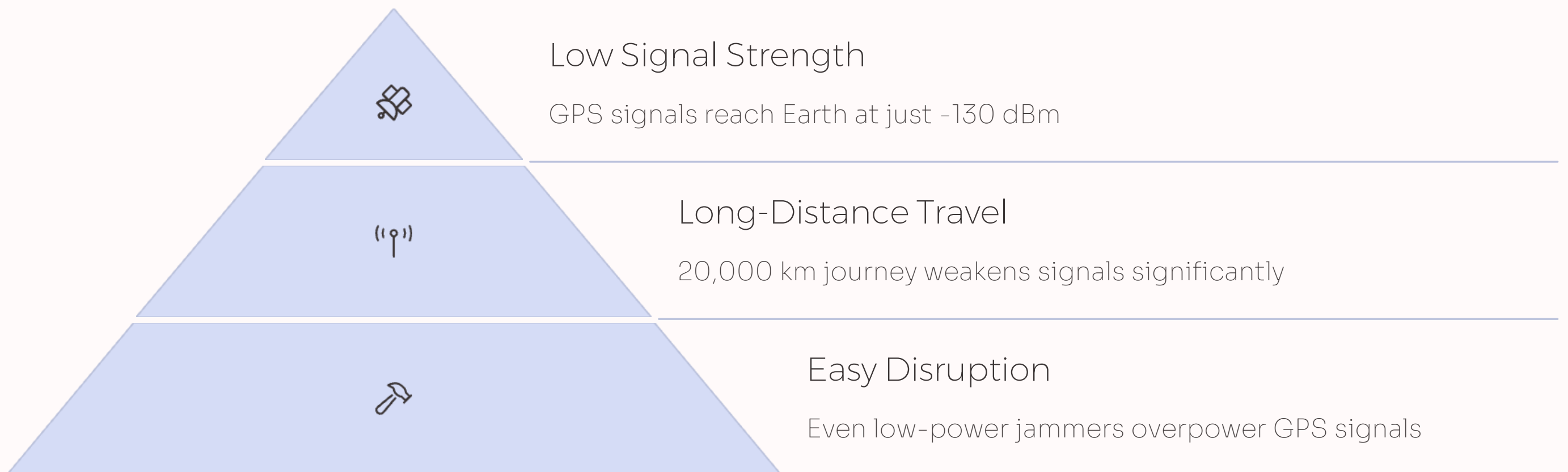


# TranSoOp: Unlocking Navigation in GNSS-Denied Environments

When GPS fails, alternative navigation becomes critical. Today we'll explore how **transformer** models are revolutionizing navigation using Signals of Opportunity (SoOp).



# The Achilles' Heel: GNSS Vulnerability





# GNSS Will Always Be a Target

As everything relies on GNSS, it's subjected to:

## Military Jamming

Targeted **electronic warfare** disrupts enemy navigation. Modern conflicts feature GNSS denial as standard tactics.

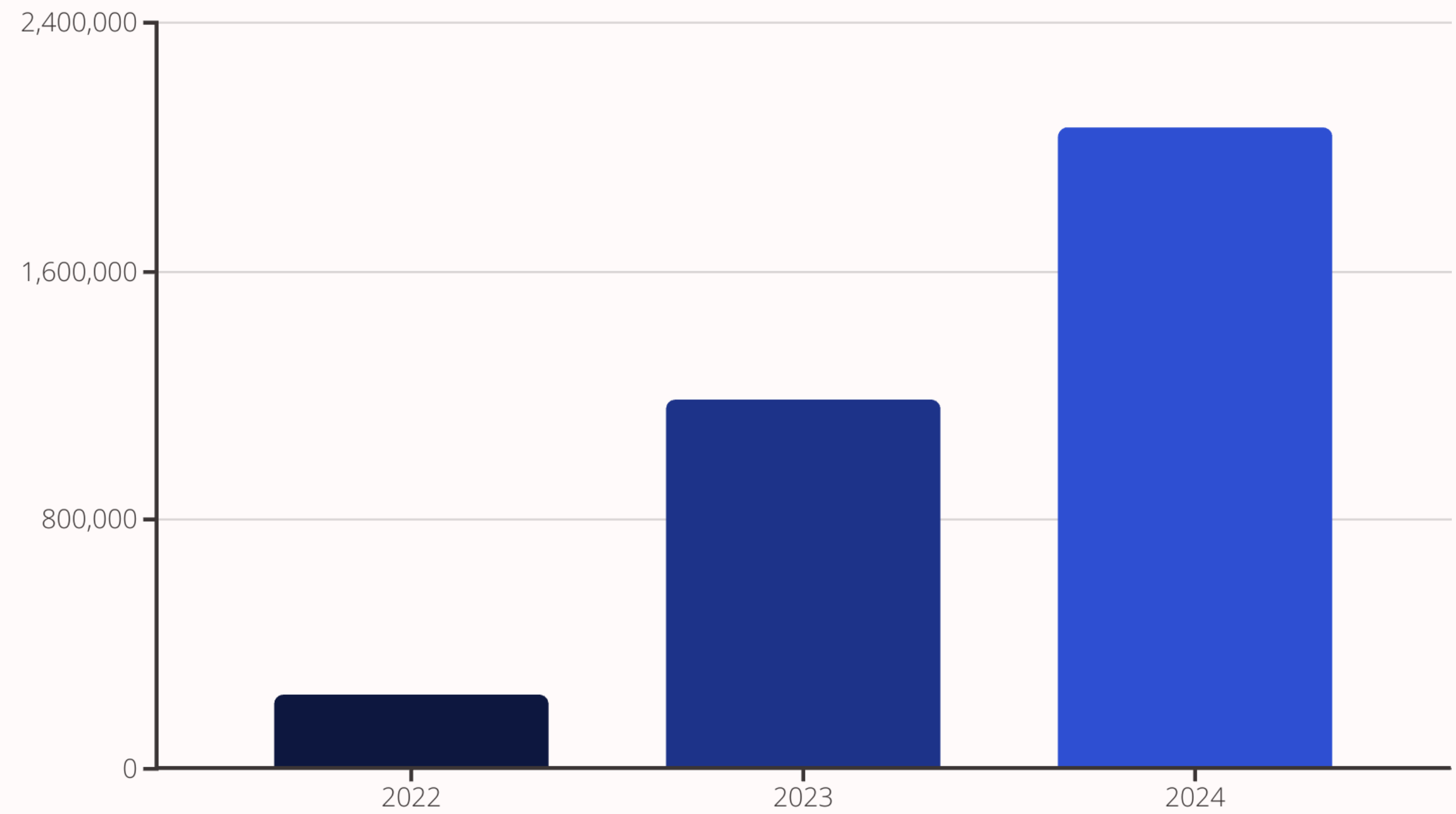
## Malicious Actors

**Criminals** use jammers to disable tracking on stolen vehicles.  
**Terrorist groups** target critical infrastructure timing.

## Commercial Interference

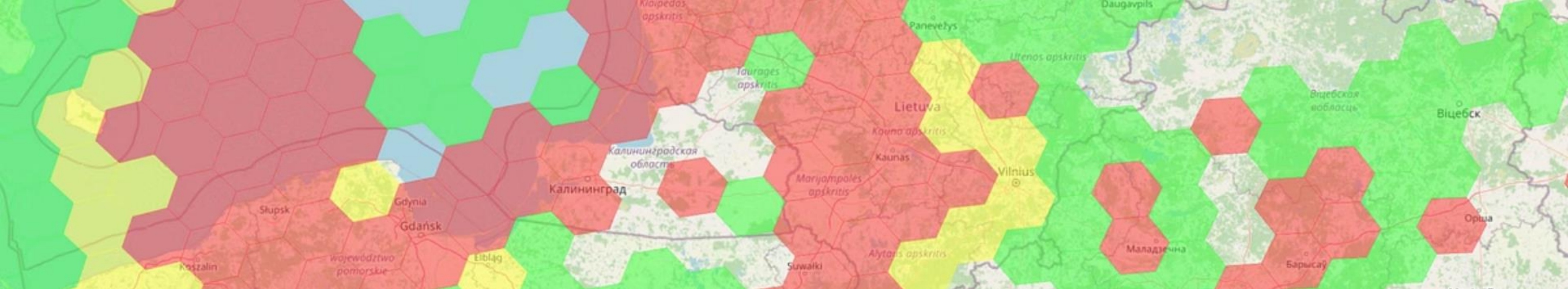
Rapid roll-out of 5G, Wi-Fi 6E, connected-vehicle radar and drone networks share frequencies with GNSS, causing widespread interference.

# Jamming: An Escalating Threat



Cheap jammers selling for as little as \$20 online are driving this exponential growth in disruption events.





# Spoofing and Denial Capabilities

## Russia-Ukraine

Thousands of GPS disruptions documented since 2022. Military and civilian navigation affected across wide areas.



## Aircraft Risk

Newark Airport (2013): approach systems affected by truck-based jammer. Pilots forced to revert to visual approaches.

## Maritime Risk

Black Sea (2023): 2000+ vessels reported position spoofing. Ships appeared at airports or inland locations.



# GNSS Backup

When GNSS works, it's the gold standard for navigation - but what can we do when it doesn't?

# What About Visual Positioning Systems (VPS)?

## Advantages

- High accuracy in visual-rich environments
- Works indoors where GNSS signals can't reach
- Doesn't require external signals that can be jammed
- Can provide centimeter-level positioning

## Limitations

- Poor performance in low light
- Fails in fog, rain, or snow
- Occlusion from objects or crowd
- Struggles in featureless environments (sea)

# What about Inertial Navigation Systems (INS)?



Self-contained

Operates without external signals



Jam-resistant

Immune to electronic warfare



But drift-prone

Accumulates 100m+ errors after just 1 hour



A composite background image featuring a large, detailed brass sextant in the foreground on the left, resting on a wooden surface. The background shows a ship's deck at night with two sailors in uniform looking at a map. A bright star chart or nebula is visible in the dark sky above the ship.

# Other Traditional Alternatives



## LORAN/eLORAN

Low-frequency terrestrial navigation system. Provides regional coverage but requires dedicated infrastructure and maintenance.



## Celestial Navigation

Uses stars and celestial bodies for positioning. Limited by weather conditions and provides slow position fixes.



## Terrain Matching

Compares radar altimeter data with terrain maps. Works only over varied terrain and requires extensive databases.

# Enter SoOp: The Untapped Opportunity



## Ambient Signals

Radio, TV, cellular, and satellite broadcasts surround us. These signals weren't designed for navigation.



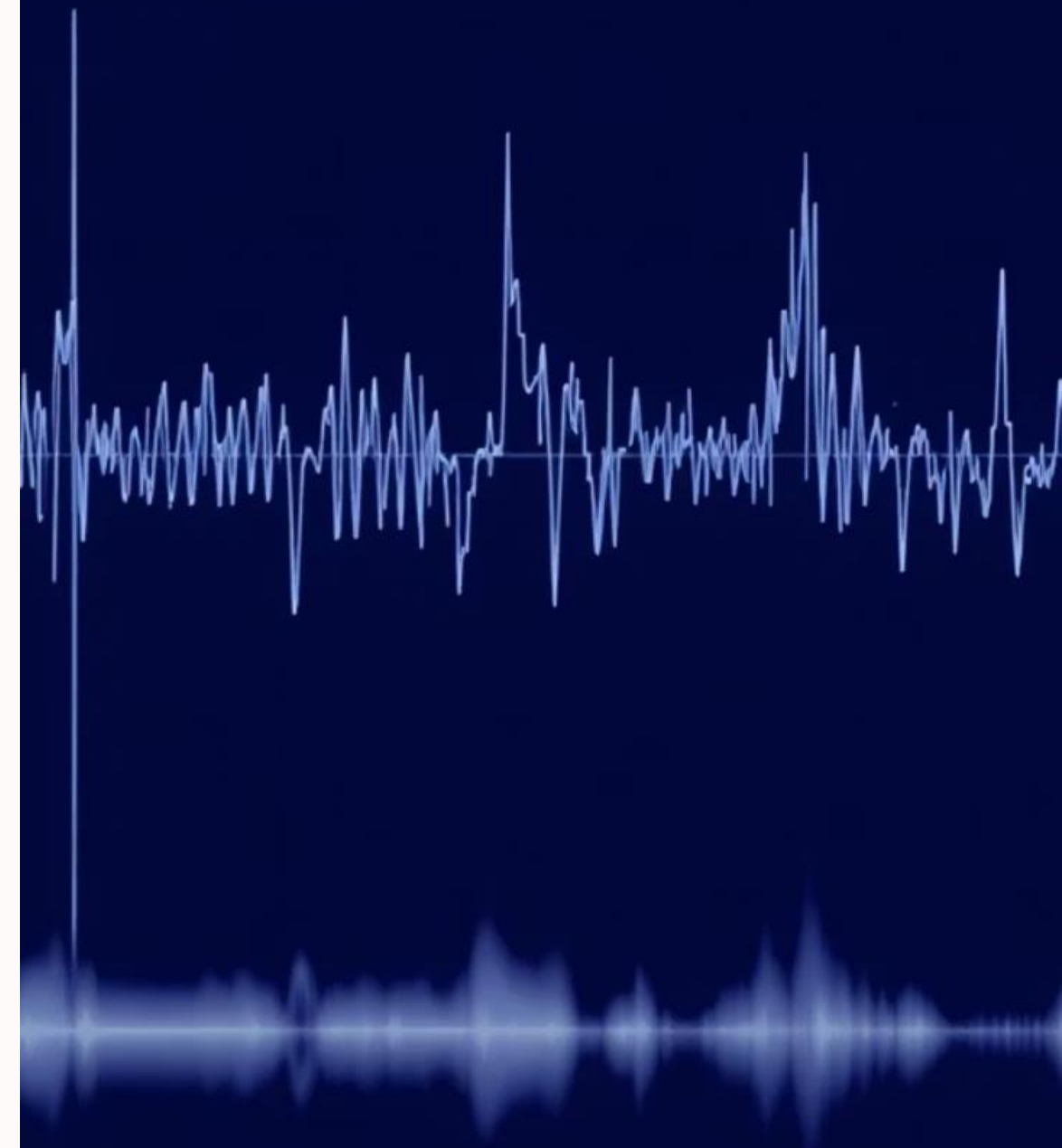
## Jamming (almost) Resistance

Diverse frequencies and signal types prevent single-point failures. Jammers can't block everything.

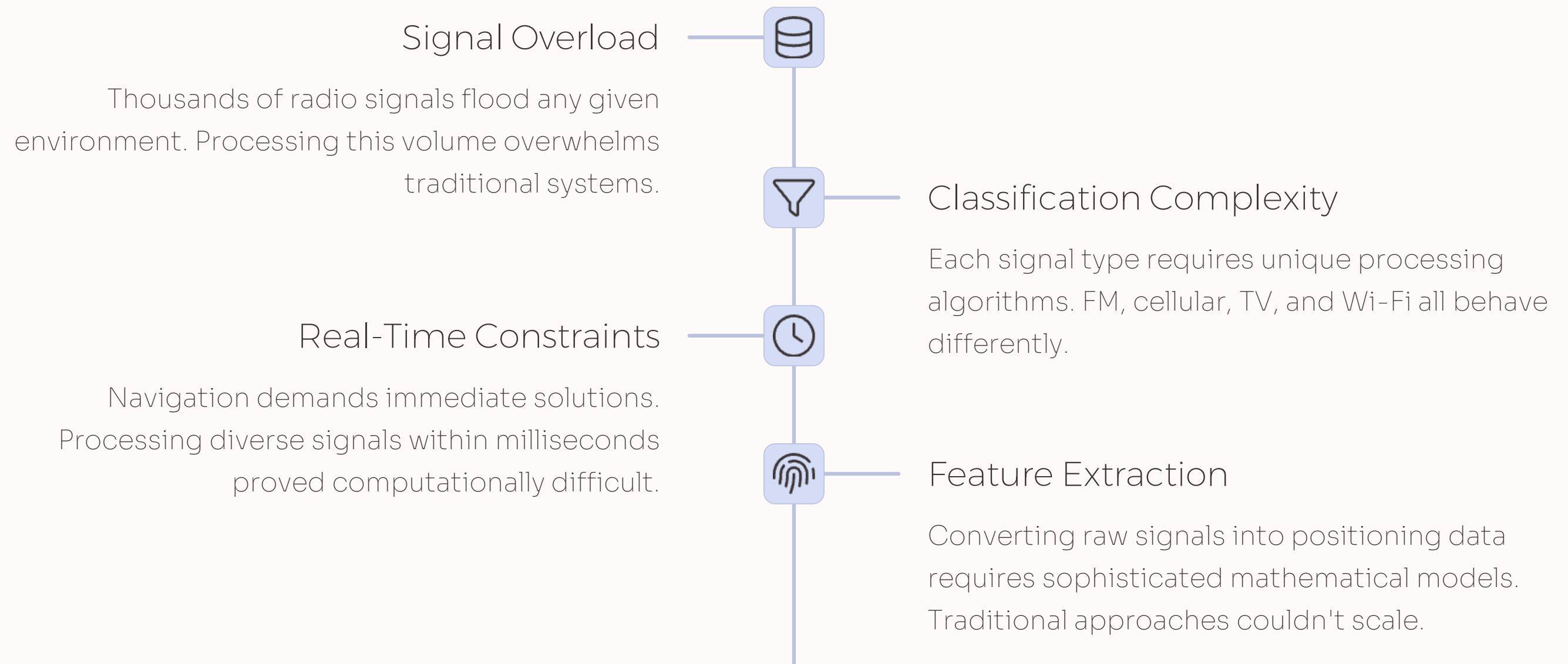


## Universal Coverage

Signals penetrate indoors and urban canyons. They work where GPS cannot reach.



# SoOp's Critical Challenge: Signal Complexity



Until now, the computational power needed to harness SoOp's potential simply didn't exist. Signal diversity that should be an advantage became an insurmountable challenge.

# Transformers: The Missing Piece for SoOp

The same revolutionary technology that transformed language processing can now solve signal complexity challenges that have stalled previous approaches.



## Uses Attention

Processes entire signal inputs simultaneously.  
Identifies meaningful patterns across complex radio environments.



## Understands Context

Dynamically weights signal importance. Distinguishes navigation-relevant features from environmental noise.



## Generalizes Well

Adapts to unfamiliar signal types without retraining.  
Transfers knowledge between FM, cellular, and WiFi signals.



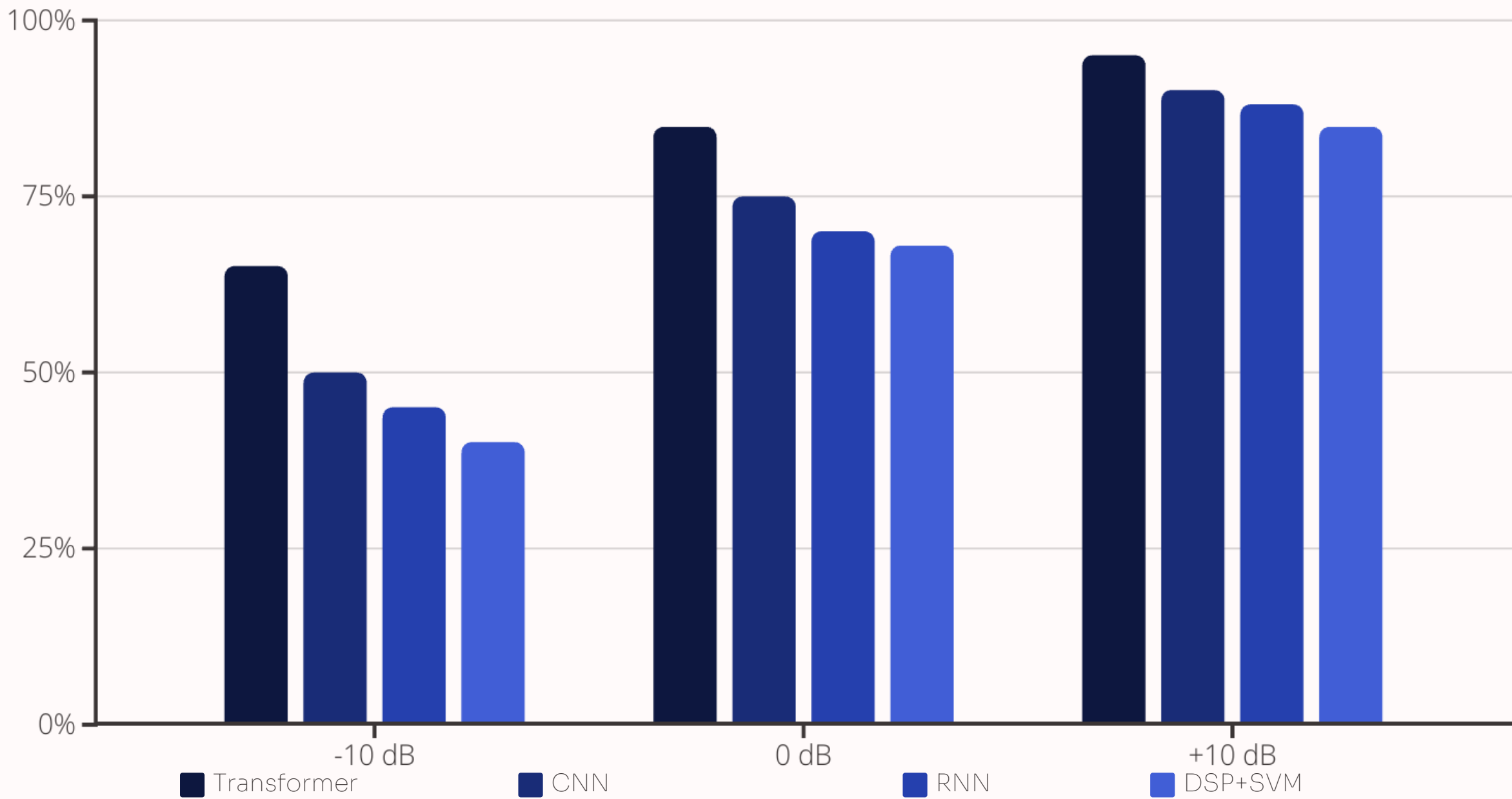
## Real-Time Processing

Delivers positioning solutions in milliseconds.  
Enables practical navigation in GNSS-denied environments.



# Transformer Outperforms Traditional Signal Models in Signal Classification

Transformer architecture demonstrates superior performance in signal classification accuracy, especially in low SNR environments where traditional models struggle.



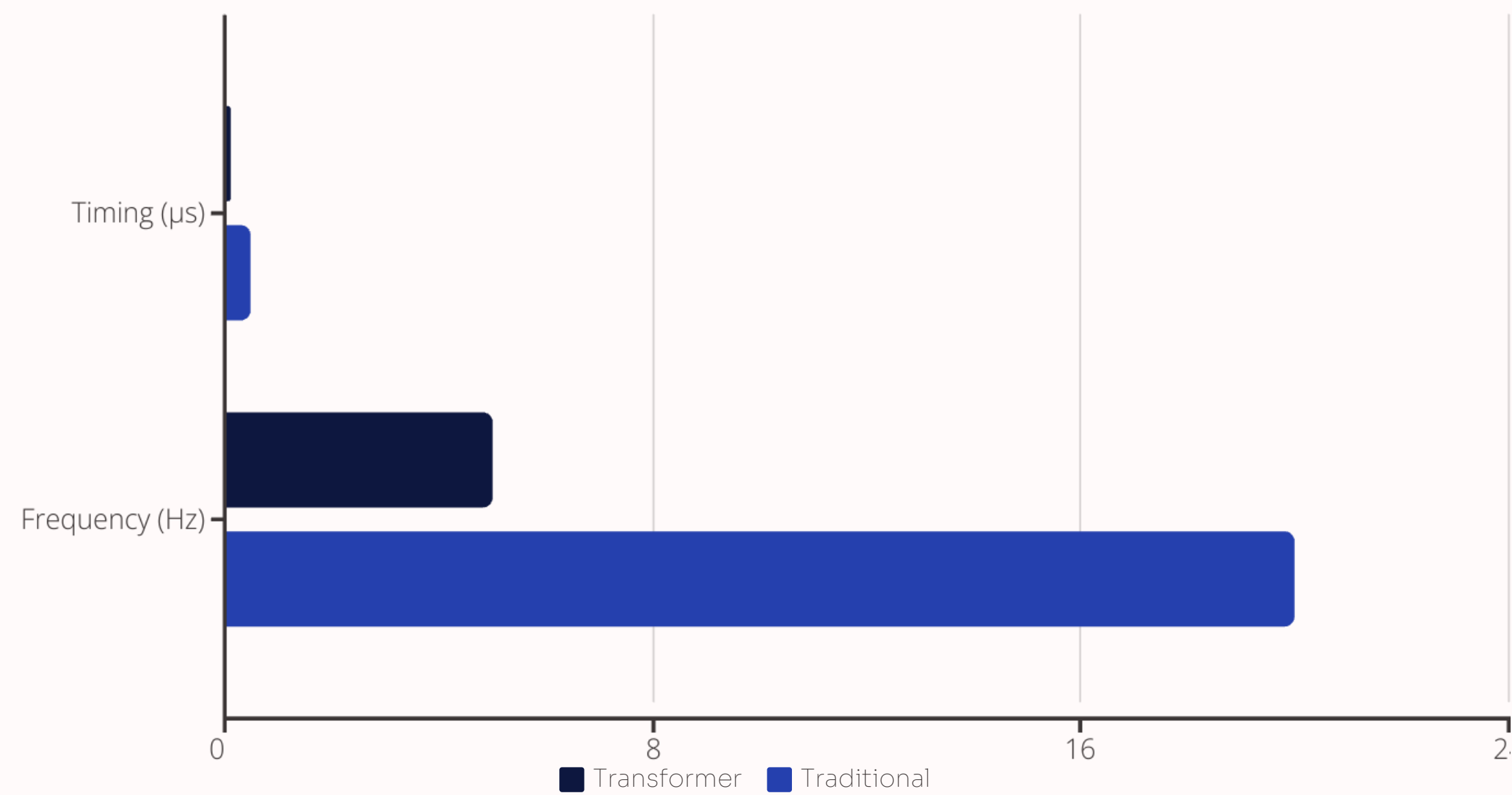
The performance gap widens in challenging environments (-10 dB), where transformers maintain 65% accuracy while alternatives fall below 50%. This resilience is crucial for navigation in signal-constrained settings.

*Based on Zhu et al., 2022 (ArXiv)*



# Transformer Feature Extraction Precision Outperforms Traditional Models

Transformers deliver superior precision in extracting critical navigation features from signals compared to traditional approaches.

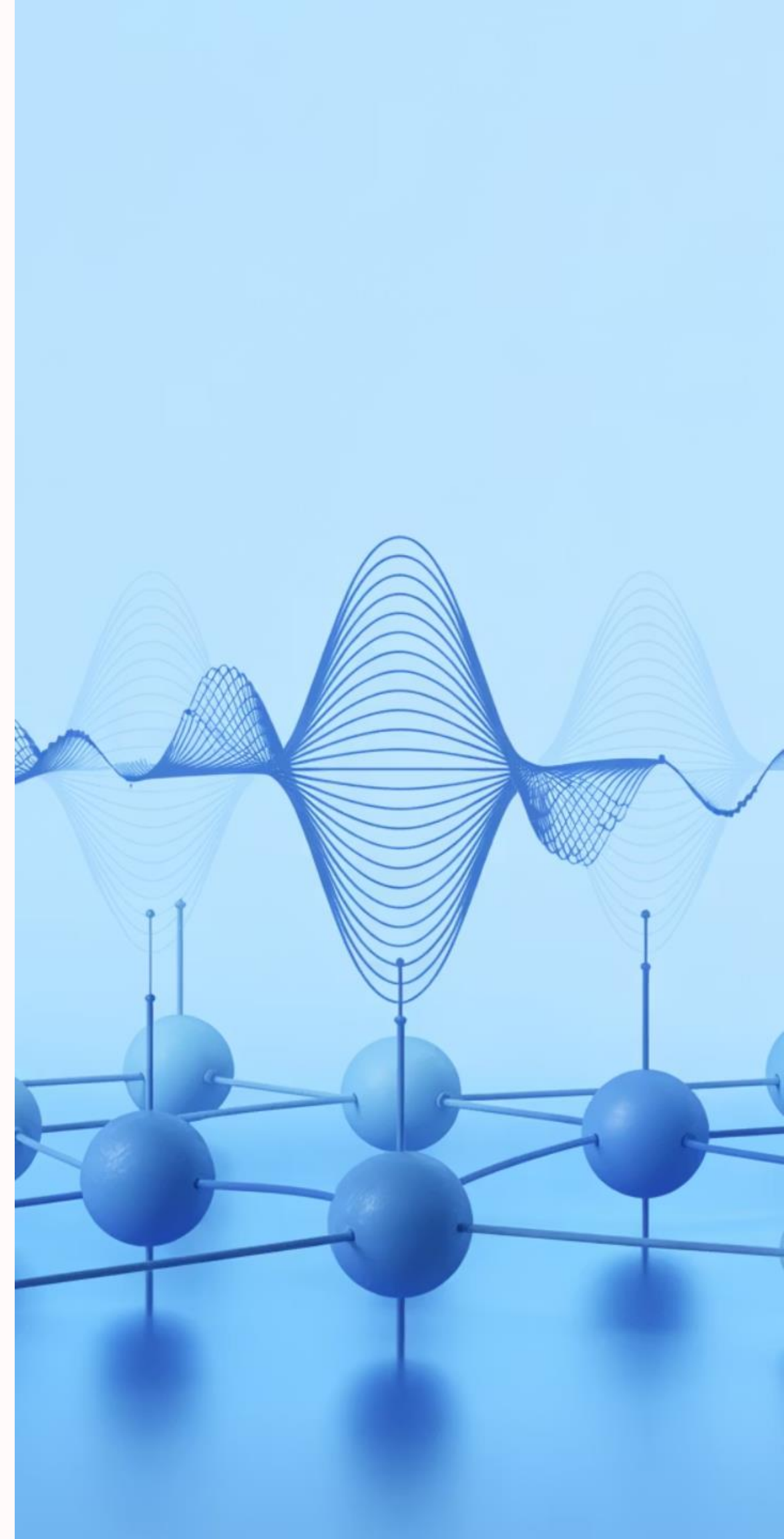


The chart compares Root Mean Square Error (RMSE) for timing and frequency estimation. Lower values indicate better performance.

Transformers achieve **5x better** pilot-tone timing precision and **4x better** carrier-frequency offset estimation than traditional DSP correlators and PLLs.

*Based on Yue et al., 2024 (Computer Communications)*

# Transformer Analysis of OFDM Signals for Navigation: A Visual Walkthrough



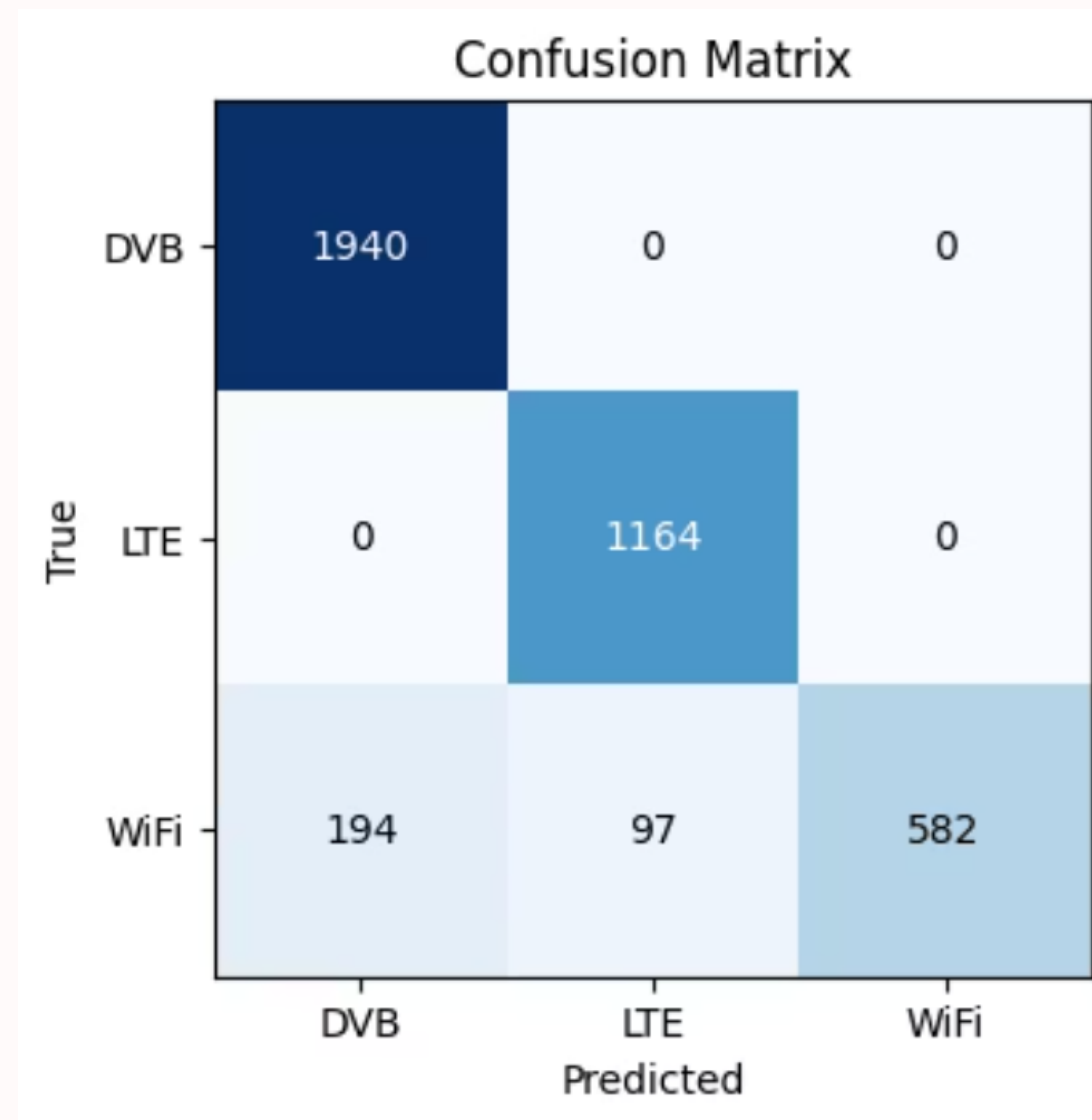
# Transformer-Based Signal Identification: Experimental Setup

We conducted an experiment of our own.

- 1** Massive Dataset Collection  
Over 10,000 diverse signal recordings across multiple countries and environments.
- 2** Signal Diversity  
LTE, Wi-Fi, and DVB-T signals captured under varying conditions.
- 3** Environmental Challenges  
Different times of day, noise levels, and interference patterns.
- 4** Advanced Processing  
Transformer architecture trained directly on raw RF IQ data samples.

What did we get?

# Transformer-Based Signal Identification: Outstanding Results



## Lightning-Fast Inference

~1ms inference time (35 ms signal) on a SBC + edge inference chip, enabling real-time classification.



## High Accuracy

Over 93% classification accuracy.

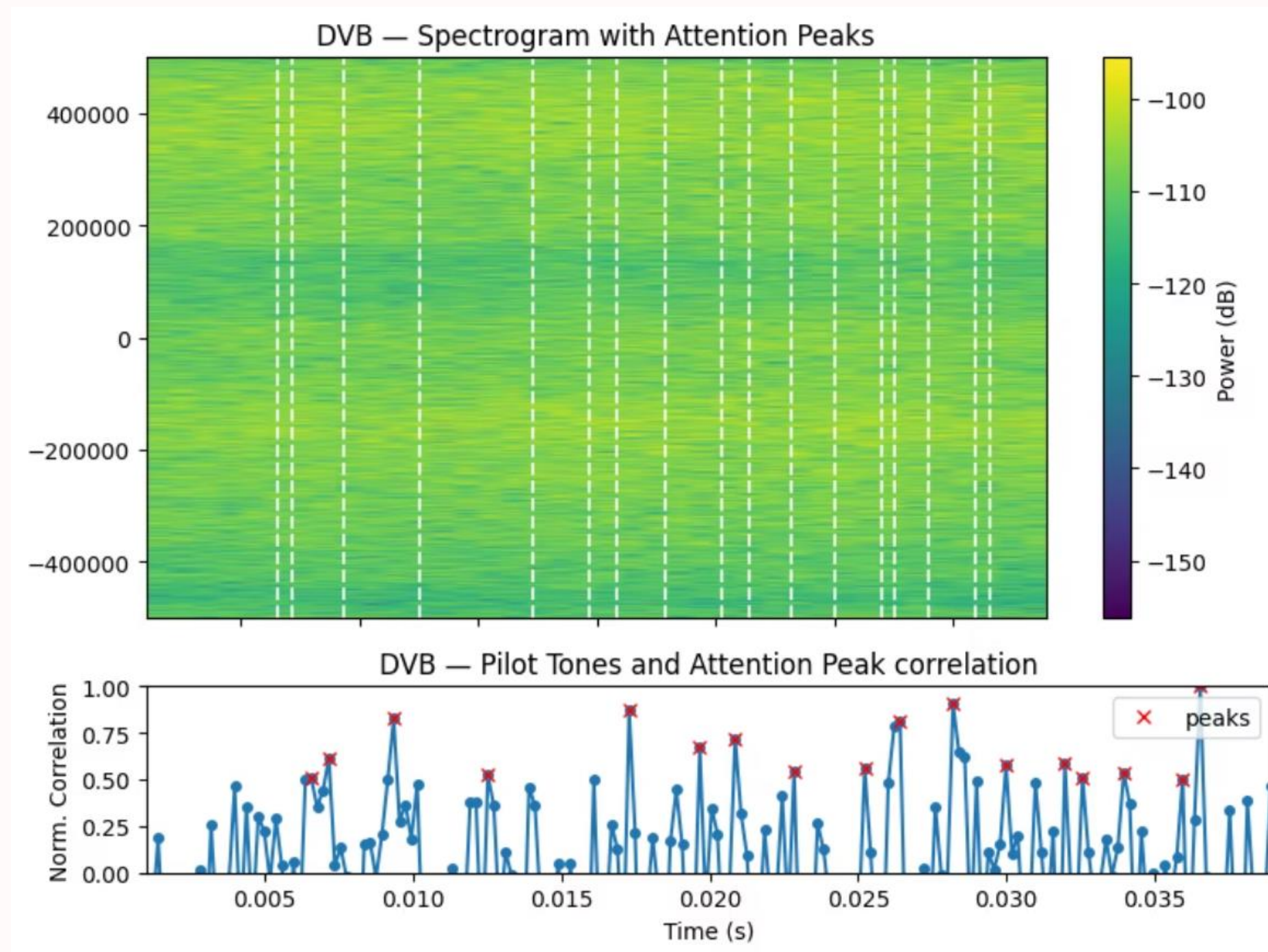
# But that is hardly the exciting part...

AI based signal identification has been demonstrated before. The novelty came from the **features** the model focuses its attention on...



# The model focuses on useful navigation artifacts

- DVB-T example



The model attention peaks **correlated** with the timing of the different OFDM symbol pilot tones, that differ between technologies.

With an average accuracy of 100ns, this enables positioning accuracy of 5-10m using multiple stations.

# We move from this...



## Search for specific signals

Manually scan for predefined signal types across crowded RF spectrum.



## Verify signal presence

Confirm detection through specialized algorithms for each signal type.



## Extract navigation features with known signal model

Apply signal-specific algorithms requiring detailed knowledge of each protocol.

This traditional SoOp approach creates significant challenges:



### Complex

Requires deep expertise in multiple signal protocols and processing techniques.



### Requires maintaining countless models

Each signal type needs unique processing models that must be constantly updated.

# ...to this!

Transformer-based approach simplifies the entire SoOp navigation process:



Highlight high-assurance signals in the spectrum

Single transformer model identifies valuable signals across the entire RF landscape.



Extract features automatically

Model attention mechanisms naturally focus on navigation-relevant features without protocol knowledge.



Calculate position with unified algorithm

Common processing pipeline handles all signal types, requiring no protocol-specific understanding.

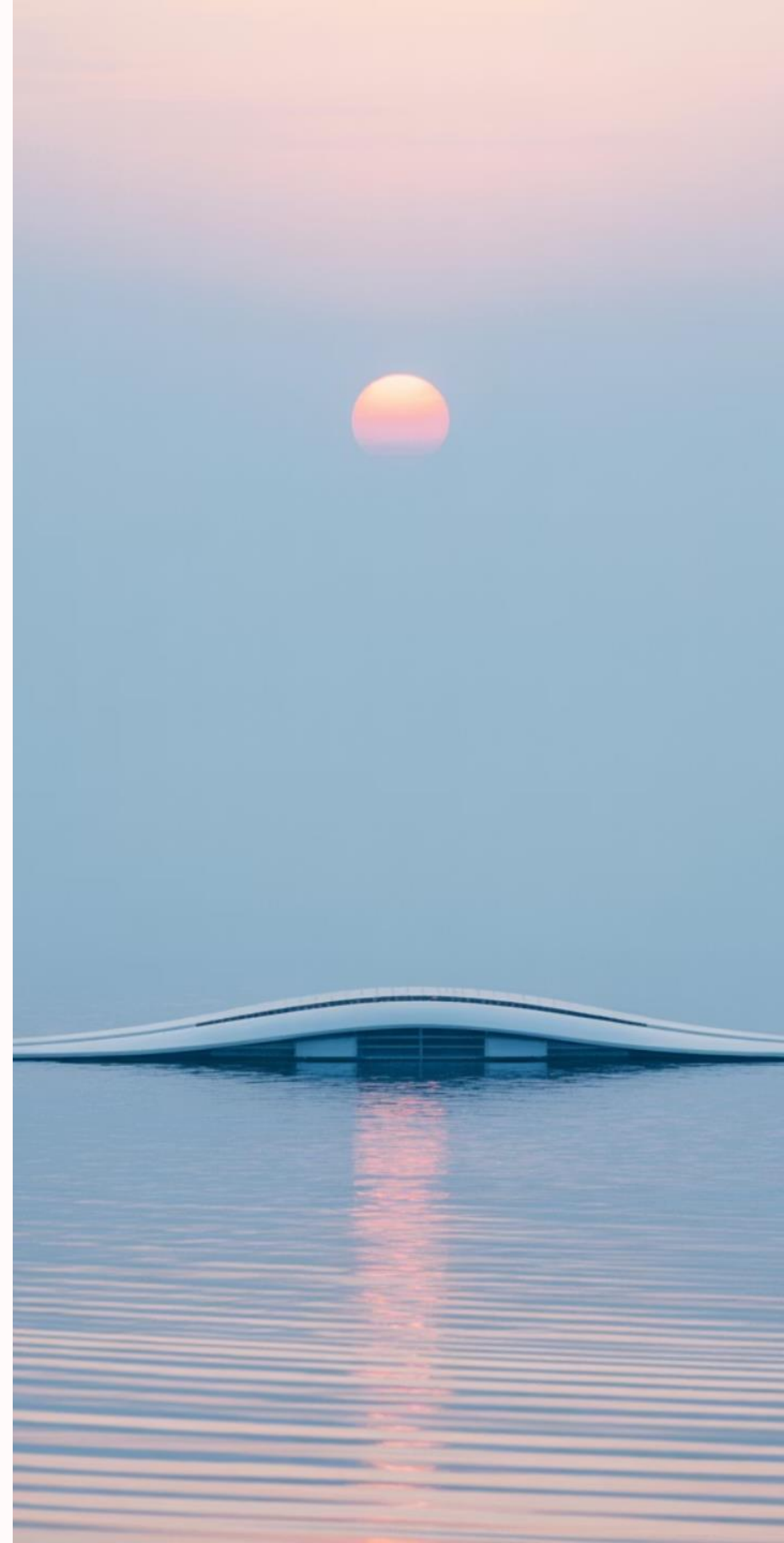


Adapt to changing signals

Self-learning capability adjusts to signal modifications without requiring manual updates.

# Challenges on the Horizon

- **Multipath complexity:** Urban environments create signal reflections that transformer models must learn to filter effectively.
- **Limited training data:** Gathering diverse RF samples across environments and conditions remains resource-intensive.
- **Edge hardware constraints:** Deploying transformer models on low-power navigation devices requires optimization.
- **Regulatory hurdles:** Using commercial signals for positioning raises complex licensing and compliance issues.



Thank you!