BedSAT: Antarctica

Exploring what lies beneath using big data and modelling

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Impact Statement

Antarctica's bed topography data currently has local uncertainties of hundreds of meters in elevation due to sparse and unevenly distributed radar surveys, significantly limiting our ability to predict ice sheet behaviour and sea level rise contributions. Through the BedSAT project, I am developing a novel modelling approach that integrates remote sensing data and airborne-derived estimates, with mathematical and numerical ice flow models to substantially improve bed topography resolution and accuracy. I aim to derive a continent-wide bed topography dataset and conduct sensitivity analyses of dynamic ice loss to different realisations of topographic roughness through 2300CE. My work will quantify how bed topography uncertainties affect ice mass loss projections. This improved understanding can provide more reliable sea level rise predictions, and enable evidence-based policy decisions for climate adaptation strategies. This open-source approach and FAIR data principles will ensure these improvements benefit the broader scientific community and support more effective climate change mitigation planning.

Contents

Antarctica's Landscape

1.1 Climate Impacts and Global Significance

The polar regions are losing ice, and their oceans are changing rapidly [1]. The consequences of this extend to the whole planet and it is crucial for us to understand them to be able to evaluate the costs and benefits of potential mitigation.

Changes in different kinds of polar ice affect many connected systems. Of particular concern is the accelerating loss of continental ice sheets (glacial ice masses on land) in both Greenland and Antarctica, which has become a major contributor to global sea level rise [1]. Impacts extend beyond direct ice loss: as fresh water from melting ice sheets is added into the ocean, it increases ocean stratification disrupting global thermohaline circulation [2]. In addition, cold freshwater can dissolve larger amounts of CO_2 than regular ocean water creating corrosive conditions for marine life [1].

While there is high confidence in current ice loss and retreat observations in many areas, there is more uncertainty about the mechanisms driving these changes and their future progression [3]. Uncertainty increases in regions with variable bed conditions, where characteristics like "slipperiness" and "roughness" are difficult to verify via direct observations. Other problematic areas involve the ice sheet's grounding line (GL), the zone that delineates ice grounded on bedrock from ice shelves floating over the ocean. The retreat rate depends crucially on topographical features like pinning points [3], which lead to increased buttressing by the ice shelf on the upstream ice sheet. Although this mechanism is established, major knowledge gaps persist in mapping bed topography across Antarctic ice sheet margins - with over half of all margin areas having insufficient data within 5 km of the grounding zone [4]. Addressing this data gap through both systematic mapping and improved interpolation utilising auxiliary data streams with more complete coverage would significantly improve both our understanding of current ice dynamics and the accuracy of ice-sheet models projecting future changes.

Topography of Antarctica

Bed topography is one of the most crucial boundary conditions that influences ice flow and loss from the Antarctic Ice Sheet (AIS) [5]. Bed topography datasets are typically generated from airborne radar surveys, which are sparse and unevenly distributed across the Antarctic continent (see figure 2.1). Interpolation schemes to "gap fill" these sparse datasets yield bed topography estimates that have high uncertainties (i.e. multiple hundreds of metres in elevation uncertainty; Morlighem et al., 2020) which propagate through simulations of AIS evolution under climate change [6]. Given the logistical challenges of accessing large parts of the Antarctic continent, there is a crucial need for alternative approaches that integrate diverse and possibly more spatially complete data streams – including satellite data.

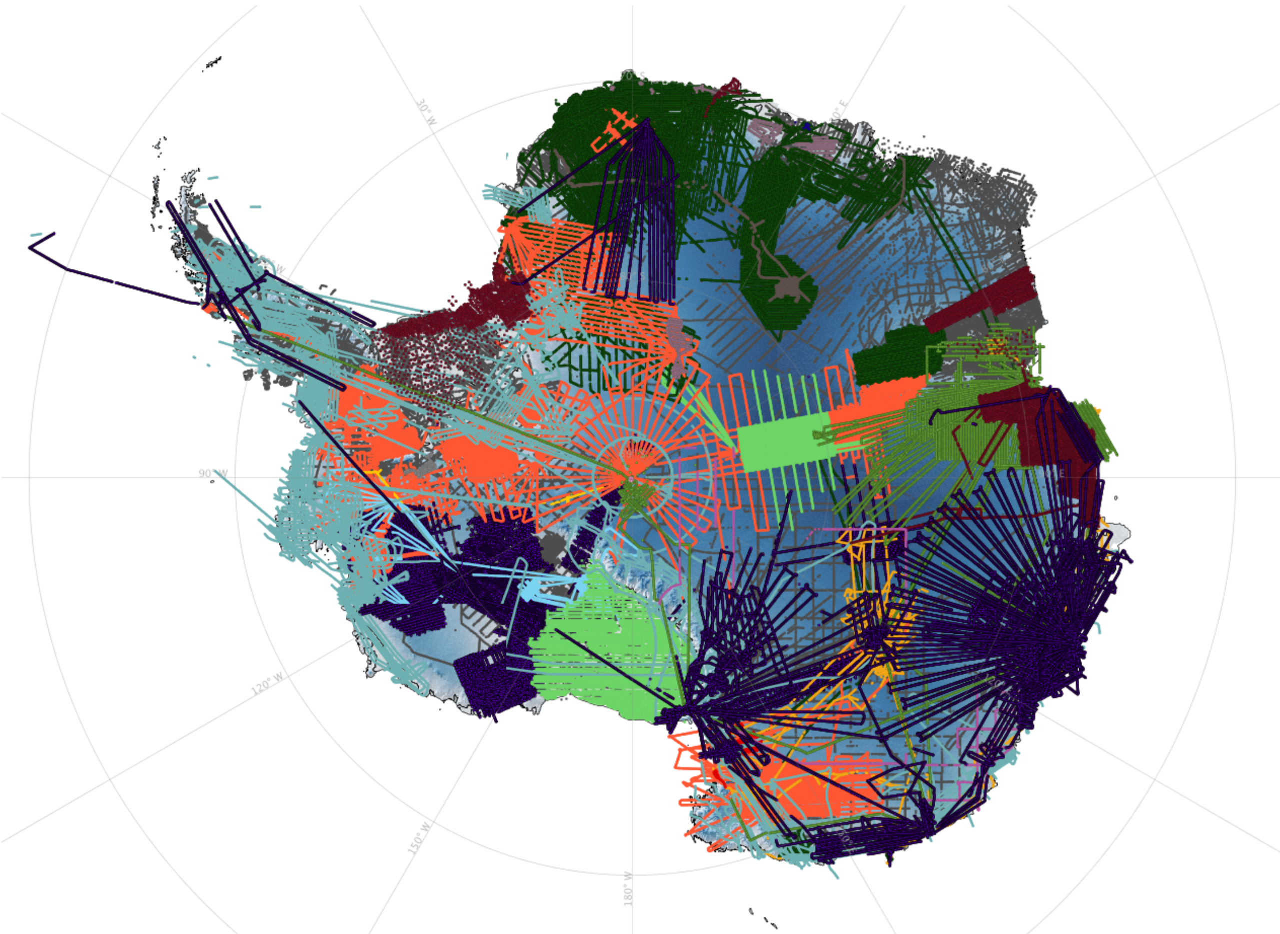

Figure 2.1: Distribution of BedMAP{1,2,3} data tracks (Source: bedmap.scar.org).

2.1 Approaches to Bed Topography Reconstruction

A key objective of this study is to understand objective is to understand the bed topography itself and how it influences ice dynamics. There are two ways to can infer information about this relationship: Through forward modelling, with assumptions of the bed conditions; and through inverse modelling that relies on surface observations.

- **Forward models**
  The aim of forward models is to see how bed properties impact ice dynamics. A key example is using a large ensemble of bed topographies to investigate how bed uncertainties impact simulated ice mass loss. In this example geostatistical methods can be used to generate bed topographies that either preserve elevation or texture:
  - **Geostatistics** Statistical methods specialized for analyzing spatially correlated data. In glaciology, this approach is used to interpolate between sparse measurements and characterise spatial patterns in bed properties, often employing techniques like kriging [7].
- **Inversion models**
  The aim of these models is to understand bed properties through knowledge of surface or other variables. A key example is the retrieval of bed topography or basal slipperiness from surface elevation and velocities.
  - **Control method inversion**: A variational approach that minimizes mismatches between observed and simulated fields through a cost function approach. Remote sensing data and theoretical ice flow models are used to obtain basal conditions [8]. Often needs regularization terms to prevent non-physical features or over-fitting [9].
  - **4dvar**: Four-dimensional variational data assimilation - Similar to the control method inversion algorithm, but adds a time dimension. Used to optimize model parameters and initial conditions [9]. Can handle time-varying data and evolving glacier states, making it more suitable for dynamic systems unlike control methods, this makes them more computationally demanding [9].
  - **Mass conservation**: Used to constrain inversion models and fill data gaps by employing physical conservation laws, particularly effective for reconstructing bed topography where direct measurements are sparse [5, 10]. Requires (contemporary) measurements of ice thickness at the inflow boundary to properly constrain the system [9].
  - **Markov Chain Monte Carlo (MCMC)**: A probabilistic method that generates sample distributions to quantify uncertainties in ice sheet parameters and models [9]. While powerful for uncertainty quantification, these methods remain computationally intensive for continental-scale ice sheet models [9].
  - **EnKF** Ensemble Kalman Filter. A sequential data assimilation method that uses an ensemble of model states to estimate uncertainty and update model parameters based on observations [9].

This study aims to develop an integrated method combining forward and inverse modeling to improve bed topography estimates by leveraging high-resolution satellite surface data in regions where radar data is sparse. Despite revolutionary advances in satellite technology that provide unprecedented surface detail, a key challenge in glaciology remains: how to fully utilize this wealth of information in regions where our understanding of subglacial conditions is limited. Our approach will integrate more comprehensive dynamical ice models with modern computational capabilities to develop better bed topography.

2.2 Theoretical Frameworks

Understanding how bed features manifest in surface observations requires a theoretical framework that connects these two domains. The modelling approach used in this project relies on two different theoretical frameworks that relate bed topography and surface features. Using synthetic data, observations and these modelling frameworks, my goal is understanding the limitations of each approach and how they can be improved.

2.2.1 Ice Flow Over Bedrock Perturbations - Budd 1970

The first framework was originally developed by Budd [11]. This model relates ice flow over bedrock perturbations to surface expressions using a two-dimensional biharmonic stress equation. The modelling carried out in [11] determined ice-sliding velocities for wide ranges of roughness, normal stress, and shear stress relevant to real glaciers [11]. Budd's framework fits in my project as a means of verifying the validity of the physics in my ice-sheet model, since it describes important effects of bedrock disturbances on the transient evolution of the transferred basal disturbances onto the surface. The theory makes several key predictions that have been confirmed through spectral analysis of real ice cap profiles:

1. A wavelength of minimum damping occurs at approximately 3.3 times the ice thickness,
2. surface undulations exhibit a $\pi/2$ phase lag relative to bedrock features with steepest surface slopes occurring over the highest bedrock points, and
3. the amplitude reduction depends systematically on ice speed, viscosity, thickness, and wavelength.

Importantly, Budd's theory demonstrates that energy dissipation and basal stress patterns are maximized for bedrock irregularities with wavelengths several times the ice thickness, while smaller-scale bedrock variations decay exponentially with distance into the ice and have minimal impact on overall ice motion. This selective filtering of bedrock signals provides crucial insights for understanding which scales of bed topography most significantly influence ice dynamics.

A critical aspect of Budd's theoretical framework is understanding how ice rheology affects the bed-to-surface transfer relationships. Glen's flow law typically employs a stress exponent $n \approx 3$ for ice under most natural conditions, reflecting the strongly nonlinear relationship between stress and strain rate. Budd's analysis revealed that under certain low-stress conditions, ice deformation can behave more linearly $n \approx 1$ than conventional wisdom suggests. This rheological distinction has profound implications for bed-to-surface transfer functions: linear rheology ($n = 1$) produces different amplitude dampening and phase relationships compared to nonlinear rheology ($n = 3$), particularly for wavelengths around the critical 3.3 times ice thickness scale. My current experimental framework systematically explores this in 1D by generating forward models for multiple synthetic bedrock profiles across four scenarios combining rheological assumptions ($n = 1$ vs $n = 3$) with basal boundary conditions (no-slip vs sliding), enabling direct comparison of how these physical assumptions affect the detectability and reconstruction of bed features from surface observations. Understanding these differences is essential for developing robust inversion methods, as the choice of rheological model fundamentally determines the mathematical relationship between observable surface expressions and the underlying bed topography I seek to reconstruct.

Crucially, Budd's work established the concept of frequency-dependent transfer functions that act as "filters" between bed and surface topography. This transfer function approach, expressed as $\psi(\omega) = \frac{\text{surface amplitude}}{\text{bed amplitude}}$ for wavelength $\lambda = 2\pi/\omega$, provides a direct mathematical framework for inversion. By inverting these transfer functions, one can theoretically reconstruct bed topography from surface observations, particularly for wavelengths where the damping factor is minimal and the signal-to-noise ratio is optimal.

2.2.2 Ice flow perturbation analysis - Ockenden 2023

The second framework in my analysis builds upon these foundational concepts through some of the recent work by Ockenden et al. in [12], which uses observed surface perturbations (in velocity and elevation) to invert for unknown basal perturbations. Ockenden et al. improve from their previous work in [13] by using full-Stokes transfer functions, which greatly improves their method when dealing with steep topography where the shallow-ice-stream approximation breaks down. Ockenden et al. find this is crucial for better resolving the topographic features they are interested in. The core principle of the method by Ockenden et al. (2023) relies on the fact that variations in basal topography, slipperiness, and roughness cause measurable disturbances to the surface flow of the ice. Through linear perturbation analysis, they establish a systematic relationship between surface observations and bed conditions. This relationship can be expressed as $y = f(x)$, where y represents surface measurements (velocity and topography), x represents bed properties (topography and slipperiness), and f is the forward model transfer function refined by Gudmundsson and Raymond in 2008 [14] this by deriving analytical transfer functions.

In their work Ockenden et al apply this framework in reverse $x = f^{-1}(y)$, to infer the bedrock from modern, high-resolution satellite data estimates. A restrictive assumption in the modeling design by Ockenden et al might be their assumption of “constant viscosity", in glaciology this is equivalent to assuming a linear rheology, where the stress exponent, n, is equal to 1. This means that the strain rate is directly proportional to the stress. This is in contrast to the more commonly used non-linear Glen's Flow Law, where n is typically around 3 or even 4. This earliest phase in my PhD project has as a goal to determine whether treating the rheology of ice as linear is adequate. Ockenden et al account for a non-linear sliding law at the base of the ice, mentioning the “sliding law parameter m”. However, the transfer of stress through the body of the ice—the core of the perturbation analysis—relies on the linear rheology (constant viscosity) assumption from the foundational work of Gudmundsson and Raymond 2008.

2.2.3 Bridging Classical and Modern Approaches

While both frameworks address the fundamental bed-to-surface relationship, they operate at different levels of complexity and make different assumptions. Budd's approach provides the fundamental physical understanding of how specific wavelengths propagate through ice, establishing theoretical limits on what bed features can be detected from surface observations. Ockenden's method extends this to practical applications using real satellite data but relies on linearised assumptions that may break down under certain conditions. My research aims to bridge these approaches by combining Budd's rigorous transfer function analysis with comprehensive forward modeling that relaxes some of the restrictive assumptions inherent in linear perturbation methods. By systematically exploring how different rheological models ($n = 1$ vs $n = 3$) and basal conditions affect the bed-to-surface transfer functions, this work aims to develop a robust inversion method that can better handle the nonlinear physics of ice flow while maintaining the theoretical rigor established by Budd's foundational analysis.

2.3 Current Opportunities

Current Antarctic bed topography reconstruction methods fail to utilize the wealth of presently available satellite-derived surface data. While mathematical models linking bed to surface through ice dynamics (such as those by Ockenden and Budd) provide a foundation for inferring bed topography from satellite data, they have significant limitations. My approach with BedSAT builds upon theoretical foundations and recent inversion methods to better understand how bed conditions—including slipperiness, roughness, and pinning points—affect both grounding line retreat rates and their surface expressions. BedSAT will connect surface observations with bed topography using more realistic rheological and geometric assumptions through an iterative process: initially inverted bed topography will feed into ice dynamics models with these improved assumptions, allowing comparison between model predictions and established datasets like NASA's ITS_LIVE. I expect to utilise Machine learning methods to systematize this process, enhancing the analytical capabilities for the project's final phase.

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Methods

3.1 Aims

I will address the following research questions:

1. How does the bed topography manifest on the ice surface?

2. To what extent do interpolation uncertainties in bed topography datasets affect the accuracy of Antarctic Ice Sheet evolution simulations under different climate change scenarios?

3. What is the impact of variable bed conditions and topography influence the rate of GL retreat in continental ice sheets?

Underpinning these research questions are the following objectives:

1. Develop an ice sheet modelling approach to assimilate satellite remote sensing datasets to improve knowledge of the bed (BedSAT) informed by mathematical models of ice flow over topography;

2. Derive a new bed topography for Antarctica using BedSAT;

3. Evaluate the impact of the improved bed topography on projections of ice mass loss from Antarctica under climate warming through sensitivity analyses.

3.2 Research plan methodology

Objective 1 is to derive the BedSAT method. I will use a regional catchment in Antarctica for which relatively more radar data are available and has an indicative range of topography features, e.g. the Aurora Subglacial Basin, East Antarctica, extensively surveyed by Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP) [15]. In developing my inversion approach, I will consider important factors like sliding variability, to distinguish between topographical signatures and sliding-induced features in surface expressions. I will implement a realistic sliding-law in the Ice-sheet and Sea-level System Model (ISSM) that incorporates Budd's determinations of ice-sliding velocities across varying roughness, normal stress, and shear stress conditions. By calibrating these advanced models against known radar-surveyed regions with varying sliding conditions and validating with other observational data, I can better isolate true bed topographical features from friction-related artifacts and create a more robust inversion framework.

The second phase of the project (objective 2) will apply the methodology developed in objective 1 to the whole Antarctic continent, deriving a continent-wide bed topography dataset. Using covariance properties from existing radar surveys, I will generate a number of realisations of bed topography with unique high-resolution, and statistically-consistent topographic roughness. In the third phase of the project will use the new bed topography datasets to conduct a sensitivity analysis of ice sheet model projections to 2300 CE, investigating the impact of the new topography and different realisations of roughness on ice and subglacial hydrological flow and ice mass loss from Antarctica.

Objective 1

1. Develop an ice sheet modelling approach to assimilate satellite remote sensing datasets to improve knowledge of the bed (BedSAT) informed by mathematical models of ice flow over topography;

Key Investigation Areas for Objective 1

1. **Model Development Strategy**
    - I will maintain invariant (but spatially variable) bed traction throughout the modeling timeframe to isolate topographical effects in the inversion approach.
    - My model will incorporate available thermal distribution, velocity field, and ice thickness data, as these parameters be constrained using observations.
    - Through spectral analysis of surface expressions, I will identify the topographical features that most strongly influence surface patterns.
    - To account for variations in ice behavior with thickness, I will simulate scenarios ranging from thick ice with slippery base to thin ice with sticky base, using observed velocity patterns as constraints.
2. **Transfer Functions**
    - I will develop efficient transfer function methods for rapid bed topography inversion, validating against known bed configurations from radar data.
    - My transfer functions will be tested across various ice thickness and flow conditions.
    - Cross-validation against radargrams will provide direct verification of my inversion results.
    - Spatial covariance analysis of existing radar data will inform my statistical framework and error propagation through the inversion process.
    - I will account for friction roughness and high-amplitude variations, using observed surface velocity patterns as constraints.
3. **Model Validation**
    - I will apply quantitative error reduction metrics and compare systematically against existing bed topography products.
    - Model limitations and breaking points will be identified through systematic testing across extreme scenarios, constrained by physical principles.

- Grid independence testing will ensure solution robustness across different spatial resolutions.
- Sensitivity analysis will examine the impact of my model assumptions.

Note: Detailed methodological outlines for Objectives 2 and 3 will be developed following the completion and refinement of the BedSAT method in Objective 1.

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Progress

Budd's sliding theory describes stress propagation through flowing ice over undulating bedrock. The stress field propagates upward at an angle, creating surface (elevation) waves that are phase-shifted by approximately $\pi/2$ relative to bedrock (elevation) features, in Budd's words: `the maximum shear stress occurs at the tops of the waves and the minimum in the troughs'' [11]`.

—-WHAT GOES HEREEEEE—-

My work up until now has been focused in building a comprehensive computational framework developed for the systematic investigation of ice dynamics. The first part of this framework is to study via simulations in 2D the ice flowline behavior over a variety of synthetic bedrock topographies to understand the relationship between basal geometry, ice rheology, and overall flow response. A key aim of this work is to understand the effect of commonly made assumptions in ice sheet modelling and their repercussions in the validity of resulting models. This initial stage is designed to be a complete, end-to-end pipeline, from environment setup to final scientific analysis.

4.1 The Computational Framework of this Study

This study is supported by a suite of interconnected scripts and tools designed for generating conditions, running simulations, processing output, and performing scientific analysis.

4.1.1 Synthetic Bedrock Generation

The `bedrock_generator.py` script generates synthetic 1D bedrock profiles for ice flow modeling. the core functionality of this script is the creation of realistic bedrock topographies with configurable geometric properties. The bedrock profiles are defined by the following four key parameters that can be varied systematically:

- Amplitude Controls the vertical scale of undulations (e.g., 19.2 m to 38.4 m).
- Wavelength Controls the horizontal scale of undulations (e.g., 3.84 km to 19.2 km).
- Skewness Controls the asymmetry of the undulations.
- Kurtosis Controls the peakedness or flatness of the features.

The generated profiles are saved to `.npz` files and are loaded by the ice flow simulation script to ensure consistent and reproducible experimental setups.

4.1.2 Ice Flow Simulation

The core of the project is an ice flow modeling script (`flowline.py`) built upon the Ice-sheet and Sea-level System Model (ISSM). The simulation solves the full-Stokes ice flow equations for a static diagnostic stress balance setup and a transient run (this includes stress balance and mass transport configurations). The simulation utilises the Bidimensional Anisotropic Mesh Generator (BAMG) for the case of 2D flowband meshes (`bamgflowband`) to create meshes where the mesh resolution is refined based on the underlying bedrock wavelength to capture key physics efficiently.

The experimental design is built around four benchmark experiments to test different physical conditions:

1. S1 No-slip (frozen) bed + Linear rheology ($n = 1$).
2. S2 No-slip (frozen) bed + Non-linear rheology ($n = 3$).
3. S3 Linear sliding + Linear rheology ($n = 1$).
4. S4 Linear sliding + Non-linear rheology ($n = 3$).

The `flowline.py` script produces `.nc` files and binary `.outbin` files for full simulation results (when run locally and on the NCI Gadi system respectively). The `flowline.py` script can also generate text files for quick analysis in the case of the static diagnostic runs.

4.1.3 Data Processing and Visualization Tools

A series of robust, high-performance scripts were developed to handle the large volume of data produced by the simulations. (Note that: All these scripts have individual file processing capabilities)

1. Binary to NetCDF Conversion A batch-capable tool (`batch_convert.py`) converts ISSM's proprietary `.outbin` files into the standard, portable NetCDF format. This script supports parallel processing for high throughput.
2. Result Extraction and Visualization A batch script (`batch_extract_results.py`) that automatically finds and processes NetCDF files to generate visualisations of key fields like velocity and pressure.
3. Targeted Scientific Plotting Additional scripts (`batch_plots.py`) are used to create specific scientific plots, such as basal velocity oscillations colored over the bed topography and basal shear stress distributions, to analyse the direct impact of the bedrock on flow.

4.1.4 Scientific Analysis Tools

In order to perform quantitative analysis on the simulation results. I developed a pair of Grid Convergence Analysis scripts capable of analysing the resolution convergence in both the static and transient runs `analyse_grid_convergence.py` and `analyse_transient_convergence.p` respectively. Convergence is assessed by comparing solutions from different mesh resolutions (e.g., factors of 0.5, 0.75, 1.0, 1.5) against the finest mesh solution. The primary metric of this script is the L2 relative error, a global, scale-independent measure that quantifies the overall difference between two solutions. An error below 1% is typically considered a sign of good convergence. A standardized 2×2 plot is generated to provide a comprehensive view of convergence, showing visual velocity comparisons, numerical L2 error bars, and the computational cost of each resolution.

To quantify the spatial phase shift between the bedrock topography and the ice surface response and verify the physical validity of my simulation based on the criteria in [11], I developed a single and a batch-processing scripts (`phase_analysis.py` and `batch_phase_analysis.py`) that use cross-correlation to calculate the lag and phase shift between the de-trended bed and surface signals for each time step in a given simulation. The scripts generates time-series plots of phase shift evolution and summary text files with numerical results. For each batch or single simulations analysed.

4.1.5 Key Findings: The Grid Independence and Stability Study

In order to validate my simulation outputs, I performed grid independence study to determine the optimal mesh resolution that balances computational cost and numerical accuracy. This study led me to a critical discovery that reshaped my simulation strategy.

My diagnostic convergence analyses yielded realistic results and showed that, for a single test profile (022 in Experiment S4), coarser resolutions appeared to provide marginally adequate accuracy when compared to the finest resolution factor 0.5 of the original element size generated by

Table 4.1: Corrected Diagnostic Convergence for Profile 022 (Experiment S4)

Resolution	Surface vx L2 Error	Basal vx L2 Error	Convergence Status
0.75	0.41%	0.22%	**EXCELLENT**
1.0	0.34%	1.30%	**MARGINAL**
1.5	1.17%	1.18%	**INADEQUATE**

Critical Discovery: The Transient Stability Crisis

Based on the promising diagnostic results, I launched a wider study using multiple bedrock profiles. This revealed a dramatic and critical disconnect between diagnostic accuracy and transient simulation stability. While coarser meshes showed acceptable *diagnostic* error, they consistently failed during *transient* simulations.

Table 4.2: Transient Simulation Stability Across 5 Distinct Profiles (Experiment S4)

Resolution	Profiles Completed	Success Rate	Stability Status
0.5	5/5%	100%	**STABLE**
0.75	2/5%	40%	**UNSTABLE**
1.0	1/5%	20%	**VERY UNSTABLE**
1.5	0/5%	0%	**CRITICAL FAILURE**

The profiles summarised here are 027, 164, 285, 433, 692. All these profiles represent different combinations of amplitudes, wavelength, skewness and kurtosis values. These findings demonstrates that good diagnostic convergence does not guarantee transient stability. Further analysis showed that stability is highly dependent on the specific bedrock geometry, with some profiles being far more sensitive to coarse resolution than others, The profiles that appear to be the most problematic are those with a parameter combination of high amplitude and short wavelength.

Opting for a“Stability-First” Strategy

This stability crisis prompted a fundamental shift in the project's methodology, away from balancing accuracy and efficiency, and towards prioritizing simulation reliability. These findings lead me to define the production standard resolution factor of 0.5× standard element size generated by `bamgflowband` as the only production-viable choice for transient simulations.

4.2 RESULTS

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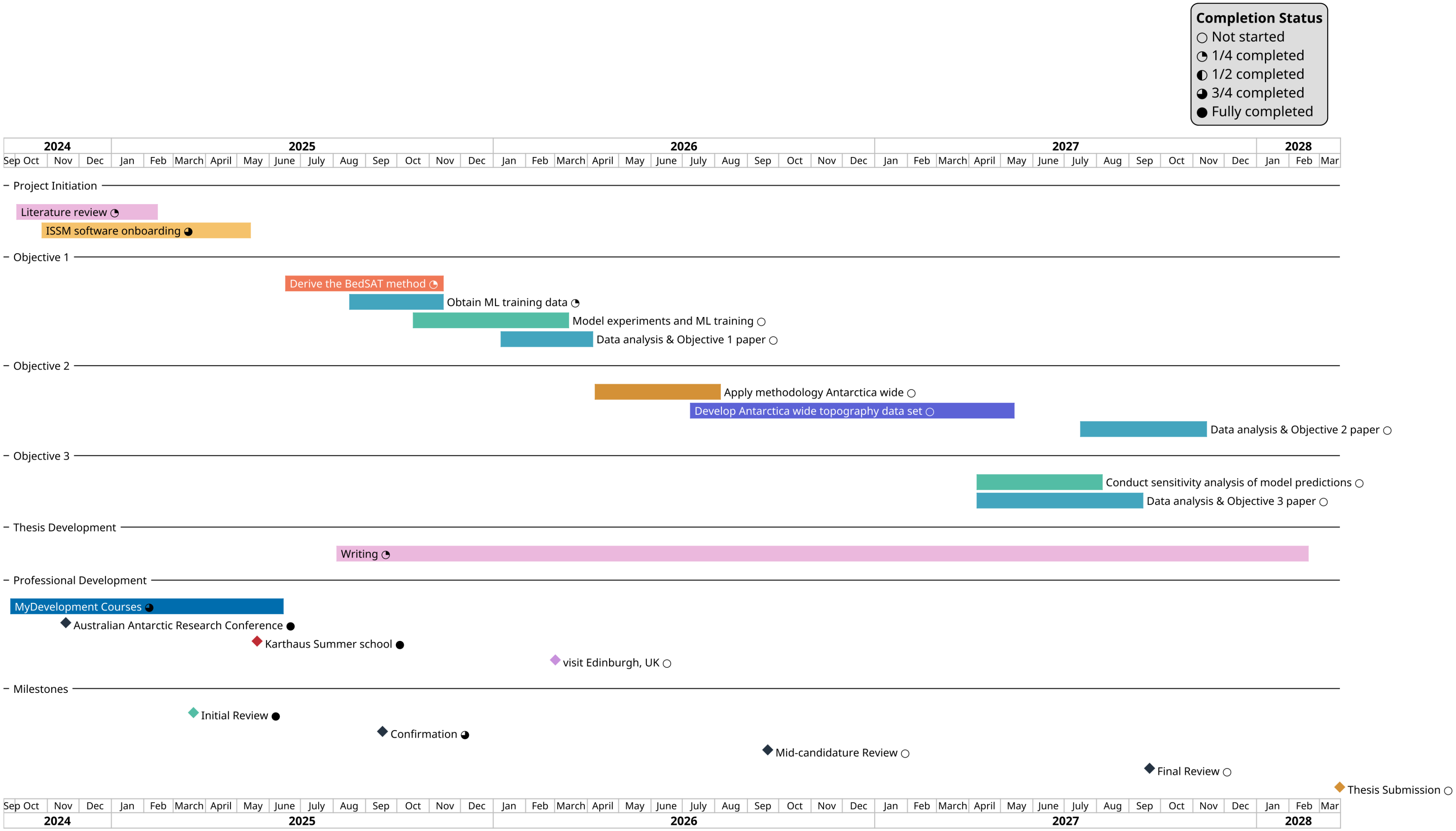
Project timeline



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