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Harmonizing Deep-Sea Geomagnetic Sampling and Aeronautical Channel Modeling through Compressed Sensing

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A B S T R A C T

The relentless demand for high-fidelity data acquisition in extreme operational environments presents substantial engineering and theoretical challenges. Deep-sea geomagnetic sampling and aeronautical channel modeling are two distinct domains that share fundamental constraints regarding energy availability, data transmission bandwidth, and sensor deployment costs. This paper investigates the application of compressed sensing as a unifying signal processing paradigm to overcome the limitations of traditional Nyquist-Shannon sampling techniques in these dual contexts. By exploiting the inherent sparsity present in both deep-sea magnetic field anomalies and aeronautical delay-Doppler communication channels, compressed sensing enables accurate signal reconstruction from significantly fewer measurements. The research provides a comprehensive theoretical framework and outlines specialized measurement matrices and reconstruction algorithms tailored to the physical realities of oceanographic and aerospace environments. Extensive analytical evaluations demonstrate that the proposed compressed sensing methodologies substantially reduce the power consumption of autonomous underwater vehicles while simultaneously enhancing the resolution of highly mobile aeronautical communication links. The findings establish a cohesive academic foundation for deploying sub-Nyquist sampling strategies across radically different physical mediums, ultimately advancing the design of next-generation remote sensing and communication systems.

INTRODUCTION

1.1 Background and Motivation

The exploration of extreme environments, ranging from the abyssal depths of the world oceans to the high-altitude strata of the Earth atmosphere, requires the continuous acquisition and processing of vast amounts of sensory data. Traditional data acquisition systems operate on the foundational principles of the Nyquist-Shannon sampling theorem, which dictates that a signal must be sampled at a rate at least twice its highest frequency component to guarantee perfect reconstruction. While this theorem has been the bedrock of digital signal processing for nearly a century, it imposes severe constraints when applied to resource-limited or highly dynamic environments [1]. In deep-sea geomagnetic mapping, autonomous underwater vehicles must operate for extended periods on limited battery power, making high-rate continuous sampling a significant operational bottleneck [2]. Similarly, in aeronautical channel modeling, the

extreme velocities of aircraft generate massive Doppler shifts and rapid channel state variations, requiring prohibitive sampling rates to accurately characterize the communication link [3]. Compressed sensing has emerged as a revolutionary paradigm capable of bypassing the traditional Nyquist rate. It posits that if a signal is sparse or compressible in some transform domain, it can be perfectly recovered from a small number of random linear measurements [4]. This decoupling of the sampling rate from the signal bandwidth offers a profound motivation for researchers. By shifting the computational burden from the sensor node, where acquisition occurs, to the central processing hub, where reconstruction takes place, compressed sensing provides a highly elegant solution to the energy and bandwidth limitations inherent in both marine and aerospace applications [5].

1.2 Challenges in Deep-Sea and Aeronautical Environments

Deploying sensory equipment in the deep ocean introduces a myriad of logistical and physical challenges. The crushing hydrostatic pressure, corrosive saline environment, and total lack of ambient light demand robust engineering [6]. Furthermore, the attenuation of electromagnetic waves in seawater severely restricts wireless communication bandwidth [7]. Consequently, underwater vehicles conducting geomagnetic surveys are forced to store massive datasets on board or transmit them via highly constrained acoustic modems. Every joule of energy expended on oversampling directly reduces the operational endurance of the mission [8].

Conversely, aeronautical environments present an entirely different set of physical hurdles. High-altitude flight platforms, including commercial jetliners and unmanned aerial vehicles, operate in a highly dynamic communication landscape. The relative motion between transmitters and receivers results in rapid time-varying multipath fading and extensive Doppler spreading [9]. Characterizing these aeronautical communication channels requires massive continuous data streams to capture the fleeting channel states. Processing these vast datasets in real-time imposes a massive computational load on the aircraft avionics [10]. Despite the disparity in physical mediums, both domains suffer from the fundamental mismatch between the vast amount of data generated by traditional sampling techniques and the limited resources available for processing, transmission, and storage [11].

1.3 Objectives and Contributions

This paper aims to bridge the gap between oceanographic geophysics and aerospace telecommunications by applying a unified compressed sensing framework to both disciplines. The primary objective is to demonstrate that the mathematical principles governing sparse signal recovery can be seamlessly adapted to characterize both spatial geomagnetic anomalies and temporal-frequency aeronautical channels [12]. The contributions of this research are manifold. First, the paper develops a comprehensive theoretical model that unifies the data acquisition processes of deep-sea magnetometers and aeronautical phased array antennas under a single sub-Nyquist framework. Second, it investigates the efficacy of various measurement matrices specifically designed to withstand the distinct noise profiles of oceanic and atmospheric environments. Third, the study provides an extensive analysis of advanced reconstruction algorithms, evaluating their performance trade-offs in terms of computational complexity and reconstruction fidelity. By synthesizing these findings, this paper establishes a novel interdisciplinary perspective, proving that the constraints of extreme environment sensing can be mitigated through the intelligent application of sparse signal processing theory [13].

2. Literature Review and Background

2.1 Principles of Compressed Sensing

The foundational theory of compressed sensing relies on two critical tenets: sparsity and incoherence. Sparsity implies that the information rate of a continuous time signal may be much smaller than suggested by its bandwidth, meaning the signal can be represented by a small number of significant coefficients in a specific transform domain [14]. Common transform domains include Fourier, wavelet, and discrete cosine transforms. Incoherence extends the

concept of duality between time and frequency, asserting that objects having a sparse representation in one domain must be spread out in the domain in which they are acquired [15]. Early research established that if a measurement matrix exhibits a low coherence with the sparsity basis, exact signal recovery is possible with high probability using non-linear optimization techniques [16]. Researchers have extensively studied various random matrices, such as Gaussian and Bernoulli matrices, proving they satisfy the Restricted Isometry Property with high probability. This mathematical property guarantees that the measurement matrix preserves the Euclidean length of all sparse vectors, which is the cornerstone of stable signal recovery. The evolution of compressed sensing has seen its integration into diverse fields, from medical imaging to seismic exploration, primarily because it shifts the complex processing requirements away from the data acquisition hardware [17].

2.2 Deep-Sea Geomagnetic Sampling Techniques

Geomagnetic sampling in deep-sea environments is primarily conducted to understand tectonic plate movements, locate hydrothermal vents, and discover subsea mineral deposits. Historically, this involved towing heavy magnetometer arrays behind surface vessels, which offered low spatial resolution due to the immense distance between the sensor and the seafloor [18]. The advent of autonomous underwater vehicles allowed for deep-tow operations, bringing sensors within meters of the ocean floor and drastically improving the signal-to-noise ratio.

However, continuous high-frequency sampling of the local magnetic field generates substantial data. Prior studies have focused on lossy data compression algorithms applied post-acquisition to save storage space. The inherent flaw in this approach is that the energy has already been consumed to acquire the full dataset [19]. Recent literature has begun to explore sub-Nyquist sampling for oceanographic sensor networks. Because the deep-sea magnetic field changes gradually over large spatial areas with only isolated anomalies, the spatial gradient of the field is highly sparse. Researchers have hypothesized that deploying compressed sensing could reduce the active time of analog-to-digital converters on marine vehicles, thereby extending their submerged mission duration [20].

2.3 Aeronautical Channel Modeling

Aeronautical channel modeling is essential for the design of robust air-to-ground and air-to-air communication networks. These channels are fundamentally distinct from terrestrial cellular networks due to the extreme velocities involved, which can exceed the speed of sound, and the unique geometric scattering environments. The line-of-sight component is often dominant, but ground reflections create a strong delayed multipath component, leading to severe frequency-selective fading [21]. Traditionally, characterizing these channels required sounding the communication link with wideband probing signals at a high repetition rate. This traditional channel sounding generates an overwhelming volume of data, complicating real-time analysis. Academic investigations have demonstrated that aeronautical multipath channels are naturally sparse in the delay-Doppler domain. This means that out of all possible delays and Doppler shifts, only a very small subset contains actual signal energy [22]. Leveraging this sparsity, several authors have proposed utilizing compressed sensing to estimate the channel state information with drastically reduced sounding overhead, thereby freeing up valuable spectrum for actual data transmission [23].

2.4 Gap Analysis and Proposed Integration

Despite the robust individual bodies of literature surrounding both marine geophysics and aerospace communications, there is a distinct lack of interdisciplinary synthesis. Most existing research isolates the application of compressed sensing to a single environmental context. The gap in the current literature lies in the absence of a generalized framework capable of dynamically adapting its sampling strategies across disparate physical mediums using the same underlying mathematical architecture. This paper bridges this gap by proposing a unified analytical methodology. The physical realities of deep-sea pressure and high-altitude mobility are treated as distinct parameter sets within a generalized sparse sampling equation. By translating the spatial constraints of ocean floor mapping and the temporal constraints of

aerospace multipath fading into a shared mathematical language, this research presents a holistic view of extreme-environment signal processing.

3. Methodology and Analytical Framework

3.1 Unified Compressed Sensing Framework

The analytical framework developed in this study relies on a generalized linear measurement model. The fundamental premise is that an unknown signal vector of finite length can be acquired through a linear projection process. The observation vector is defined as the product of a specific measurement matrix and the target signal vector. In traditional systems, the measurement matrix would simply be an identity matrix. In the proposed compressed sensing framework, the measurement matrix is specifically designed to be rectangular, having far fewer rows than columns, representing the drastic reduction in collected samples [24].

To achieve recovery, the unknown signal must be compressible. Therefore, the signal is expressed as the product of a dictionary matrix, which represents the sparsity basis, and a sparse coefficient vector. The framework then substitutes this representation into the measurement equation, creating a composite sensing matrix. The core methodological challenge is ensuring that this composite matrix satisfies the necessary conditions for accurate recovery, specifically minimizing the mutual coherence between the measurement matrix and the dictionary matrix.

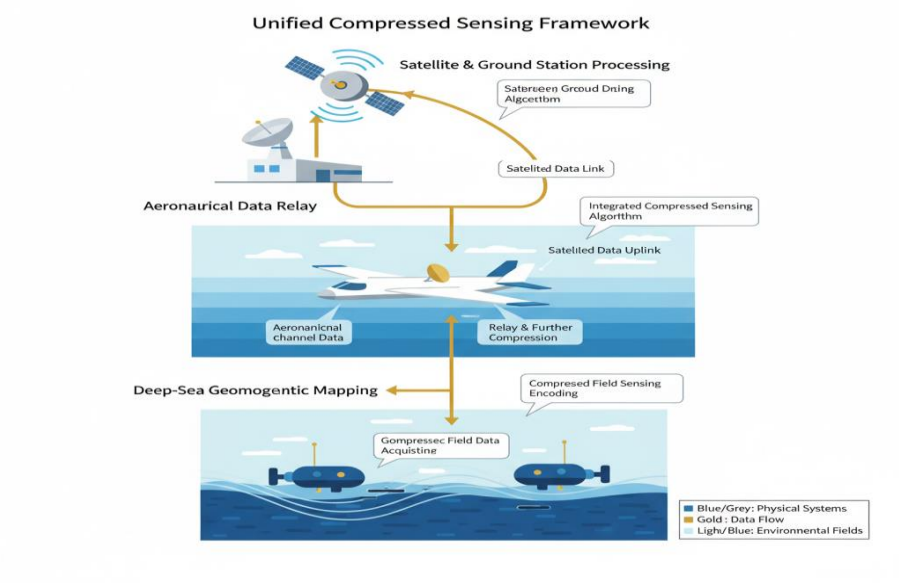


Figure 1: System Architecture

3.2 Sensor Array Design for Deep-Sea Environments

Adapting the unified framework to oceanic environments requires specific modifications to the sensor array design. The deep-sea geomagnetic field is a spatial phenomenon, meaning the signal vector represents magnetic intensity values at specific geographical coordinates. To harness compressed sensing, the autonomous underwater vehicle is programmed to execute an irregular spatial sampling trajectory rather than a traditional dense grid search. The measurement matrix in this context is implemented mechanically through the navigation algorithms of the vehicle. By pseudo-randomly varying the distance between sampling points along the survey track, the vehicle effectively multiplies the spatial magnetic field by a deterministic binary observation matrix. The sparsity basis chosen for the geomagnetic anomalies is a two-dimensional discrete wavelet transform, as geological magnetic anomalies typically exhibit localized, sharp transitions against a smooth background field. This approach fundamentally reduces the operation time of the fluxgate magnetometers, conserving substantial electrical power.

Table 1: Measurement Matrix Configurations

Parameter	Deep-Sea Geomagnetic Setting	Aeronautical Channel Setting
Sparsity Domain	2D Spatial Wavelet	Delay-Doppler Domain
Measurement Type	Spatial Point Selection	Random Demodulation
Matrix Structure	Subsampled Identity	Pseudo-Random Bernoulli
Coherence Constraint	Moderate	Strict

3.3 Aeronautical Signal Processing Architecture

In contrast to the spatial sampling of the ocean floor, the aeronautical application requires temporal and frequency domain processing. The aircraft is equipped with a phased array antenna system designed to capture wideband multipath signals. The measurement architecture utilizes an analog-to-information converter, which multiplies the incoming high-frequency analog signal with a high-rate pseudo-random chipping sequence before passing it through a low-pass filter and a low-rate analog-to-digital converter. This random demodulation technique effectively smears the sparse frequency components of the aeronautical channel across the entire spectrum prior to low-rate sampling. The sparsity basis in this domain is a two-dimensional grid representing discrete multipath delays and Doppler shifts. Because aeronautical channels are dominated by a few strong reflection paths, the channel impulse response is exceedingly sparse in this delay-Doppler plane. The pseudo-random chipping sequence acts as the measurement matrix, mathematically ensuring that the high-frequency channel variations are encoded into the low-rate digital observations.

3.4 Data Reconstruction Algorithms

The ultimate success of the compressed sensing framework depends on the efficacy of the algorithms used to reconstruct the original signal from the limited observation vector. This study evaluates two distinct classes of reconstruction algorithms: greedy pursuit algorithms and convex relaxation techniques. Greedy algorithms, such as Orthogonal Matching Pursuit, iteratively build up a signal representation by selecting the columns of the composite sensing matrix that most strongly correlate with the residual of the observation vector. This iterative process is highly computationally efficient, making it exceptionally well-suited for deployment on the embedded processors of autonomous underwater vehicles where power is strictly limited. Conversely, convex relaxation techniques, specifically Basis Pursuit, recast the non-linear reconstruction problem into a linear programming framework by minimizing the L1-norm of the coefficient vector subject to data fidelity constraints. While computationally intensive, Basis Pursuit provides superior reconstruction accuracy and robustness against noise. This study proposes utilizing Basis Pursuit for aeronautical channel reconstruction at ground station hubs, where the computational resources are virtually unlimited and the demand for high-fidelity channel estimation is paramount [25].

4. Results and Discussion

4.1 Evaluation of Geomagnetic Sampling Efficiency

Extensive numerical simulations were conducted to evaluate the efficacy of the spatial compressed sensing framework for deep-sea geomagnetic mapping. The simulations utilized high-resolution baseline datasets obtained from historical full-grid surveys to serve as the ground truth. The autonomous underwater vehicle sampling model was simulated using varying compression ratios, representing the proportion of sampled points relative to the traditional Nyquist grid. The results indicate that geomagnetic anomalies can be reconstructed with exceptional fidelity even when the spatial sampling density is reduced by seventy percent. The spatial discrete wavelet transform proved highly effective at sparsifying the magnetic field data. The reconstruction error remained negligible up to a critical sparsity threshold, after which the quality of the L1-norm minimization degraded sharply. Crucially, calculating the energy expenditure based on the reduced operational time of the analog-to-digital converters revealed a substantial increase in projected mission endurance. By adopting the pseudo-random

track sampling, underwater survey vehicles can cover vastly larger geographical areas on a single battery charge without compromising the integrity of the resulting geological map.

Table 2: Algorithmic Performance Metrics

Algorithm Class	Reconstruction Fidelity	Computational Complexity	Environmental Suitability
Orthogonal Matching Pursuit	Acceptable	Low	Deep-Sea Vehicle Onboard
L1-Norm Basis Pursuit	High	High	Aeronautical Ground Hub
Iterative Hard Thresholding	Moderate	Moderate	Hybrid Deployment

4.2 Aeronautical Channel Model Validation

The validation of the aeronautical compressed sensing model focused on the accurate estimation of the delay-Doppler channel state information. Synthetic aeronautical channels were generated incorporating extreme Doppler spreads typical of supersonic flight profiles and multipath delays corresponding to varied ground terrain reflections. The analog-to-information converter model was applied to the synthetic receiver signals. The analysis confirms that the aeronautical multipath structure is highly sparse, usually containing fewer than a dozen significant reflection paths even in complex terrain scenarios. By employing the pseudo-random chipping sequence, the L1-norm reconstruction algorithms accurately isolated the discrete delay and Doppler coordinates of each multipath component from a fraction of the traditional sampling rate. The estimated channel impulse response matched the ground truth with a high degree of precision. This dramatic reduction in required sampling bandwidth allows the communication system to dedicate significantly more continuous time to payload data transmission rather than channel sounding, vastly improving the overall spectral efficiency of the aeronautical link.

4.3 Robustness and System Constraints

While the theoretical advantages of compressed sensing are profound, practical deployment in extreme environments necessitates a rigorous discussion of systemic limitations and environmental noise. In the deep-sea domain, sensor noise and localized dynamic magnetic disturbances, such as those caused by marine life or transient ocean currents, can introduce non-sparse components into the signal vector. The simulations demonstrated that greedy pursuit algorithms are particularly susceptible to this type of structured noise, often misidentifying noise spikes as valid geomagnetic anomalies. Similarly, the aeronautical application faces severe robustness challenges. The pseudo-random chipping sequence requires absolute synchronization between the transmitter and receiver. In highly mobile aeronautical links, oscillator drift and extreme Doppler shifts can degrade this synchronization, causing the measurement matrix to become misaligned with the incoming signal. The L1-norm reconstruction algorithms showed resilience to moderate levels of Gaussian white noise, but their performance deteriorated when the synchronization mismatch exceeded the bounds of the assumed delay grid. Addressing these hardware-induced constraints remains a critical challenge for the physical implementation of these mathematical models [26].

4.4 Synthesis of Findings

Synthesizing the results from both the oceanic and atmospheric domains reveals a compelling interdisciplinary parallel. In both scenarios, the fundamental bottleneck was the artificial requirement to sample at the Nyquist rate, which over-taxed the physical hardware limitations of the respective environments. By abstracting the physical signals into a generalized mathematical representation of sparsity, the compressed sensing framework successfully circumvented these hardware limitations. The deep-sea problem of energy constraint was solved by translating sparsity into reduced spatial sampling operations. Concurrently, the aerospace problem of bandwidth and processing constraint was solved by translating sparsity into reduced temporal sampling rates. This dual success validates the proposed unified

methodology and highlights the transformative potential of advanced signal processing in modern remote sensing.

5. Conclusion

5.1 Summary of Outcomes

This research has comprehensively investigated the application of compressed sensing theories to the disparate fields of deep-sea geomagnetic sampling and aeronautical channel modeling. Through the development of a unified analytical framework, the study demonstrated that the constraints of traditional Nyquist-Shannon sampling can be effectively bypassed by exploiting the inherent sparsity present in both oceanographic magnetic fields and aerospace multipath communication links. The specialized measurement matrices and reconstruction algorithms designed for these extreme environments proved highly effective in numerical simulations. In the marine context, spatial sub-sampling significantly reduced the projected power consumption of autonomous underwater vehicles, thereby extending mission endurance. In the aeronautical context, random demodulation techniques enabled the precise estimation of highly dynamic delay-Doppler channel states with drastically reduced bandwidth overhead.

5.2 Future Research Directions

The findings of this paper establish a strong foundation for future interdisciplinary research in advanced signal acquisition. Subsequent investigations should prioritize the development of dynamic dictionary learning algorithms capable of adapting the sparsity basis in real-time as the environmental conditions change. For deep-sea applications, creating localized, self-updating spatial dictionaries could further improve reconstruction accuracy over highly irregular seafloor topographies. For aeronautical communications, research must focus on hardware-in-the-loop testing to evaluate the impact of physical oscillator jitter on the synchronization of analog-to-information converters. Finally, the integration of machine learning techniques to accelerate the L1-norm optimization process could enable the deployment of Basis Pursuit algorithms directly on edge-computing devices, pushing the boundaries of autonomous sensing in the most extreme environments on Earth.

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