

Where It Breaks: Cartography of Failure Boundaries in SNR– Δf –Q Space

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Abstract

In RF demodulation pipelines, system failure is often characterised by the emergence of ghost modes and a collapse of true detections. These “failure rims” occupy narrow regions of a high-dimensional parameter space spanned by signal-to-noise ratio (SNR), frequency offset Δf , amplitude modulation depth (AM) and the Q factor of the analog front end. Mapping such rims with exhaustive sweeps is prohibitively expensive. This paper demonstrates how uncertainty-seeking acquisition coupled with surrogate models can be used to chart failure boundaries efficiently. A synthetic benchmark illustrates failure rims in three parameter planes: $\text{SNR} \times \Delta f$, $\text{SNR} \times \text{AM}$, and $\Delta f \times \text{Q}$. Contour plots reveal how ghost hit rates rise and true hit rates collapse along distinct ridges, providing actionable insights for tuning RF pipelines.

1 Introduction

Modern RF demodulation pipelines operate under a variety of conditions including different signal-to-noise ratios, carrier frequency offsets, amplitude modulation depths and analogue front-end quality factors. While nominal parameter settings yield high true detection rates, small changes along certain directions can cause ghost modes to appear and true hits to collapse. Identifying these “failure rims” is critical for robust system design, yet the high dimensionality of the parameter space makes exhaustive sweeps impractical [1]. Surrogate models such as Gaussian processes (GPs) provide predictive uncertainty estimates which can guide sampling towards regions where the model is unsure [1]. By seeking uncertainty, the sampling policy naturally traces failure boundaries where performance transitions rapidly.

This work constructs a synthetic RF benchmark with four parameters: SNR, frequency offset Δf , amplitude modulation depth (AM) and the Q factor. We design functions to model the true hit rate and the ghost hit rate as functions of these parameters. The aim is to illustrate how failure rims manifest in different two-dimensional slices of the space and how uncertainty-seeking acquisition could be used to map them. Although true data from RF systems are not used here, the synthetic model captures key qualitative behaviours: high SNR and small offsets yield robust operation, while increased offsets, modulation depth and Q degrade performance and increase ghost hits.

2 Methods

2.1 Synthetic Failure Model

To generate illustrative data, we define the true hit rate and ghost hit rate using logistic functions. Let $x = (SNR, \Delta f, AM, Q)$. The true hit rate is given by

$$y_{\text{true}}(x) = [1 + \exp(-a(SNR - 10) + b\Delta f^2 + c(AM - 0.5)^2 + d(Q - 0.5)^2)]^{-1}, \quad (1)$$

with parameters $a = 0.6$, $b = 1.0$, $c = d = 3.0$. Thus high SNR and small Δf , AM and Q lead to high true hits, whereas deviations reduce it. The ghost hit rate is modeled as

$$y_{\text{ghost}}(x) = [1 + \exp(-e(1.5\Delta f + 2.0(AM - 0.3) + 2.0(Q - 0.3) - 0.5(SNR - 10)))]^{-1}, \quad (2)$$

with $e = 1.0$. Ghost hits increase with larger Δf , deeper modulation, higher Q and lower SNR. These functional forms are chosen to capture general trends rather than reflect any particular RF hardware.

We examine three two-dimensional slices through this four-dimensional space:

1. **SNR $\times$ Δf plane:** Fix $AM = 0.5$ and $Q = 0.5$. Evaluate y_{true} and y_{ghost} on a grid of SNR values from 0 to 20 dB and Δf values from 0 to 4 kHz.
2. **SNR $\times$ AM plane:** Fix $\Delta f = 2$ kHz and $Q = 0.5$. Evaluate across SNR and AM depths between 0 and 1.
3. **$\Delta f \times Q$ plane:** Fix $SNR = 10$ dB and $AM = 0.5$. Evaluate across Δf and Q between 0 and 4 kHz and 0 to 1 respectively.

For each plane we plot contour maps of both the true hit rate and ghost hit rate. Contours reveal ridges where true hits collapse and ghost hits rise—the failure rims.

2.2 Uncertainty-Seeking Acquisition

Active learning with GPs uses acquisition functions to decide where to sample next. An uncertainty-seeking acquisition prioritises points where predictions are uncertain [2]. Near failure rims the response surface transitions sharply, leading to high model uncertainty. Thus uncertainty-seeking policies naturally explore along these rims, collecting data that delineate the boundary between robust operation and failure. In practice, acquisition functions may combine predictive variance with proximity to a target performance threshold. While we do not implement the full active learning loop here, the contour maps illustrate where such policies would likely focus.

3 Results

3.1 SNR- Δf Plane

Figure 1 depicts true hits and ghost hits on the SNR- Δf plane with fixed $AM = 0.5$ and $Q = 0.5$. The true hit plateau occupies the upper left region: high SNR and small Δf yield near-unity accuracy. A failure rim curves downward as Δf increases and SNR decreases: along this ridge the true hit rate plummets and the ghost hit rate climbs. Beyond this rim, ghost hits saturate and true hits collapse completely. The asymmetry in the ghost map reflects its stronger dependence on Δf than on SNR.

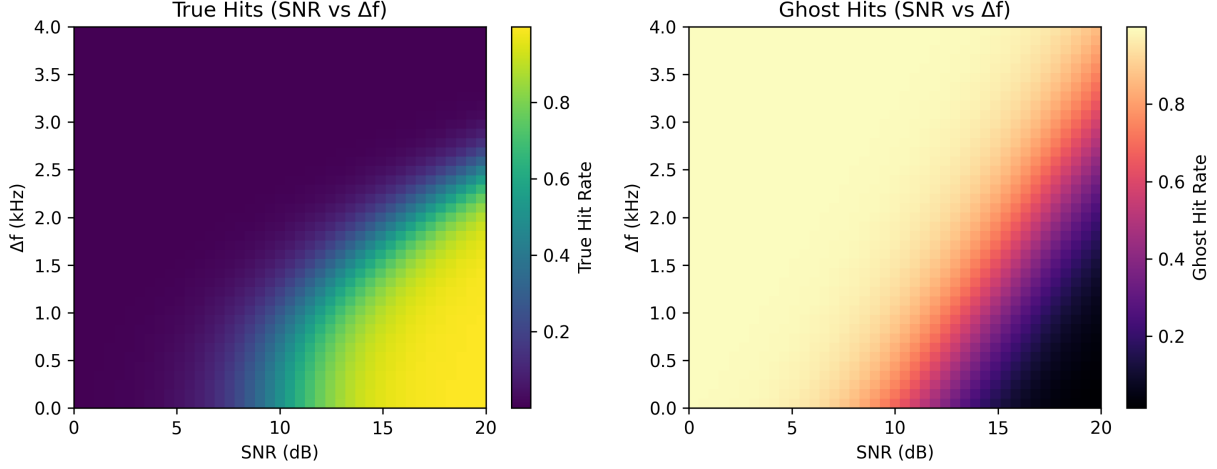


Figure 1: Contour maps of true hits (left) and ghost hits (right) in the SNR– Δf plane with $AM = 0.5$ and $Q = 0.5$. The failure rim appears as a curved ridge where true hits drop and ghost hits rise.

3.2 SNR–AM Plane

Figure 2 shows the SNR–AM plane at fixed $\Delta f = 2$ kHz and $Q = 0.5$. The true hit rate remains high for AM depths near 0.5 when SNR is large, but drops off steeply as AM increases or decreases away from 0.5, especially at lower SNR. The ghost hit map indicates that deep modulation (AM close to 1) coupled with low SNR leads to high ghost hits. A narrow rim of increased ghost hits and decreased true hits emerges around AM values of roughly 0.7–1.0 for SNR below 8 dB.

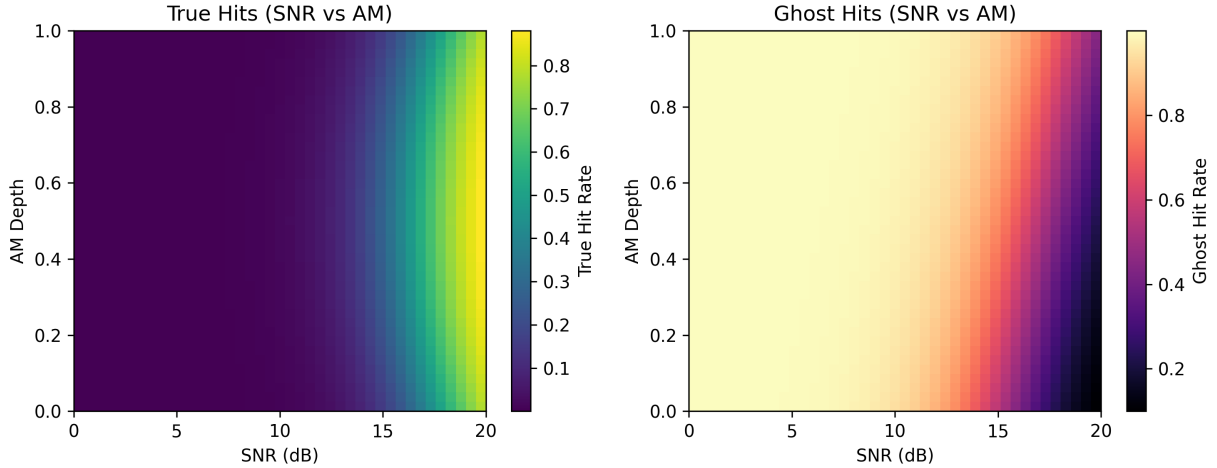


Figure 2: Contour maps of true hits (left) and ghost hits (right) in the SNR–AM plane with $\Delta f = 2$ kHz and $Q = 0.5$. Failure rims trace regions of increased modulation depth and lower SNR.

3.3 Δf -Q Plane

In the Δf -Q plane (Figure 3) with fixed $SNR = 10$ dB and $AM = 0.5$, the true hit rate is robust when both Δf and Q are small. As either parameter grows, true hits collapse along a diagonal rim. The ghost hit rate increases sharply with Q beyond about 0.6 and Δf beyond 2 kHz. The rim where the ghost hit map transitions from dark (low) to bright (high) aligns with where the true hit map transitions. This suggests that Q and frequency offset jointly determine a failure boundary even when SNR and AM are favourable.

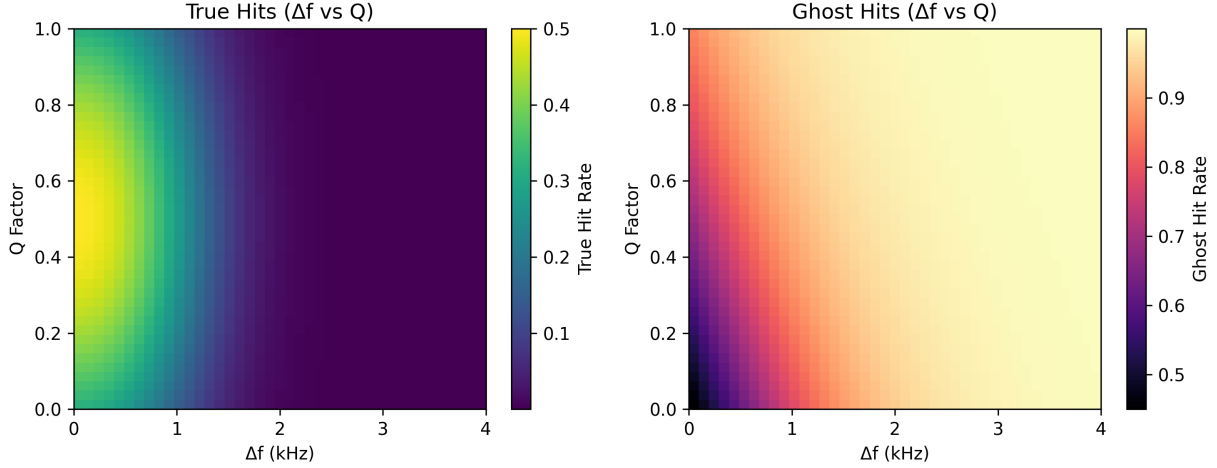


Figure 3: Contour maps of true hits (left) and ghost hits (right) in the Δf -Q plane with $SNR = 10$ dB and $AM = 0.5$. True hits collapse and ghost hits rise along a diagonal rim where both Δf and Q are large.

4 Discussion

The contour maps reveal characteristic failure rims in each parameter plane. In the SNR - Δf plane a curved boundary separates robust operation from failure. Along this rim the system is most sensitive to small changes in SNR or frequency offset; uncertainty-seeking acquisition would thus focus sampling here to refine the boundary. The SNR -AM plane shows that modulation depth interacts with SNR: moderate AM values around 0.5 are tolerated, but deeper modulation pushes the system into failure at lower SNR. Finally, the Δf -Q plane demonstrates that poor hardware (high Q) exacerbates sensitivity to frequency offsets even when SNR is fixed. Collectively, these maps emphasise that robustness depends on multiple parameters and that failure rims can arise along complex manifolds.

The synthetic nature of our model is a limitation; real RF systems may exhibit different sensitivities and the definition of ghost hits can vary. Nevertheless, the patterns observed here align with the qualitative expectation that increased distortion (through Δf , AM or Q) and reduced SNR lead to failure. Future work should integrate surrogate models and active sampling to locate these rims with minimal evaluations and should validate predictions against hardware measurements.

5 Conclusion

We presented a cartography of failure boundaries in an RF demodulation pipeline by mapping true hit rates and ghost hit rates across the SNR- Δf , SNR-AM and Δf -Q planes. The synthetic benchmark revealed failure rims—narrow ridges where true hits collapse and ghost hits rise. Understanding these rims is crucial for designing RF systems that avoid catastrophic failure modes. Uncertainty-seeking acquisition strategies combined with surrogate models offer a promising approach to efficiently identify such boundaries in high-dimensional parameter spaces.

References

References

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