Resources for Research and Education:

We increased our capabilities to conduct detailed measurements of polar snow properties through the design and construction of state-of-the-art equipment.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference

OPP-0440792 FINAL TECHNICAL REPORT

Firn density is a basic quantity used in numerous glaciological studies, such as the calculation of accumulation rates from shallow cores, the conversion of altimeter-derived elevation changes to volume- and mass-change rates, and understanding the physics of firn metamorphism from snow to ice. Manual in-field measurements of firn and ice density are notoriously difficult to make, have crude spatial (vertical) resolution, and are subject to potentially large uncertainties. The need for high precision and high resolution density measurements provided the motivation for our design and development of MADGE (Maine Automated Density Gauge Experiment). MADGE is a field-deployable gamma-ray density gauge, capable of operating on 2- or 3-inch firn/ice cores. It uses a relatively low energy gamma-ray from Americium-241 and operates in pulse mode (instead of current mode) which allows for better counting statistics. 241-Am is an ideal source because it is easily shielded, enabling safe operation, and relatively easily transported, meaning it can be shipped to/from the field. We deployed MADGE during two field seasons in East Antarctica, and have also operated it in our cold room at the University of Maine.

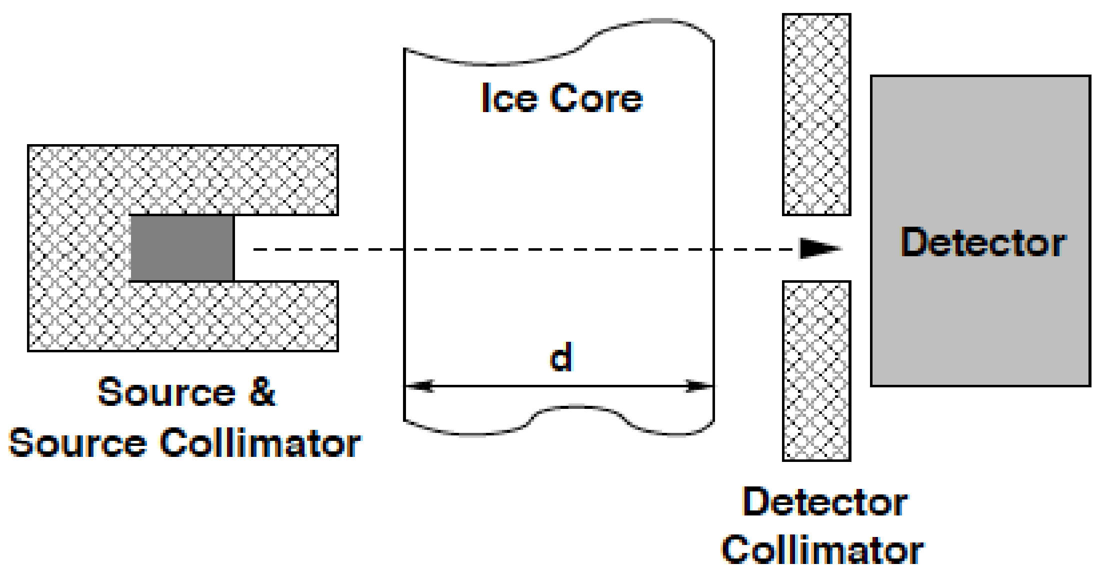


Figure 1. Cartoon schematic of a gamma-ray density gauge such as MADGE.

Gamma-ray profiling in a non-destructive method for sampling density (Figure 1), meaning the same core can be used for density studies and glaciochemical analyses. The instrument has only a few individual parts: (1) Gamma-ray source (2) Source and detector collimators to define the gamma-ray beam and the active measurement volume (3) Gamma-ray detector and associated electronics, and (4) Sample thickness calipers. A precise stepper motor moves ~1 m sections of core through the collimated beam. Beer's Law predicts the number of uncollided gamma rays which will pass through a sample of a given density and diameter, so by making simultaneous measurements of diameter (using the calipers) and gamma-ray counts (using the collimator-detector), we can solve for density (Figure 2). By optimizing the energy source and counting statistics for a granular matrix like polar snow, we were able to achieve high-precision throughput at a rate of ~1.5 m/hr for samples with densities of around 0.5 g/cm^3. In operational mode, vertical resolution is 3.3 mm, and each density determination has an uncertainly of only 0.004g/cm^3, far exceeding any existing instrument or method. The system is designed in such a way that vertical resolution and uncertainty can be reduced even further if necessary, the trade-off being slower throughput speeds.

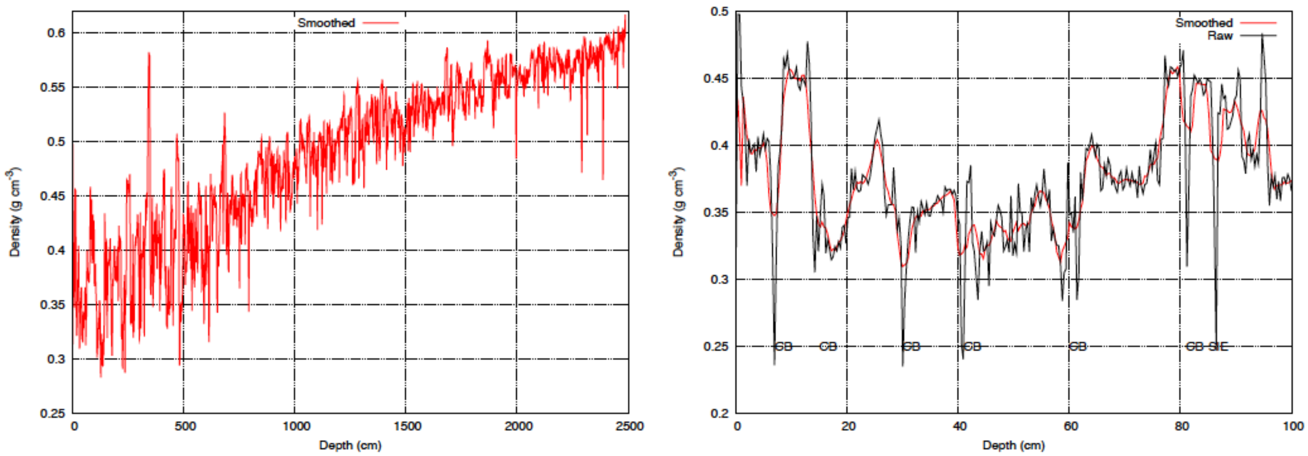


Figure 2. MADGE-derived density profile for a firn core collected at Taylor Dome, East Antarctica. The left-hand panel shows the entire 25 m record. The right-hand panel shows detail of the top meter.

MADGE is fully-operational and available for use by other investigators, either in our cold laboratory at UMaine or in the field (requires RSO concurrence from the home and temporary host institutions in order to ship the sealed source).

MADGE was used to profile several cores recovered at sites along the US ITASE traverse route in East Antarctica. A common feature of many density profiles was a zone of unconsolidated, low-density firn (~0.1 g/cm^3) ranging in thickness from 2-20 m. We interpret this material as depth-hoar, where persistent vapor transport due to wind moving through firn causes extensive post-depositional mass loss. Its occurrence in the density profiles provides confirmation for our interpretation of ground-penetrating radar (GPR) survey data in the same region, showing extensive echo-free (i.e., no detectable internal layering) zones in near-surface firn over large portions of the survey line (e.g., Figure 3).

The detection of depth hoar in our radar surveys is related to a complex interaction of ice flow over a rough bed which gives rise to a special kind of surface balance regime in East Antarctica (Figure 4). Depth hoar is observed in radar profiles collected in regions directly downflow of surface megadunes. These megadunes in turn are generated by subtle slope changes caused by ice flowing over bumps in the bedrock, which serves to alter the surface wind field and leads to preferential deposition/erosion of snow. Snow accumulates on windward sides of the dunes, while the leeward sides become glazed (Figure 3). Because the windward sides are permeable, katabatic winds are able to pump air into the firn, which scavenges moisture and

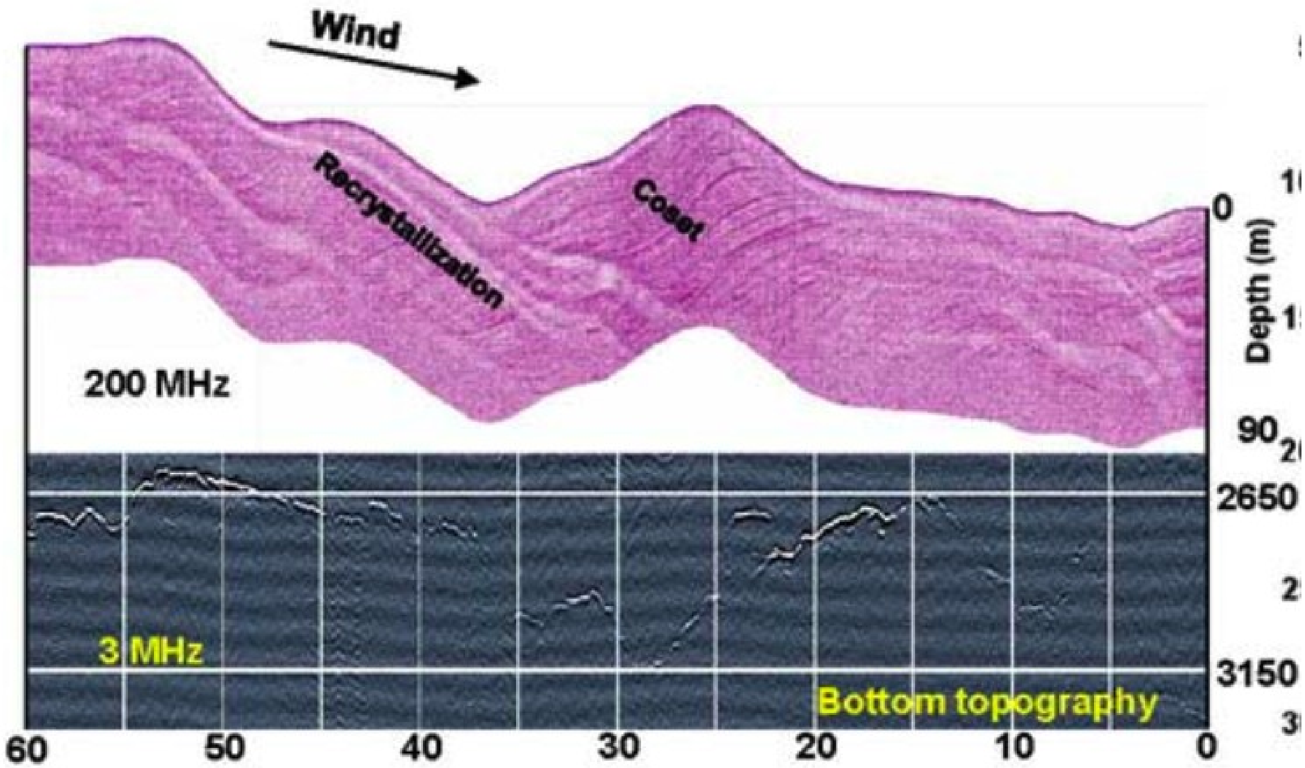


Figure 3. Ground-penetrating radar cross-section showing windward side accumulation, leeward glaze and buried zones of metamorphism, caused by ice flow over subglacial topography (bottom panel).

leads to the formation of depth hoar beneath the glazed surfaces. Snow accumulation on the windward slopes progrades over these recrystallized layers. The intense recrystallization eliminates density stratification, and the altered layers appear to thicken into a connected network. We modeled this stratigraphic formation using inferred wind and measured ice flow speeds and directions (from GPS surveys), and were able to reproduce the observed dimensions and morphology. However, model results require accumulation rates well above current regional estimates. The implication of this analysis is that accumulation is restricted to spatially-limited surfaces (windward slopes of megadunes), while much more extensive regions of East Antarctica have zero accumulation. This interpretation is significant, because it demonstrates current mass accumulation estimates for East Antarctica are likely to be in error. Any ice sheet mass balance estimates produced using the flux-in/flux-out method will propagate this error, hence are likely to be unreliable. Further analysis of our GPR and density data will help reduce this uncertainty and improve mass balance estimate reliability.

Designing a Gamma-Ray Density Gauge for Firn and Ice

Daniel J. Breton

Department of Physics and Astronomy & Climate Change Institute, University of Maine

Motivation

Manual in-field measurements of firn and ice density are notoriously difficult and are necessarily of crude spatial resolution. There is a need for high precision and high resolution density measurements in many important areas of glaciology:

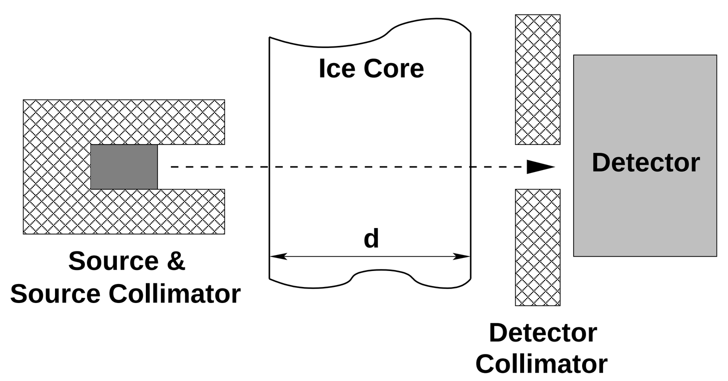
- Determining both long and short term accumulation rates in Antarctica
- Understanding the 'firnification' process: the metamorphosis of snow → firn → ice and effects on the climate records stored therein
- Modeling electromagnetic interactions with the firn for both ground penetrating radar and satellite-borne remote sensing studies

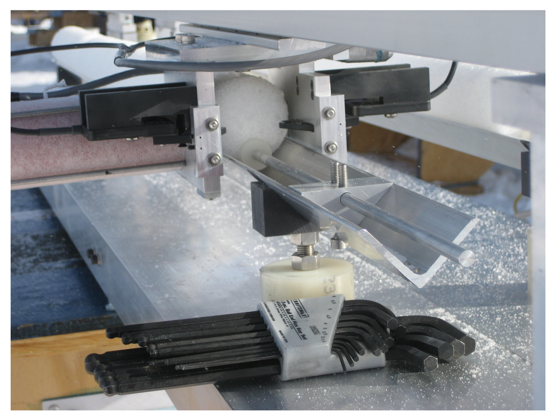
This poster outlines the design of MADGE: the Maine Automated Density Gauge Experiment which was designed and built at the University of Maine and subsequently tested over the course of two Antarctic field seasons as part of the International Trans-Antarctic Scientific Expedition.

Introduction to Gamma-Ray Density Gauging

A gamma-ray density gauge has only a few parts:

- Gamma-ray source
- Source and detector collimators to define the gamma-ray beam and the active measurement volume
- Gamma-ray detector and associated electronics
- Sample thickness calipers





If we count individual photons and use a monoenergetic gamma-ray, the *uncollided* number of gamma-rays C transmitted through the sample to the detector is given by Beer's Law,

$$C = C_0 e^{-\mu_m \rho d} \quad (1)$$

where C_0 is the count with no sample present, μ_m is the mass attenuation coefficient for the material, ρ is the density of the sample and d is the sample thickness. Solving for density, we obtain

$$\rho = -\frac{\ln(C/C_0)}{\mu_m d} \quad (2)$$

For a complete density measurement, we must measure C and C_0 with the nuclear counting system and d with electronic calipers. The mass attenuation coefficient μ_m is a function of the energy of the gamma-ray, the atomic number of the sample material and the geometry of the density gauge itself. This value therefore must be determined in the calibration process.

Optimization of Gamma-Ray Energy

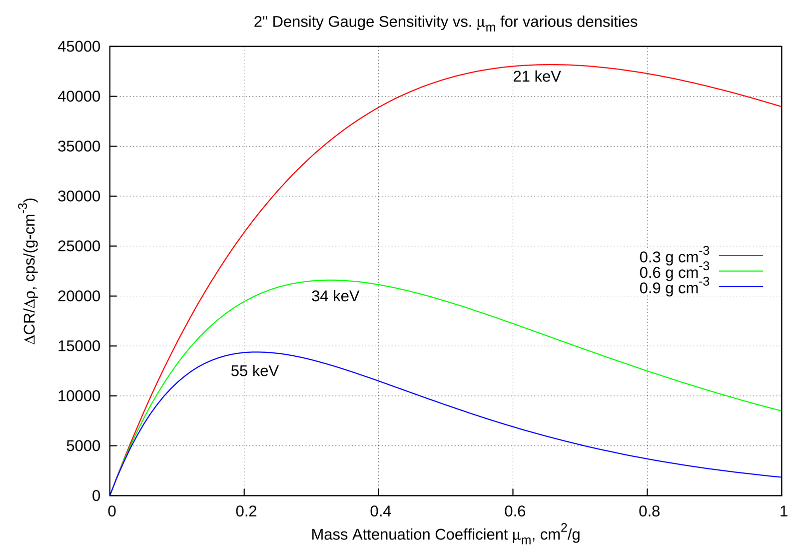
With Eq. 2 we have a straightforward relationship for determining the density. Assuming that the sample size (ice core diameter) and material (water) are known, there is only one unknown parameter left, μ_m, which is determined by the gamma-ray energy.

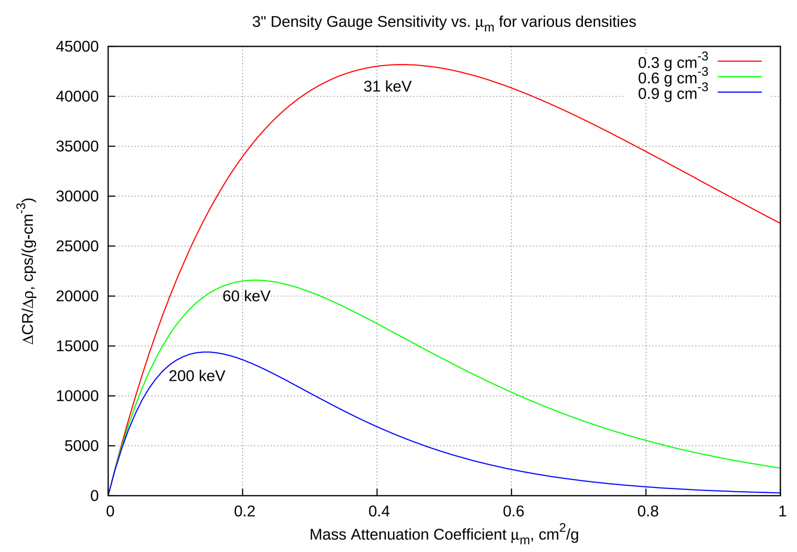
Let us define the *sensitivity* of the gauge with respect to density as

$$\frac{\partial C}{\partial \rho} = -(C_0 \mu_m d) e^{-\mu_m \rho d} \quad (3)$$

This shows that the sensitivity

- Depends on ρ, d and μ_m
- Has a functional xe^{-x} form and therefore has a maximum
- Gives us an optimum energy for a given material and sample size





MADGE was designed to operate primarily on 2 and 3 inch firn and ice cores, therefore we chose the 59.5keV gamma-ray from ^{241}Am, the same radioisotope commonly used in residential smoke detectors.

Measurement Uncertainty

All measurements have some uncertainty associated with them, and the density gauge is no different. Beginning with Eq. 2, we apply standard error propagation techniques:

$$(\Delta\rho)^2 = \left(\frac{\partial\rho}{\partial \ln(C/C_0)}\right)^2 (\Delta \ln(C/C_0))^2 + \left(\frac{\partial\rho}{\partial d}\right)^2 (\Delta d)^2 + \left(\frac{\partial\rho}{\partial \mu_m}\right)^2 (\Delta\mu_m)^2$$

$$= (\text{Nuclear Term})^2 + (\text{Thickness Term})^2 + (\mu_m \text{Term})^2 \quad (4)$$

$$= \left[\frac{1}{d^2\mu_m^2}\right]\left[\frac{1}{C} + \frac{1}{C_0}\right] + \frac{\ln^2(C/C_0)}{d^4\mu_m^2}[\Delta d]^2 + \frac{\ln^2(\frac{C}{C_0})}{\mu_m^4 d^2}[\Delta\mu_m]^2$$

These relationships show that for a given sample thickness and mass attenuation coefficient, we can minimize $\Delta\rho$ by making C and C_0 as large as possible.

How long will we have to wait to collect those counts? This depends on the source strength, density gauge geometry and materials and the sample density itself.

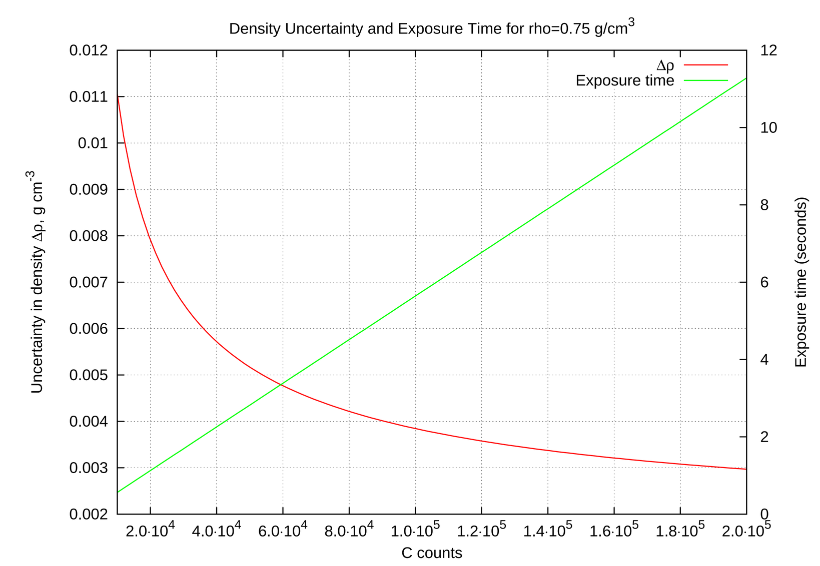
Our goals: $\Delta\rho \leq 0.004 \mathrm{g/cm^3}$ and a throughput of more than 1 m/h at 3.3mm measurement spacing.

Determining Source Strength

Using a 2 inch core as an example, we can determine the following:

- Fixed geometric efficiency $\frac{A_{beam}}{4\pi r^2} \approx 1.16 \times 10^{-4}$
- Variable losses associated with sample (19% to 62% loss)
- Fixed losses in instrument structure and air (25% loss)
- Combined, transmission of 3.34×10^{-5} from source to detector for maximum density sample ($0.917 \mathrm{g/cm^3}$)
- $(100\mathrm{mCi})(0.36 \gamma/\mathrm{dis})(3.7 \times 10^7 \mathrm{Bq/mCi})(3.34 \times 10^{-5}) = 4.47 \times 10^4 \gamma/\mathrm{sec}$.
- This count rate is sufficient to meet our statistical needs (shown below) but is not so high that our detection system suffers dead time losses.

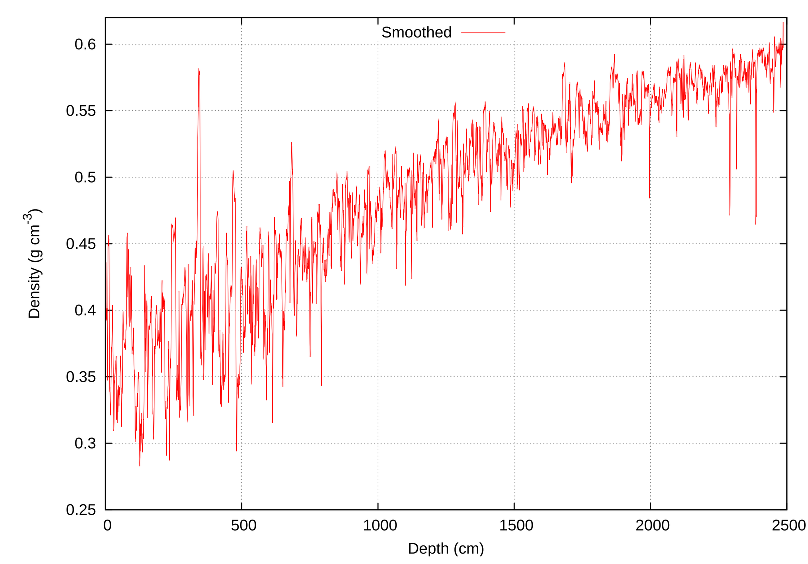
If we choose $C_0 = 1.5 \times 10^6$, then we can plot $\Delta\rho$ and count time for a representative sample density and various values of C:

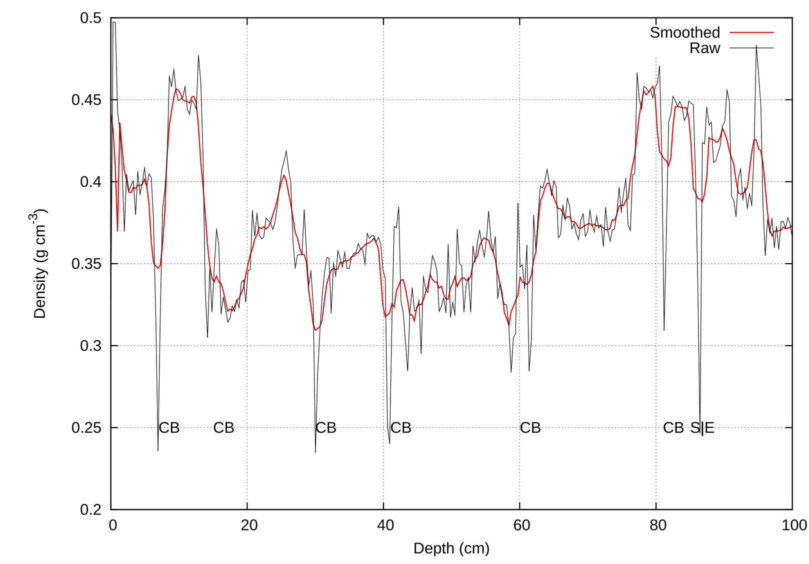


At this point, we must decide on a compromise between speed and accuracy. MADGE typically operates at $C = 1.5 \times 10^5$ which yields a throughput of 1.5 m/h at $\rho = 0.5 \mathrm{g/cm^3}$.

MADGE data from East Antarctica

The following figures show examples of the density profiles obtained from a 2 inch diameter, 25m deep ice core recovered near Taylor Dome.





Conclusions

- Density gauge design is based on complicated relationships between sample and instrument geometries, sample material, desired precision and throughput specifications
- Optimized values of gamma ray energy can be determined to help in choosing a source radioisotope

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