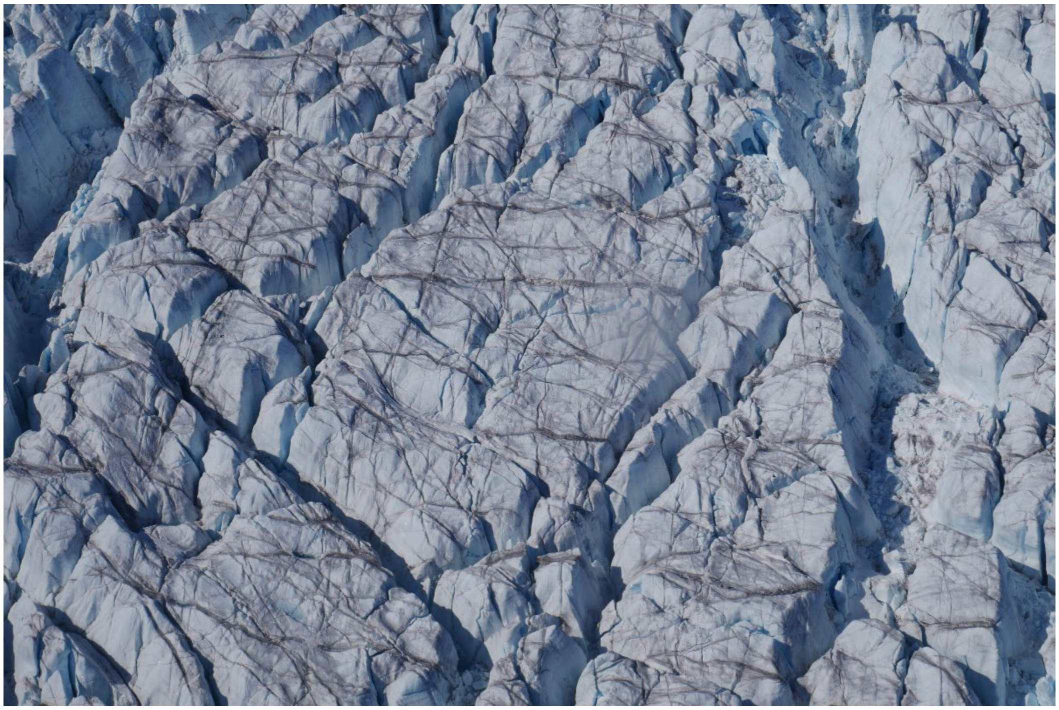
2023 Crevasse Webinar Series Review



Credit: Thomas Chudley

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Introduction

The U.S. National Science Foundation (NSF) hosted a Crevasse Webinar Series between March 27 and April 6, 2023. This four-part webinar series focused on using technology to increase the ability to detect crevasses, an essential need while doing fieldwork in rapidly changing, ice-laden landscapes. This webinar series evolved from discussions held during the NSF-sponsored Crevasse Risk Management and Safety Workshop in June 2021. The four webinar topics were: 1) Using Modeling to Predict Where Crevasses Form, 2) Using Drones, Automated Radar Collection and Other Techniques in the Field to Detect Crevasses, 3) Using Satellite Imagery and Remote Sensing for Crevasse Detection, and 4) Automated Detection of Crevasses from Remote Sensing. Each webinar had between 25 and 40 participants from academic, government and logistical providers and was facilitated by a panel of experts in these fields.

Using Modeling to Predict Where Crevasses Form

The modeling webinar focused the current state of modeling capabilities with panelists Ching-Yao Lai (Princeton University), Ellyn Enderlin (Boise State University) and Tim Bartholomaus (University of Idaho). The distribution and size of crevasses from such models are useful in research aimed at better understanding the evolution of dynamics and stability of polar ice sheets and impacts to sea level rise, as well as for use in operational and safety scenarios for personnel working in crevassed areas. The goals of modeling crevasse formation in order to answer science questions versus operational needs are different; modeling at higher spatial and temporal resolution is needed for operational purposes, and typically operational needs have lower tolerances for error. The discussion focused on the needs and limitations of current models, and presented priorities for improvements which if implemented, could be used to predict crevasse formation and ultimately to support safety and mapping in crevassed areas. The panelists agreed that existing models are not at the point where they can be relied on for safety purposes due to a lack of theory for certain fundamental processes (i.e., advection of crevasses from upstream regions and ice rheology evolution), limits in spatial resolution, and a paucity of observations for both model input and validation. Developments for the models themselves as well as validation datasets from remote sensing and ground truth, field-based observations are needed.

The most commonly used models of crevasse formation are based on Nye's derivation of perfect plastic approximation (Nye, 1951, 1952, 1953) and linear elastic fracture mechanics (LEFM) models. Typical crevasse theory must assume both the stresses as well as the stress criteria needed to form a crevasse as in-situ observations are not feasible. Often, strain rates are used as a proxy for stress, but these don't always align. Also, these methods model crevasse location and geometry (i.e., depth) based on discrete observations. Using this approach, the assumption is made that velocity doesn't change seasonally, which doesn't hold as well in places such as Greenland where seasonal changes can be large. Another issue with traditional modeling approaches is that the inheritance of ice properties and crevasses from upstream areas (advection) is not valid in areas outside of ice shelves. The inheritance issues can change the rheology of the ice, i.e., crevasses change over time after initiation, and traditional models don't take that into account. Related to this issue, areas of complex flow are harder to model, especially when ice flows from area of high strain rate to low strain rate. Observations of crevasse location and geometry are dependent on the resolution of remote sensing imagery and parameters derived from satellite imagery (e.g., strain rate estimates) are sensitive to image quality, terrain effects, and observation geometry (Zhao et al., 2022). Additional in situ and remote sensing analyses are needed before Nye and LEFM models can be considered predictive (Enderlin and Bartholomous, 2020).

In addition to more traditional modeling methods, damage fracture approaches as well as methods examining the distribution of crevasses within a strain-envelope (Vaughn, 1993; Kaluzienski et al., 2019) were discussed. Damage fracture methods are currently on too small of a scale, extent-wise, to be useful, and require some model development to up-scale. Approaches applying a strain rate envelope can typically be applied in only one location due to variation in ice and basal properties as well as the issue of advection of ice and crevasse features from one location to another through ice motion. The strain envelope approaches also rely heavily on estimation of strain rate derived from satellite imagery which are subject to uncertainty in satellite imagery analysis and are compounded as a derived product.

The panelists discussed the largest sources of uncertainty in the various modeling approaches, roughly in order of priority 1. Advection, or the inheritance and history of crevasses at a specific site; 2. Ice rheology; 3. Temperature structure; 4. Strain rate; 5. Basal properties; 6. Coupling of fracture mechanics and flow dynamics to understand how rift occurs; 7. Observations of crevasse distribution, crevasse properties, and ice flow estimates from satellite imagery; 8. Site to site variability, and related, seasonal variability at given sites.

One concern about the use of modeling approaches to develop crevasse maps to be used for safety that was raised was the concern of liability, particularly since the resolution of current modeling approaches is not good enough to address all safety concerns. Disclaimers describing the limitations of models (i.e., "the absence of evidence is not the evidence of absence") and the need for proper training in a multi-faceted approach to reducing risk, i.e., the use of models in an approach that includes satellite imagery analysis, ice motion and terrain analysis, and use of ground penetrating radar and traditional mountaineering techniques in the field areas was discussed. One participant noted in the chat, "That ethical question of detection problems where false negatives can have large consequences know many parallels in medicines—the disclaimers are indeed important but should not withhold creation of a product."

Specific recommendations from this session include:

- There is a need within the modeling community to improve current models, with damage fracture modeling showing a lot of promise in terms of being able to create models that include advection and are not as site-specific (Technical/Research).
- There is a need for more observations and data that can be used in validation. One low-hanging objective mentioned in this session of the webinars as well as others is that current operational data sets, primarily generated at the Cold Regions Research and Engineering Lab (CRREL) and including manually digitized crevasse locations from satellite imagery as well as labeled ground penetration data, are potentially useful for model development and validation (Technical/Research).
- There is also a need to define the operational needs including timing, location, extent, and size of crevasses that need to be detectable in a model (Logistical).
- Training in terms of risk mitigation in operating in crevassed areas is needed (Training/Policy).

Using Drones, Automated Radar Collection and Other Techniques in the Field to Detect Crevasses

The use of automated airborne- and ground-based data collection and processing to detect crevasses webinar featured panelists Austin Lines (CRREL), Laurent Mingo (Blue Systems Integration) and Seth Campbell (University of Maine). This webinar focused primarily on the current state and recent developments in drone technology as well as limitations and challenges to employing drone technology. Some of the main advantages of using autonomous drones or rovers in a field situation are increased safety by removing a human operator from having to traverse hazardous terrain to collect data and the ability to collect higher resolution surveys compared to ground-based (human collected) or satellite-based imagery. Drones are particularly useful in research in shear margins and other dangerous areas to determine basal and rheology properties at high resolution. Additionally, they have the capability of being near real-time, which is extremely challenging with satellite-based platforms and modeling. As with the remote sensing discussion, one collection platform is unlikely to work in all scenarios, and a platform with several options (e.g., ground-based, drone-based, helo-based, aircraft-based, tethered) is likely to be the best solution.

The major issues discussed in this webinar were technological issues in employing automated collection techniques, i.e., unmanned aerial vehicles or rovers, data issues involving the transfer and processing of data, and need for training. In terms of drones, the main technical issue is power, in addition to the potential for crashes, getting stuck and other mobility failures. These technical issues are likely to be solved in the near future with possible solutions such as hybrid drones, tethered drones, and terramechanics options currently being developed and/or available commercially. Limitations for flying heights due to Federal Communications Commission regulations, typically restricting radar flights to 1m, were also discussed, as well as instrumentation issues, e.g., magnetometer and radar interference from heavy metal objects. As with the modeling discussion, the operational need for automated data collection needs to be defined in order to develop an efficient drone-based or rover-based platform. For example, one outstanding question is whether the use of drones would be most efficient as a means of real-time data collection and crevasse detection, or in a pre-deployment scenario where data can be collected and then processed ahead of a field campaign. The use of drones in research campaigns versus operational support was also discussed. Drone use can dramatically increase the extent of surveys that can be completed, as well as the spatial and temporal resolution of the data that can be collected. However, very high temporal and spatial resolution, can increase data processing needs enough to cause inefficiencies, and is not always needed in areas that are traversed infrequently.

Managing and processing data is another issue that was discussed, as drone and rover-collected data increases the number of data sets generated in the field and consequently the time and effort needed to process those data. Automated data processing tools have been developed and are currently in the process of being operationalized.

Other concerns about the use of drones or rovers in an operational context are the additional resources needed for pre-deployment use as well as the extra people needed in a field party to support drones and GPR analysis. Currently, drones and rovers are advanced and simple enough that they can be operated by anyone in a field party and do not necessitate a dedicated operator. However, the interpretation and processing of radar data is harder and does require an expert with training in crevasse detection and surveying techniques.

Alternatives to autonomous drones and rovers discussed include helicopters and the Herc-based crevasse detection X-band SAR radar that was developed by Sandia circa 2010. The advantage of the more traditional air-borne platforms are that they are more reliable without the power, mobility, regulation, and weather restrictions, but do not afford the flexibility of an autonomous collection platform that can be operated in the field.

Specific recommendations from this session include:

- Training is needed for field parties in a holistic approach to field safety in crevassed areas using radar (Training/Policy).
- Definition of ideal mode (real time vs. pre-deployment) and/or needs for autonomous platforms (Training/Policy).

- Many technical hurdles, power, mobility, automated data processing, data transfer, seem close to having solutions (Technical).

Using Satellite Imagery and Remote Sensing for Crevasse Detection

The panelist for the satellite imagery discussion were Leigh Stearns (University of Kansas), Eli Deeb (CRREL), Oliver Marsh (British Antarctic Survey) and Dan Price (University of Canterbury). The discussion focused on limitations and capabilities of current remote sensing data as well as new instruments with the potential to increase reliability of remote sensing-based methods. One common theme in the discussion is that no one instrument or type of data can work in all situations, optical gets good surface features while radar allows for penetration into snow bridges and buried crevasses. The best approach is to combine several types of data including radar (SAR), optical, interferometry, and ground-based methods, i.e., seismic (particularly when identifying thermally-induced cracks), velocity and shear analysis.

The panel discussed available imagery in terms of visible (Landsat, Sentinel, WorldView), radar (TerraSARX, Radarsat), and altimetry (ICESat, LiDAR) data commonly used now. Upcoming new satellite missions including Pleiades (optical) and Capella (X-band SAR radar) that would have spatial resolutions of 10 cm, compared to the 30 cm resolution of current satellite imagery. Current needs for remote sensing imagery are 1-m or less spatial resolution for individual crevasses; larger resolution imagery can see damaged areas but not individual crevasses. There is a temporal difference between ideal optical and radar collection times that must be considered when tasking new collections. For optical imagery, summer collections are needed in order to capture collapsed or visible bridges. For radar imagery, winter collections are ideal to minimize melt and liquid water. Look direction and sun conditions are also important (have to be perpendicular versus parallel to sensor track with radar imagery, and need sun angle correct for optical imagery). It is ideal to try to identify a cross orbit to get at least two viewing geometries, but that is not always possible. UAV's/airborne become more critical in those cases. The availability of radar imagery was another issue that was discussed. For example, Sentinel-1 with a repeat cycle of 12 days is readily available but does not have the resolution required for identifying individual crevasses. TerraSAR-X has the capability for individual crevasse detection but does not have regular global coverage and is not publicly available. There is a need for airborne assessments from plane, helo or UAV support to get the temporal and spatial resolution required. Consideration of radar frequency is also important. For example, L-band and S-band, which allow deeper penetration (up to 30 m) versus X band (up to 10 m observationally). The upcoming NiSAR mission with dual frequency could determine crevasse bridge depth, and will cover Antarctica and margins of, but not interior, Greenland. Also of note from a navigational perspective is that there can be a crevasse location offset due to sensor viewing geometries/absolute position.

In-situ data are needed to help improve the interpretation and analysis of satellite imagery, particularly of radar satellite data, and include crevasse geometry information, snow properties (e.g., density) and the seasonal variation of these properties. The lack of snow property data is an issue also brought up in an earlier session and is further needed in terms of safety and risk assessment for crevasse crossing criteria determination. GPR data is a useful tool for determining crevasse location, depth and bridge information, but is not a full substitute for manual measurements. There is also a need for more training data for machine learning methods.

Synthesis of sensors and techniques is needed. Identifying features and merging sensors is pervasive research question that covers a lot of earth science. No current standardized method exists, and the panelists recommend developing a community paper. There is also a need for international cooperation and data sharing as part of this effort. The methods will be evolving, so some consideration for updating methodology/SOPs being developed should be included. NSF is trying to standardize imagery collection at the proposal stage, with the imagery collection and analysis occurring for any field campaign on an ice sheet. There has been some work towards automation of crevasse detection from satellite images but it remains challenging for the scales that are needed for operational use. This is further discussed in the final session.

Specific recommendations from this session include:

- Synthesis of sensors and techniques needs to be developed, and airborne and ground-based data are needed to validate interpretation of satellite imagery and instrumentation. There is a need for resources to merge and use this information that does not currently exist (Technical/Research).
- There is a need for snow property information to help interpret radar imagery in particular, and to address both the need for spatially as well as temporally varying snow properties. Field groups working in crevassed terrain could collect data to help with this effort (Technical/Research).
- Training in terms of a holistic approach to risk mitigation using satellite imagery and ground-based methods (e.g., GPR, manual measurements) (Training/Policy).
- More open science and more open data (Policy).
- Development of software tools and machine learning tools is needed (Technical).
- Community paper determining and outlining standardized data synthesis methods. There is also a need to coordinating targets and knowledge gaps and should involve international coordination across academic, government and logistical providers/safety personnel. Note that this will be an evolving methodology as new sensors and techniques become available (Technical/Research/Policy).

Automated Detection of Crevasses from Remote Sensing

Panelists for the session discussing the use of automated crevasse detection from satellite imagery included Matt Siegfried (Colorado School of Mines), Joanna Millstein (Massachusetts Institute of Technology / Woods Hole Oceanographic Institution), Shane Grigsby (Colorado School of Mines), Gabe Lewis (University of Nevada, Reno), and Ching-Yao Lai (Princeton University). This session focused on current limitations of crevasse detection in satellite imagery, possible solutions, and data and processing limitations and solutions. As with the other sessions, the need for defining the level of resolution for operational purposes (i.e., extent of area and size of crevasses) was discussed.

The main technical and research issues that were discussed were the resolution of current available satellite imagery, snow-buried crevasses being difficult to detect, and designing a data pipeline. Infrastructure is very important, particularly at the spatial resolution needed and time series of data that are needed. Upcoming high resolution satellite missions have the potential to greatly increase the ability to detect smaller crevasses, but there is a need for frequent imagery collection to capture formation in dynamic areas. There is a need to combine several types of datasets collected from multiple platforms, i.e., remote sensing and ground-based radar data, but this type of data fusion is difficult. The challenge is to make sure that datasets are precisely co-registered. Small geolocation offsets will be a real issue for this kind of fusion. Airborne collections with multiple sensors installed are useful for cross-validation of datasets. There is also a need for high spatial and temporal resolution data due to changing conditions.

In terms of using automated detection methodology, snow covered crevasses present a particularly challenging issue since they are only visible in radar imagery, which has its own set of limitations (i.e, need to consider viewing geometry and snow properties). Visible crevasses in optical imagery also pose their own unique technical issues depending on the resolution and weather conditions during imagery collection. The parameters of the crevasse that are most relevant for science and logistical considerations also have to be defined including orientation, aspects, widths across the crevasse, and what a specific concept outline for a crevasse actually is. And finally, in order to scale up current methods, more observations are needed.

The session included a discussion of machine learning techniques specifically, including questions posed about what automated means, how datasets are generated for machine learning, how to automate the generation of datasets, how to generate useful crevasse information, and how to define what useful crevasse information might be, e.g., crevasse width along the crevasse span, and crevasse depth. Concern over properly developing training data was raised, for instance, not training machine learning algorithms solely on visible crevasses from optical imagery since many crevasses are buried. One approach suggested is to manually tune machine learning algorithms using other techniques, like edge detection. Important considerations are that manual methods are time consuming and can't be applied to the continent scale, traditional methods remain important to tune the machine learning approaches, and it is important to quantify and report biases of the methods and to define what is needed for accurate methods.

Finally, the need for improved storage and processing of satellite data was discussed. Remote sensing datasets are often large and as projects are upscaled to include more area, the computational expense and storage capacity becomes unfeasible for local systems. The importance of migrating data and associated algorithms to the cloud and building modernized data and processing pipelines was stressed.

Specific recommendations from this session include:

- Need for coincident observations of LiDAR, radar, optical, and potentially seismic (for definition of thermally induced cracks) data along with strain rate information (Technical/Research).
- Labeled GPR data for training data sets are potentially very useful for machine learning approaches (Logistical).
- Need to define crevasse metrics/outlines with a common definition (Logistical).
- Need to define operational concerns in terms of crevasse widths that are safety issues, along with the locations needed. In addition, the error and definition of how accurate the models need to be must also be defined (Logistical).
- Design/develop a data pipeline up-front and in the cloud, potentially partnering with cloud providers. Make current remote sensing data downloading more efficient. There are some new resources available that are potential models of how this can be done, e.g., cryocloud, access-ci.org (jetstream) (Logistical).
- Develop a data processing methodology that addresses common start-up issues amongst new users (i.e., making an area of interest) to eliminate common hurdles when first using remote sensing imagery tools. Develop lists of common problems to avoid in image processing steps, e.g., image edges being flagged in edge detection algorithms. Include instruction in current remote sensing, glaciology classes (Logistical/Training/Policy).

Common Themes and Needs

- Training focused on field-based and remote crevasse detection equipment and software is vital for performing science safely on the ice. There is a need for more people with abundant crevasse detection expertise, so short and long-term training methods need to be established. The oceanographic community used to use "training cruises" for training chief scientists and might be a possible avenue for lessons on training individuals in for this space. One panelist stated that from a safety perspective, putting money and resources into training is the best option.

There needs to be continued evaluation of how communication between logistics and science, as well as between countries, considering risks and approaches, occurs.

- All four webinar audiences discussed a desire for more access to crevasse data to increase models, software and training resources. However, there are concerns about the liability issues with sharing data, as there are many disclaimers needed to accompany the data especially for those interested in accessing this data regarding assessing field site safety. This discussion should continue in the future about what data could be shared more openly and in what capacity, and how those providing the data can do so without liability concerns. In addition to more open data needs, there was also a common thread of the need for more open science development and similar coordination between international logistical and operations groups working on safety issues in crevassed areas.
- Operational versus research constraints and needs differ in terms of the spatial and temporal requirements for input data as well as instrumentation and logistical needs in terms of technology.
- Need to define safety concerns in terms of crevasse risks (e.g., width of crevasses, snow bridge properties) and the allowable error and detection limits of technological solutions.
- In response to the discussions across the webinars, ideas for future actions include hosting additional webinar series, consolidating training opportunities, and holding a field safety centered town hall or open hour at future American Geophysical Union (AGU) Fall meetings. One future webinar series could focus specifically on brainstorming short and long-term training ideas, recruitment into the field of crevasse detection, and what funding could be available for such endeavors. Before this event, a shareable document could be created to share current crevasse detection training opportunities or future ideas. Another webinar series could focus on data management and sharing with community, and the liability concerns. At future AGU Fall meetings, NSF could request time in the ARCUS rooms to hold an event focused on crevasse safety or field safety in polar regions in general, led by the science community, NSF, Battelle ARO and others. As crevassing becomes an even bigger concern in the polar regions, the field community at large needs to come together to pool resources and expertise to advance detection and safety in these environments.