Threading the Ocean: Mapping Digital Routes Across Submarine Cables using Calypso

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Abstract

The Internet's connectivity relies on a fragile submarine cable network (SCN), yet existing tools fall short in assessing its criticality. We introduce Calypso, a new framework that leverages traceroute data to map traffic to submarine cables. Validated through real-world case studies, Calypso reveals hidden risks and offers new insights to enhancing SCN resilience.

CCS Concepts

• **Networks** → **Network measurement**; *Network topology*.

Keywords

Submarine cables, Network measurement, Network topology

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1 Introduction

The submarine cable network (SCN) underpins global Internet connectivity, spanning over 500 cables across 1.8 million kilometers [6, 20, 22]. As dependence on this infrastructure grows, so do the risks: from fishing accidents and natural disasters [8, 12, 17, 21] to geopolitical disruptions such as the 2024 Houthi attack, which severed multiple Red Sea cables [5]. Failures can be costly and slow to repair, with outages potentially affecting entire regions [13, 16, 18].

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Submarine cable failures are difficult to analyze due to opaque infrastructure, complex routing, and limited visibility into ownership and usage. Virtualization techniques like MPLS decouple logical from physical paths, and inland interconnection points place traceroute hops far from landing stations, making geographic proximity an unreliable indicator. As a result, mapping traceroutes to physical cables faces four major obstacles: (1) inconsistent visibility into right-of-use arrangements; (2) logical hops that span multiple cables or domains; (3) ambiguity due to multi-path routing and measurement noise; and (4) ingress and egress points that lie far from landing stations, undermining geographic inference.

We introduce Calypso, a framework for mapping traceroute paths to the submarine cables they traverse. It consists of two components: Chartbook, a curated database of cable layout and usage rights, and Navigator, an inference engine that maps traceroutes to candidate cable segments using latency bounds and feasibility constraints. The design of Calypso acknowledges that the greatest challenge in mapping submarine cable dependencies lies not in tracing individual IP hops, but in reconciling fragmented, often ambiguous physical infrastructure data with inferred routing behavior from traceroutes. Compared to prior work [4, 19], Calypso offers higher fidelity by incorporating inland paths, rights-of-use, and route virtualization.

We validate Calypso through expert feedback (56/66 mappings confirmed) and alignment with real-world disruptions. Through case studies in Australia and Africa, we demonstrate how Calypso reveals hidden cable dependencies and surfaces rerouting patterns that shape global resilience.

2 Design Overview

Calypso maps traceroute paths to the submarine cables they traverse by combining infrastructure metadata with path-level inference. At the core of Calypso framework is the dual-engine inference pipeline composed of two components, namely Chartbook and Navigator (Figure 1). Chartbook encodes the physical blueprint of submarine cable geography

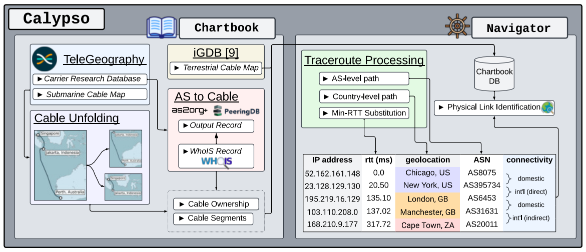

Figure 1: High-level architecture of Calypso.

and ownership, whereas Navigator maps dynamic traceroute data atop the blueprint. Their integration enables Calypso to distinguish not just *where* traffic flows, but *how* and *under whose control*, offering a lens into both submarine cable infrastructure and its operational semantics.

Chartbook: Cable Infrastructure and Rights-of-Use. Chartbook integrates submarine cable layouts from TeleGeography [22] and terrestrial infrastructure from iGDB [2]. It models submarine cables as a GeoJSON polyline [7] and decomposes these into pairwise segments for fine-grained path inference. To align submarine and terrestrial layers, landing points are mapped to iGDB-defined regions. ASN-to-cable associations are derived by reconciling commercial network names from TeleGeography with ASNs using as2org+ [3], PeeringDB [1], and WHOIS data.

Navigator: Mapping Traceroutes to Cables. Navigator transforms traceroutes into AS and country-level paths using bdrmapIT [15] and geolocation [11, 14]). It builds a connectivity graph where nodes are cities and edges are submarine or terrestrial cable segments, annotated with type, length, and network rights. To infer *international links*, Navigator looks for direct submarine cables with matching usage rights and latency bounds for each cross-country transition. If none are found, it identifies viable indirect paths through intermediary countries. For *domestic links*, within each country Navigator connects ingress and egress points using domestic fiber or submarine infrastructure, applying the same graph-based model. When multiple cable paths are plausible, Navigator applies *latency filtering*, removing paths that violate speed-of-light constraints, preserving only physically feasible candidates.

3 Validation and Results

Validating Calypso. We validate Calypso using expert feedback and analysis of cable failures, providing both direct and indirect evidence of accuracy despite limited ground truth.

Expert Feedback. We collaborated with industry experts to evaluate the accuracy of Calypso's inferences. For each traceroute, we validated (**Q1**) *whether our cable-level mapping was correct*, or (**Q2**) *if disclosure was limited due to confidentiality, whether our inference was plausible based on their operational knowledge.* Using 66 IP transport links drawn from case studies, we received feedback confirming 56/66 mappings as correct (**Q1**), with no reported inaccuracies. For the remaining 10 cases (**Q2**), experts declined to comment, citing sensitivity, particularly for links involving terrestrial-only infrastructure. This validation covers approximately 80% of traceroutes in our analysis and reinforces confidence in Calypso's precision.

Failure-Based Validation. We further assess Calypso using traceroute changes during submarine cable failures. Paths to anycast root servers remain mostly stable [23], so observed changes during an outage likely indicate real physical obstruction. Across six major failure events from 2019-2024, we analyze traceroute before, during, and after and validate Calypso's inferences against known cable disruptions.

Case Studies. We show two examples where Calypso reveals critical infrastructure dependencies and resilience gaps.

Australia's Cable Dependencies. Australia's reliance on a small set of cables and ISPs raises concerns about concentrated risk. Despite growing geopolitical tensions, no new Cable Protection Zones (CPZs)[9, 10] have been declared since 2007. Using 480K traceroutes from 100 RIPE Atlas probes, Calypso mapped 92.5% of international paths, revealing that just six cables handle the majority of Australia's outbound traffic, the majority of which towards the United States (*SCCN*, *SC Next & Hawaiki*) and Singapore (*Indigo West*, *SeaMeWe-3 & ASC*). Calypso's mappings, validated across major ISPs, supports recent policy recommendations to reassess CPZ coverage using empirical data.

Africa's Cable Disruptions. Two back-to-back failures in early 2024 exposed how regional resilience depends on routing practices as much as physical topology. In February, a Houthi attack disrupted cables in the Red Sea, degrading Kenyan connectivity but sparing South Africa. In March, a West African landslide reversed the effect: South Africa experienced major disruptions while Kenya remained less affected. Calypso mapped 700K traceroutes, showing that the most impacted cables also carried the highest *Route Stress* – a metric estimating importance of submarine cables based on observed measurements. We discovered that the cables with the highest Route Stress in South Africa (*ACE*, *WACS*, and *SAT-3/WASC*) were the same cables disrupted in March 2024, explaining the severe impact on South African networks.

These examples highlight how Calypso can quantify critical dependencies and support risk-aware planning.

4 Conclusion

We introduced Calypso, a framework that maps traceroutes to submarine cables and quantifies their criticality through the Route Stress metric. Our validation and case studies in Australia and South Africa highlight its accuracy and utility in assessing infrastructure dependencies and failure impacts.

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