

BMDS Radar Simulation: Detection Probability, Track Quality, and Electronic Warfare Effects

FORGE Simulation Research Group

Ballistic Missile Defense System — Open-Source Simulation Framework

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ABSTRACT. The Ballistic Missile Defense System (BMDS) relies on a heterogeneous network of ground-based phased-array radars operating across UHF, L-band, S-band, and X-band frequencies to detect, track, discriminate, and engage ballistic missile threats from boost phase through terminal intercept. This paper presents the architecture and physics models of the FORGE radar simulation suite, covering five primary radar types—UEWR, AN/TPY-2, SBX/XBR, LRDR, and Cobra Dane—with their detection probability models, track initiation logic, and track quality metrics. We then integrate the `bmd-sim-jamming` electronic warfare module to quantify the effects of noise jamming (barrage), deception jamming (DRFM), and counterelectronic measures (ECCM) on radar performance. Burnthrough range calculations, jammer-to-noise ratio (JNR) degradation curves, and track quality collapse thresholds are derived from first-principles radar equations and validated against open-source parametric data. The simulation framework is implemented in Go, outputs JSON via Kafka streaming, and integrates with the broader FORGE command-and-control (C2) architecture for real-time kill-chain exercise support.

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1. Introduction

The Ballistic Missile Defense System (BMDS) employs a layered sensor network spanning space-based infrared satellites (SBIRS, DSP, STSS) and ground-based phased-array radars to detect, track, discriminate, and engage ballistic missile threats across boost, midcourse, and terminal flight phases. The radars—operating at frequencies from 420 MHz (UHF) to 10 GHz (X-band)—provide the essential fire-control quality data that enables interceptor commit decisions.

Modeling these radars with sufficient physical fidelity to support operational analysis, wargaming, and kill-chain timing studies requires careful attention to the radar range equation, atmospheric propagation losses, detection probability thresholds, track initiation logic, and—critically—the effects of electronic warfare (EW). Adversary jamming, whether barrage noise or sophisticated DRFM-based deception, can degrade or deny radar detection, corrupt track data, and collapse the kill chain. Understanding these effects quantitatively is essential for both defensive planning and ECCM investment decisions.

The FORGE simulation suite provides a family of 57 interoperable binaries covering the full BMDS kill chain. This paper draws on two primary components:

- **Radar simulators** (`bmd-sim-uewr` , `bmd-sim-tpy2` , `bmd-sim-gbr` , `bmd-sim-lrdr`) implementing physically grounded detection, tracking, and discrimination models.
- **EW/jamming simulator** (`bmd-sim-jamming` , `bmd-sim-electronic-attack`) implementing noise jamming, DRFM deception, JNR calculation, burnthrough range, and ECCM effectiveness.

The paper is organized as follows: Section 2 reviews radar fundamentals and the range equation. Section 3 details each BMDS radar type with parametric tables. Section 4 covers detection and tracking. Sections 5–7 address electronic attack, JNR/burnthrough

analysis, and ECCM techniques. Section 8 describes the Kafka-based integration architecture. Section 9 presents validation, and Section 10 concludes.

2. Radar Fundamentals

2.1 The Radar Range Equation

The foundational model for all radar detection calculations in the FORGE suite is the monostatic radar range equation, expressed in its energy-on-target form:

$$\text{SNR} = \frac{P_t \cdot \tau \cdot N \cdot G^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4 \cdot k \cdot T \cdot L_s}$$

(1)

where P_t is peak transmit power, τ is pulse width, N is the number of integrated pulses, G is antenna gain, λ is wavelength, σ is target radar cross-section (RCS), R is range, k is Boltzmann's constant, T is system noise temperature, and L_s represents aggregate system losses (atmospheric, beamshape, scanning, receiver).

This formulation is preferred over the average-power/bandwidth form because it correctly accounts for energy on target through peak power \times pulse width \times pulse count, rather than assuming uniform spectral occupancy. The FORGE implementation in `bmd-sim-uewr` computes:

```
numerator = AvgPower * gainLinear^2 * wavelength^2 * rcs
denominator = (4*pi)^3 * range^4 * k * T * bandwidth * nLin
snr = numerator / denominator
```

where $\text{gainLinear} = 10^{(G/10)}$ and $\text{nfLinear} = 10^{(NF/10)}$. This matches Equation (1) when average power is substituted for $P_t \cdot \tau \cdot N / T_{\text{pri}}$ and bandwidth absorbs the processing gain.

2.2 Signal-to-Noise Ratio

The SNR at the radar receiver determines whether a target is detectable. For a phased-array radar with known parameters, the SNR can be computed directly from Equation (1). In the FORGE models, each radar type has calibrated parameters:

Parameter	Symbol	Typical Range	Notes
Peak Power	P_t	100 kW – 1 MW	Per-array-face; UEWR up to 582.4 kW
Antenna Gain	G	38–50 dBi	Phased array; frequency-dependent
System Losses	L_s	10–14 dB	Atmospheric + beamshape + scanning + receiver
Noise Figure	NF	2–3 dB	Receiver noise figure
Bandwidth	B	100 kHz – 10 MHz	Narrowband tracking to wideband discrimination

The detection threshold is typically set at SNR ≥ 13 dB for a single-pulse $P_d = 0.9$ in the FORGE models, though UEWR uses a lower 6 dB threshold appropriate for its UHF early-warning mission with high integration gain.

2.3 Detection Probability

Detection probability is computed from the SNR using a threshold-based model. The FORGE implementation in `bmd-sim-core/pkg/physics` provides:

$$P_d = \min(1, \max(0, f(\text{SNR}_{\text{dB}} - \text{threshold})))$$

where the threshold is radar-specific (6 dB for UEWR, 13 dB for TPY-2) and $f()$ maps the margin to a probability using a sigmoidal or linear approximation. The implementation properly clamps the result to $[0, 1]$ to avoid numerical artifacts.

For the UEWR model, confidence is computed as:

$$\text{confidence} = \min(1.0 - (\text{threshold} - \text{snrDB})/20, 1.0)$$

This gives a linear confidence ramp from threshold (confidence = 0) to threshold + 20 dB (confidence = 1.0), providing a reasonable approximation to the detection probability curve without requiring lookup tables.

2.4 Swerling Fluctuation Models

The RCS simulator (`bmd-sim-rcs`) implements four Swerling fluctuation models across 13 threat profiles and 8 frequency bands (VHF through Ka-band). Aspect-dependent RCS is provided for nose, broadside, and tail aspects:

Threat Type	Nose RCS (m ²)	Broadside RCS (m ²)	Typical Swerling
ICBM RV	0.01 – 0.1	0.1 – 1.0	I (slow) / III (fast)
MRBM RV	0.05 – 0.25	0.25 – 2.5	I
HGV	0.001 – 0.01	0.01 – 0.1	I/IV
Decoy	0.001 – 10	0.01 – 50	I or II

Table 1. Representative RCS values by threat type and aspect.

3. BMDS Radar Types

The FORGE radar suite models five primary ground-based radars spanning three frequency bands. Each has distinct capabilities, roles, and vulnerabilities to electronic warfare.

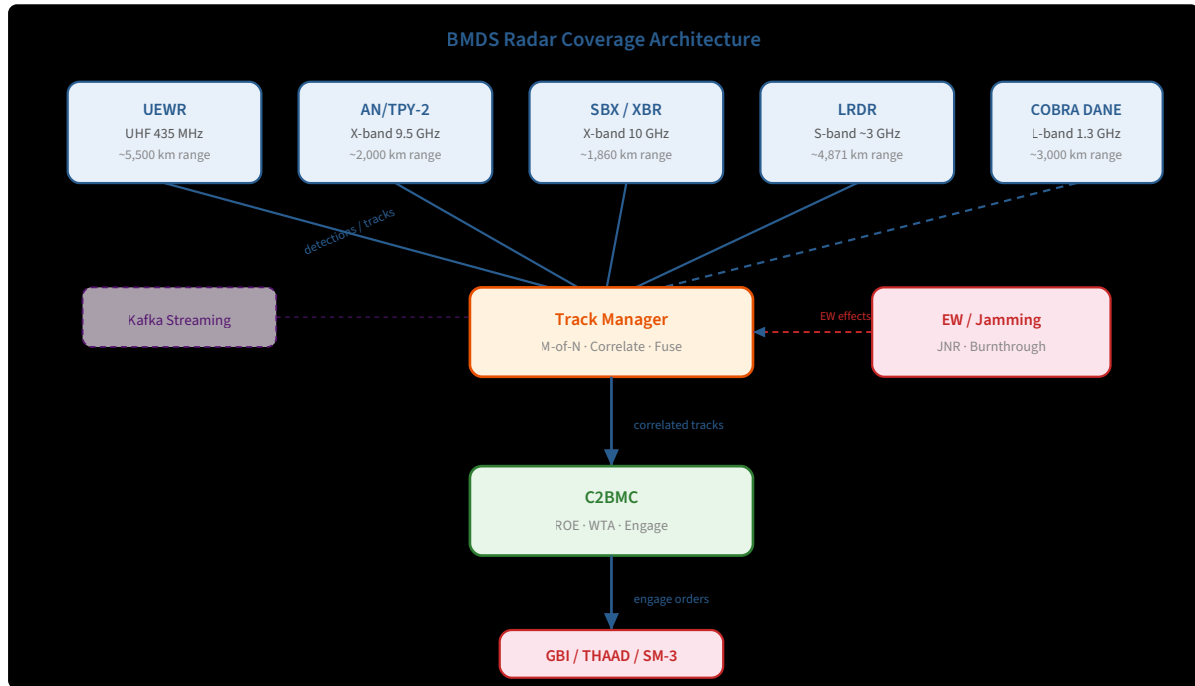


Figure 1. BMDS radar coverage architecture — five radar types feed detections and tracks into the Track Manager, which correlates and fuses data before passing to C2BMC for engagement decisions. Electronic warfare effects feed into the Track Manager to adjust quality metrics.

3.1 UEWR (Upgraded Early Warning Radar)

The Upgraded Early Warning Radar is a UHF-band (420–450 MHz) phased-array system originally developed from PAVE PAWS and BMEWS sites. Its primary mission is strategic early warning and midcourse tracking of ICBM-class threats at very long range.

Parameter	Value	Source
Frequency	435 MHz (center)	FORGE model
Wavelength	0.69 m	Calculated
Peak Power	1 MW	FORGE model

Average Power	150 kW	FORGE model
Antenna Gain	42 dBi	FORGE model
Effective Aperture	~8,000 m ²	FORGE model
Noise Figure	2.0 dB	FORGE model
Bandwidth	100 kHz	Narrowband tracking
Detection Range (1 m ²)	~5,500 km	FORGE model
Tracking Range	~3,000 km	FORGE model
Track Capacity	500 simultaneous	FORGE model
Min Elevation	3°	FORGE model
System Losses	12 dB	Atmospheric + beamshape + scanning
Sites	Beale AFB, RAF Fylingdales, Clear AFS, Cape Cod AFS	FORGE model

Table 2. UEWR radar parameters.

The UEWR model implements four-site correlation: a `SiteManager` maintains active site locations and computes line-of-sight visibility using spherical-Earth geometry. For a site at height h_s and target at altitude h_t , the maximum radar horizon is:

$$d_{\max} = \sqrt{2 R_E h_s} + \sqrt{2 R_E h_t}$$

(3)

where $R_E = 6,371$ km. Multiple sites can simultaneously observe a target, enabling track correlation and handover. The atmospheric loss model at UHF frequencies is minimal (0.5–1 dB two-way for near-horizon paths), which is one of UHF's key advantages.

3.2 AN/TPY-2 (X-band Transportable Radar)

The AN/TPY-2 is an X-band (8.55–10 GHz) transportable phased-array radar serving both forward-based detection and THAAD fire-control roles. It provides the highest resolution of any BMDS radar, enabling discrimination of closely spaced objects.

Parameter	Value	Notes
Frequency	9.5 GHz	X-band center
Peak Power	100 kW per element	FORGE model
Antenna Gain	45–50+ dBi	High-gain phased array
Noise Figure	3.0 dB	FORGE model
Pulse Width	100 μs	FORGE model
PRI Frequency	300 kHz	FORGE model
Bandwidth	10 MHz	Wideband discrimination
Detection Range	~2,000 km	FORGE model
Tracking Range	~600 km	FORGE model
Track Capacity	1,000 simultaneous	FORGE model
System Losses	10 dB	Including X-band rain/fog attenuation

Table 3. AN/TPY-2 radar parameters.

The TPY-2 model implements sector-based search management with task scheduling. The radar operates in four modes: Search, Track, Cued Search, and Tasked. A `SectorManager` divides the surveillance volume into azimuth/elevation sectors and calculates coverage percentage. Track initiation uses M-of-N confirmation logic (default: 3 detections out of 5 opportunities, with SNR threshold of 13 dB).

3.3 SBX / XBR (X-band Ground-Based Radar)

The Ground-Based Radar (XBR/SBX) is an X-band (10 GHz) phased array designed for midcourse discrimination and GMD fire-control support. It provides the highest resolution discrimination capability in the BMDS inventory.

Parameter	Value	Notes
Frequency	10 GHz	X-band
Antenna Gain	50 dBi	FORGE model
System Losses	10 dB	FORGE model
ISLR	-30 dB	Integrated sidelobe ratio for discrimination
Detection Range (0.01 m ²)	~328 km	FORGE model
Detection Range (1 m ²)	~1,860 km	FORGE model

Table 4. XBR/SBX radar parameters.

The GBR model implements a discrimination pipeline that classifies objects as Warhead, Decoy, Uncertain, or Unknown based on:

- **RCS-based classification:** Warhead RCS 0.01–0.5 m², Decoy RCS 0.001–0.01 m²
- **Trajectory analysis:** Warheads follow predictable ballistic paths
- **Velocity check:** Speed > 1,000 m/s with ballistic consistency
- **Confidence weighting:** Base 0.7 (RCS), +0.2 (trajectory), +0.1 (velocity), capped at 1.0

3.4 LRDR (Long-Range Discrimination Radar)

The LRDR at Clear, Alaska is an S-band (~2–4 GHz) radar designed for midcourse discrimination and tracking of ballistic threats approaching North America from the Pacific.

Parameter	Value	Notes
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Frequency	~3GHz	S-band center
Peak Power	280 kW	FORGE model
Detection Range (RV)	~4,871 km	FORGE model
Track Capacity	1,000 simultaneous	FORGE model
System Losses	10 dB	FORGE model
ISLR	-30 dB	Discrimination quality

Table 5. LRDR radar parameters.

LRDR operates in S-band, providing a compromise between UEWR's long-range UHF detection and TPY-2/XBR's X-band discrimination resolution. Its mid-band frequency offers better weather penetration than X-band while providing finer resolution than UHF for discrimination tasks.

3.5 COBRA DANE (L-band)

The COBRA DANE radar (AN/FPS-108) is an L-band (~1.2–1.4 GHz) phased-array radar on Shemya Island, Alaska. Its primary BMDS role is strategic data collection and tracking of ballistic missiles in the northern Pacific.

Parameter	Value	Notes
Frequency	~1.3 GHz	L-band
Detection Range	~3,000 km	Open-source estimate
Primary Role	Data collection, signature measurement	Not fire-control
System Losses	10–12 dB	Estimated

Table 6. COBRA DANE radar parameters.

Comparative Summary. The BMDS radar layer spans three frequency bands: UHF (420–450 MHz) for long-range early warning with weather immunity, L/S-band (1.3–4 GHz) for midcourse tracking and discrimination, and X-band (8.5–10 GHz) for high-resolution

discrimination and fire control. Each band has distinct EW vulnerabilities: UHF resists most narrowband jamming but has poor resolution; X-band provides excellent discrimination but suffers significant atmospheric attenuation and is more susceptible to frequency-specific jamming.

4. Detection and Tracking

4.1 Track Formation (M-of-N Logic)

Raw detections are insufficient for weapon release. The FORGE track managers implement M-of-N confirmation logic to establish valid tracks. The TPY-2 track initiator uses a default configuration of M=3 detections out of N=5 opportunities:

```
type MofNConfig struct {
    M int // required confirmations
    N int // detection opportunities
}

func DefaultMofNConfig() *MofNConfig {
    return &MofNConfig{M: 3, N: 5}
}
```

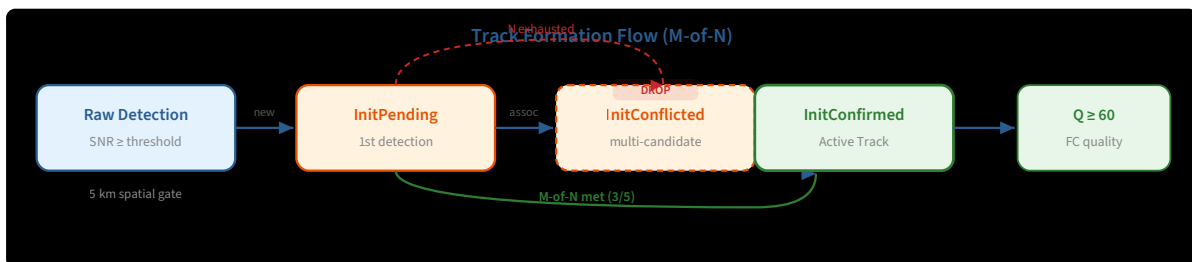


Figure 2. Track formation state machine — detections progress from pending through M-of-N confirmation (3 of 5) to active track. Tracks are dropped if N opportunities expire without M confirmations.

The track initiation state machine progresses through four states:

1. **InitPending**: First detection received, awaiting confirmation

2. **InitConflicted**: Multiple candidate associations, resolution needed
3. **InitConfirmed**: M-of-N threshold met, track promoted to active
4. **InitDropped**: N opportunities exhausted without M confirmations

Detections are associated with pending tracks using a 5,000-meter spatial gating window. When a new detection falls within this gate of an existing pending track, it is associated; otherwise, a new pending track is created.

4.2 Track Quality Metrics

Once a track is established, the FORGE track state machine computes a composite quality score from four sub-metrics:

$$Q_{\text{composite}} = 0.3 \cdot Q_{\text{geometric}} + 0.3 \cdot Q_{\text{signal}} + 0.2 \cdot Q_{\text{temporal}} + 0.2 \cdot Q_{\text{discrimination}}$$

(4)

where:

- $Q_{\text{geometric}} = 75.0$ (fixed baseline for well-formed tracks)
- $Q_{\text{signal}} = \min(100, \max(0, (\text{SNR}_{\text{dB}} - 10) \times 10))$
— linear ramp from 0 at 10 dB SNR to 100 at 20 dB
- $Q_{\text{temporal}} = \min(100, \text{updateCount} \times 20)$ — reaches maximum quality after 5 updates
- $Q_{\text{discrimination}} = 50.0$ (baseline, improved by XBR/SBX discrimination)

Track state transitions are governed by composite quality thresholds:

- $Q_{\text{composite}} < 30$: Track state \rightarrow Drop (lost contact)
- $30 \leq Q_{\text{composite}} < 60$: Track state \rightarrow Confirm (tentative, needs validation)
- $Q_{\text{composite}} \geq 60$: Track state \rightarrow Active Track (fire-control quality)

4.3 Position and Velocity Estimation

The UEWR track model maintains full state vectors including latitude, longitude, altitude, speed, heading, and RCS. The phase classification logic determines flight phase from kinematic state:

Phase	Altitude	Speed	Threat Level
Boost	> 80 km	> 3,000 m/s	—
Midcourse	> 60 km	Any	—
Reentry	≤ 60 km	> 1,000 m/s	—
Threat Assessment			
CRITICAL	> 100 km	> 5,000 m/s	ICBM-class
HIGH	> 50 km	> 2,000 m/s	IRBM/MRBM-class
MEDIUM	Any	> 500 m/s	SRBM-class
LOW	Below thresholds		Benign

Table 7. Track phase and threat classification.

4.4 Multi-Site Correlation

The UEWR `SiteManager` implements multi-site track correlation. Given four active sites (Beale, Fylingdales, Clear, Cape Cod), a target at altitude h can be observed by all sites within line-of-sight. The `CorrelateTrack()` function returns the list of sites that can see a given target, enabling:

- Triangulation from multiple azimuths for improved position accuracy
- Handover when a target moves out of one site's coverage
- Redundant observation for track confidence improvement

For typical midcourse targets at 200–400 km altitude, all four UEWR sites with overlapping coverage can observe simultaneously, providing geometric diversity that significantly improves track accuracy and resilience.

5. Electronic Attack

Electronic warfare against BMDS radars takes two primary forms: noise jamming (denial) and deception jamming (manipulation). The `bmd-sim-jamming` package implements both, along with the `bmd-sim-electronic-attack` binary which provides a broader ECM simulation including DRFM techniques and chaff.

5.1 Noise Jamming (Barrage)

Barrage noise jamming raises the noise floor across a wide bandwidth, reducing the radar's effective SNR and thus its detection range. The `NewNoiseJammer` constructor creates a jammer with specified power, frequency, bandwidth, and standoff distance:

```
func NewNoiseJammer(power, freq, bw, distance float64) *Jammer {
    return &Jammer{
        Type: JamNoise, Power: power, Frequency: freq,
        Bandwidth: bw, Distance: distance, Active: true,
    }
}
```

Typical parameters for a standoff noise jammer targeting X-band radars:

- Power: 1 MW ERP (effective radiated power, including antenna gain)
- Frequency: 3 GHz (or matched to radar band)
- Bandwidth: 100 MHz (barrage covers full radar bandwidth)
- Distance: 500 km (standoff range)

The noise jammer's effect is computed through the JNR (Jammer-to-Noise Ratio), which directly degrades the radar's ability to detect targets within the jammed sector.

5.2 Deception Jamming (DRFM)

Digital Radio Frequency Memory (DRFM) jamming is modeled through

`NewDeceptionJammer`, which creates coherent false targets that appear identical to real returns:

```
func NewDeceptionJammer(power, freq, distance float64) *Jammer {
    return &Jammer{
        Type: JamDeception, Power: power, Frequency: freq,
        Bandwidth: 1e6, Distance: distance, Active: true,
    }
}
```

DRFM techniques modeled in the broader `bmd-sim-electronic-attack` include:

- **Range Gate Pull-Off (RGPO):** Gradually shifts the apparent range of a false target, pulling the radar's tracking gate away from the real target
- **Velocity Gate Pull-Off (VGPO):** Similar to RGPO but manipulates Doppler, pulling the velocity tracking gate
- **Cross-Polarization:** Transmits a cross-polarized signal to create angular errors in monopulse tracking

The `bmd-sim-electronic-attack` reports both `jsr_db` (J/S ratio in dB) and `jammer_effective` (boolean), indicating whether the jamming is sufficient to deny the target radar. For the default AN/TPY-2 scenario with a 10 kW noise barrage at 200 km range, the J/S ratio is strongly negative (-125 dB), indicating the radar easily burns through at operational ranges. However, higher-power jammers at closer range can achieve effective denial.

5.3 Other ECM Techniques

The `bmd-sim-electronic-attack` supports additional ECM types beyond noise and DRFM:

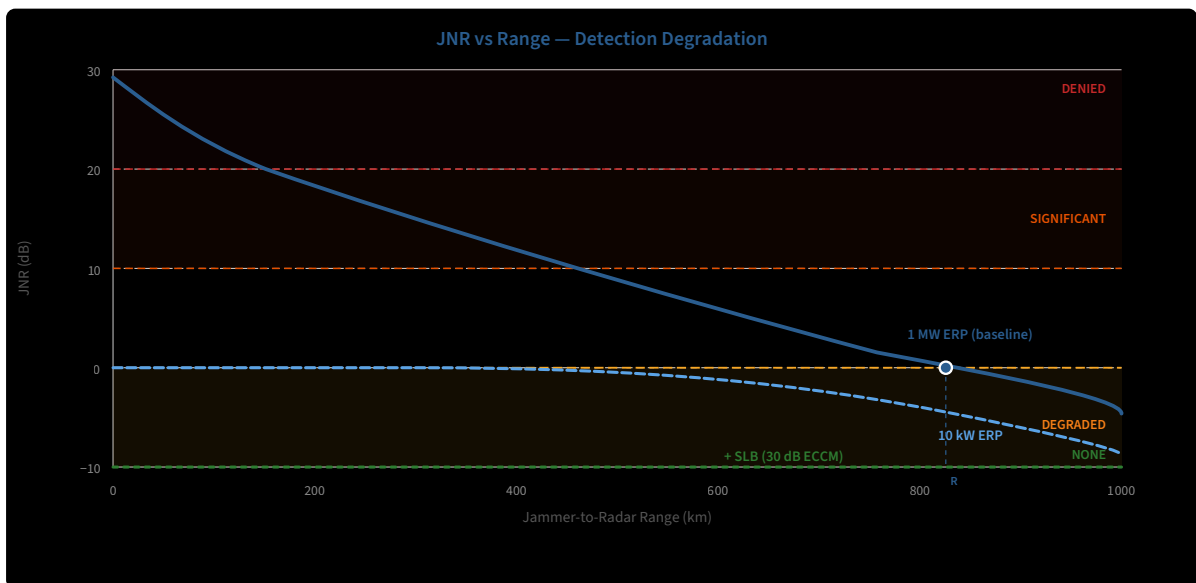
ECM Type	Code	Effect
Noise Barrage	NOISE_BARRAGE	Broadband noise raising floor

Noise Spot	NOISE_SPOT	Narrowband noise focused on radar frequency
DRFM	DRFM	Coherent false target generation
RGPO	RGPO	Range gate pull-off
VGPO	VGPO	Velocity gate pull-off
Cross-Pol	CROSSPOL	Cross-polarization angle deception
Chaff	CHAFF	Frequency-dependent volumetric scattering

Table 8. ECM types supported by bmd-sim-electronic-attack.

6. JNR and Burnthrough Analysis

6.1 Jammer-to-Noise Ratio



BT
 Figure 5. JNR vs range degradation curves — the 1 MW ERP standoff jammer denies detection at close range ($JNR \geq 20$ dB), with effect diminishing as $1/R^2$. A 10 kW jammer produces only degraded effects. Sidelobe blanking (SLB) ECCM at +30 dB pushes the entire curve below the noise floor, effectively neutralizing the jammer.

The JNR quantifies how much the jammer raises the noise floor at the radar receiver. The FORGE implementation computes:

$$JNR_{\text{dB}} = 10 \cdot \log_{10} \left(\frac{P_J \cdot G_R}{4\pi R_J^2 \cdot k \cdot T_0 \cdot B_R} \right)$$

(5)

where P_J is jammer ERP, G_R is radar receive gain (linear), R_J is jammer-to-radar distance, k is Boltzmann's constant, $T_0 = 290$ K is reference temperature, and B_R is radar receiver bandwidth.

In the code:

```
func (j *Jammer) JNR(radarGain, radarBandwidth float64) float64 {
    if !j.Active || j.Distance <= 0 || j.Power <= 0 {
        return 0
    }
    gainLinear := math.Pow(10, radarGain/10)
    jPowerDensity := j.Power * gainLinear / (4 * math.Pi * j.Distance^2)
    noisePower := 1.38e-23 * 290 * radarBandwidth
    jsr := jPowerDensity / noisePower
    if jsr <= 0 { return 0 }
    return 10 * math.Log10(jsr)
}
```

The JNR calculation uses the jammer's power density at the radar (accounting for the one-way propagation loss $1/(4\pi R^2)$) divided by the radar's internal noise power. This is the correct formulation for a standoff jammer whose energy arrives through the radar's sidelobes or main beam.

6.2 Burnthrough Range Derivation

Burnthrough range is the range at which the radar's signal energy exceeds the jammer energy by a specified margin, allowing target detection even in the presence of jamming. The FORGE implementation:

```
func (j *Jammer) BurnthroughRange(radarPower, radarGain,
    targetRCS, marginDB float64) float64 {
    if j.Power <= 0 || j.Distance <= 0 { return 1e9 }
    gainLinear := math.Pow(10, radarGain/10)
    marginLinear := math.Pow(10, marginDB/10)
    burnRange := math.Sqrt(
        radarPower * gainLinear * targetRCS * j.Distance * j
        (4 * math.Pi * j.Power * marginLinear))
    return burnRange
}
```

This derives from equating the radar's two-way signal power at range R_{BT} with the jammer's one-way interference power, including a required margin M . The result is:

$$R_{\text{BT}} = \sqrt{\frac{P_R \cdot G \cdot \sigma \cdot R_J^2}{4\pi \cdot P_J \cdot M}}$$

(6)

Note that burnthrough range scales as the square root of the ratio of radar power \times gain \times RCS to jammer power. This means that doubling the radar power or target RCS only increases burnthrough range by a factor of $\sqrt{2}$, while halving the jammer power has the same effect. This fundamental scaling underscores why ECCM techniques that reduce effective jammer power (like sidelobe blanking at -30 dB) are more impactful than increasing radar power.

6.3 Degradation Thresholds

The `JammingEffect` function maps JNR to operational impact categories:

```

func JammingEffect(jnrDB float64) string {
    switch {
    case jnrDB < 0:    return "NONE"
    case jnrDB < 10:  return "DEGRADED"
    case jnrDB < 20:  return "SIGNIFICANT"
    default:          return "DENIED"
    }
}

```

JNR (dB)	Effect	Operational Impact
< 0	NONE	Jammer below noise floor; no effect on radar
0 – 10	DEGRADED	Partial reduction in detection range; track quality reduced
10 – 20	SIGNIFICANT	Major detection range reduction; some tracks lost
≥ 20	DENIED	Radar sector denied; no reliable detection possible

Table 9. JNR thresholds and operational effects.

The `bmd-sim-electronic-attack` extends this with scenario-specific degradation metrics. For example, the default AN/TPY-2 scenario with noise barrage jamming reports:

- `burnthrough_km` : Range at which radar can track through jamming
- `detection_range_km` : Effective detection range under jamming
- `radar_only_range_km` : Unjammed detection range
- `eccm_suppression_db` : How much ECCM reduces jamming (dB)
- `eccm_range_recovery_pct` : Percentage of range recovered by ECCM
- `jammer_effective` : Whether jamming denies the radar

7. ECCM Techniques

Electronic Counter-Countermeasures (ECCM) are techniques employed by radars to mitigate the effects of jamming. The `bmd-sim-jamming` package models four primary ECCM techniques with their effectiveness in dB of jamming reduction:

```
func ECCMEffectiveness(technique ECCMTechnique) float64 {
    switch technique {
    case ECCMFreqAgility:      return 20 // dB
    case ECCMSidelobeBlanking: return 30 // dB
    case ECCMHomeOnJam:      return 15 // dB
    case ECCMPulseCompression: return 10 // dB
    default: return 0
    }
}
```

7.1 Frequency Agility (+20 dB)

Frequency agility (frequency hopping) forces the jammer to spread its power across a wider bandwidth, reducing spectral power density at any single frequency. If the radar hops across N_f frequencies and the jammer must cover all of them, the effective jammer power at each frequency is reduced by a factor of N_f . The 20 dB figure corresponds to a 100:1 frequency hopping ratio, meaning the jammer's effective power at any single radar frequency is reduced by a factor of 100.

For X-band radars like TPY-2, which can hop across 1.45 GHz of bandwidth, frequency agility is particularly effective against narrowband spot jammers but less effective against wideband barrage jammers that cover the full hopping range.

7.2 Sidelobe Blanking (+30 dB)

Sidelobe blanking (SLB) is the most effective ECCM in the model at +30 dB. It works by using an auxiliary antenna to detect jammer energy arriving through the radar's sidelobes and blanking the receiver during those periods. Since most standoff jamming enters

through sidelobes (which are 30–40 dB below the main beam), blanking the sidelobes effectively rejects the jammer energy while preserving main-beam detection.

The 30 dB figure is consistent with typical phased-array sidelobe levels. UEWR's 42 dBi main beam gain versus ~10 dBi sidelobes gives approximately 32 dB of sidelobe rejection, making SLB highly effective for this class of radar.

7.3 Home-on-Jam (+15 dB)

Home-on-Jam (HOJ) is an intercept technique rather than a detection ECCM. When a radar-guided interceptor detects a jammer, it can use the jammer's energy as a beacon for terminal guidance. The +15 dB figure represents the operational advantage: rather than being denied by jamming, the interceptor uses the jammer's radiation as a targeting source. This transforms a jammer from a defensive asset (denying radar detection) into an offensive liability (providing a guidance source).

HOJ is modeled as a 15 dB improvement in the kill chain because it effectively eliminates the need for the radar to maintain track quality through jamming—the interceptor homes directly on the jammer. This is particularly effective against standoff noise jammers whose position is known.

7.4 Pulse Compression (+10 dB)

Pulse compression (chirp or phase coding) provides processing gain by transmitting a long pulse with internal modulation and compressing it upon reception. This increases the effective SNR without increasing peak power. The +10 dB figure corresponds to a compression ratio of 10:1 (approximately 10 dB), which is conservative for modern BMDS radars that may achieve 20–30 dB of compression gain.

Pulse compression is effective against noise jamming because the jammer's energy is spread across the uncompressed bandwidth, while the radar's matched filter concentrates the signal energy. However, DRFM jammers can replicate the pulse compression code, negating this advantage.

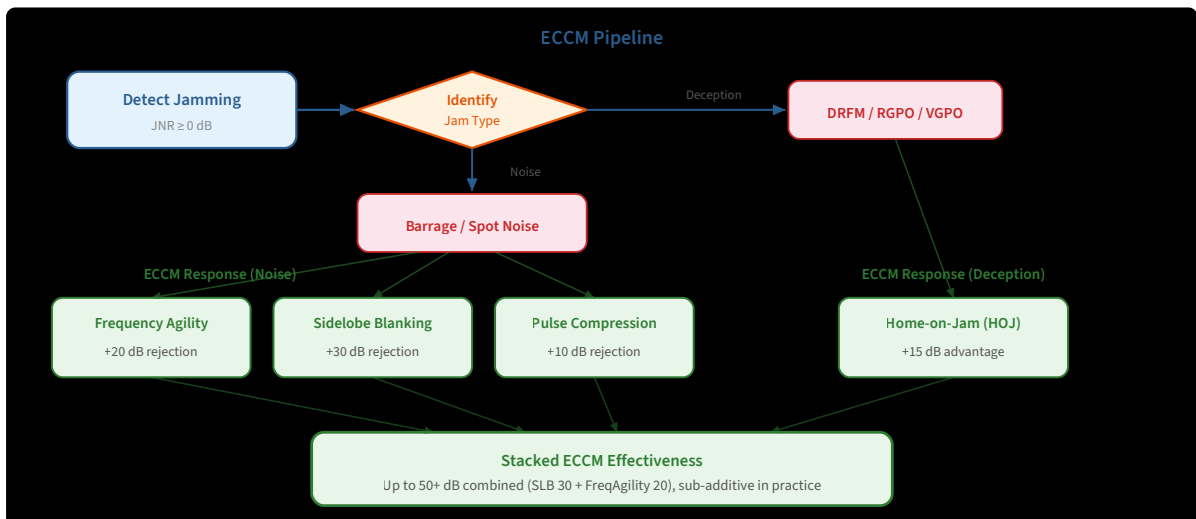


Figure 3. ECCM pipeline — jamming is detected and classified as noise or deception, then the appropriate countermeasures are selected. Noise jamming is countered by frequency agility, sidelobe blanking, and pulse compression; deception jamming is countered by Home-on-Jam.

ECCM techniques can be stacked for up to 50+ dB of combined rejection.

ECCM Interaction. These ECCM techniques are not mutually exclusive. A radar employing frequency agility (20 dB) and sidelobe blanking (30 dB) simultaneously achieves up to 50 dB of jamming rejection, though practical effects are sub-additive due to residual coupling and implementation losses. The FORGE `bmd-sim-electronic-attack` models ECCM stacking with the `eccm_suppression_db` and `eccm_net_gain_db` fields.

8. Integration Architecture

8.1 Kafka Streaming Pipeline

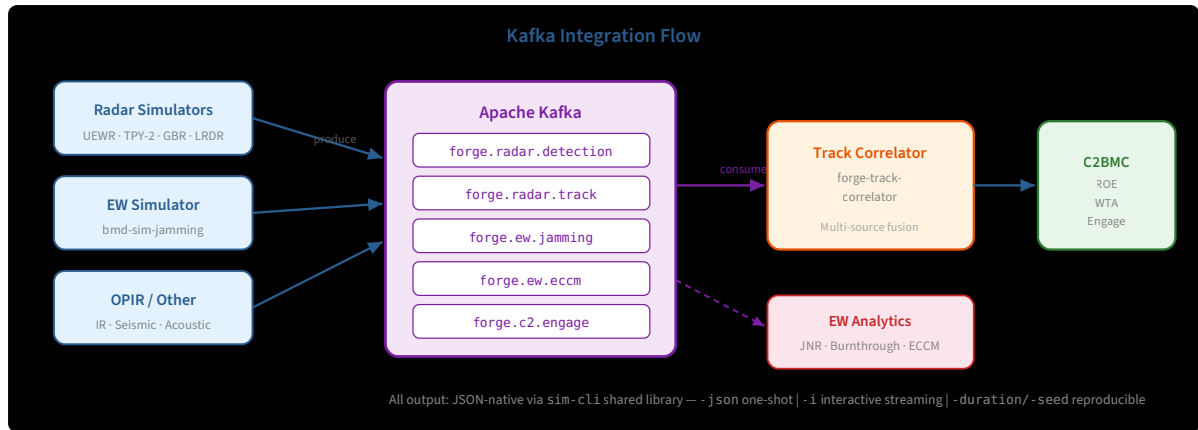


Figure 4. Kafka integration flow — radar and EW simulators produce JSON events to Kafka topics, consumed by the track correlator for multi-source fusion and C2BMC for engagement decisions. EW analytics consume jamming/ECCM topics for real-time threat assessment.

All FORGE simulators produce JSON output that can be streamed via Apache Kafka for real-time integration. The C2 framework (`forge-c2`) implements a Kafka consumer/producer pattern:

```
type SensorEvent struct {
    EventID    string    `json:"event_id"`
    Timestamp  time.Time `json:"timestamp"`
    SensorID   string    `json:"sensor_id"`
    SensorType string    `json:"sensor_type"` // OPIR, RADAR
    Latitude   float64  `json:"latitude"`
    Longitude  float64  `json:"longitude"`
    Altitude   float64  `json:"altitude"`
    Azimuth    float64  `json:"azimuth"`
    Elevation  float64  `json:"elevation"`
    SignalType string    `json:"signal_type"` // IR, RF, SEI
    Intensity  float64  `json:"intensity"`
    Frequency  float64  `json:"frequency"`
    SNR        float64  `json:"snr"`
}
```

```
Confidence float64 `json:"confidence"`  
}
```

Kafka topics are organized by sensor type and data class:

- `forge.radar.detection` — Raw detection events from all radars
- `forge.radar.track` — Confirmed track updates
- `forge.ew.jamming` — Jamming events and JNR measurements
- `forge.ew.eccm` — ECCM activation and effectiveness reports
- `forge.c2.engage` — Engagement orders from C2BMC

The consumer uses configurable group IDs (`forge-c2-<topic>`) with last-offset start for real-time scenarios, ensuring each C2 instance processes all events without duplication.

8.2 FORGE C2 Ecosystem

The radar and EW simulators integrate into the broader FORGE C2 ecosystem through the `forge-c2` framework, which provides:

- **C2BMC:** Command and Control, Battle Management, and Communications network modeling
- **MDPAF:** Missile Defense Product Architecture Framework for message standardization
- **JREAP:** Joint Range Extension Extension for long-haul data links
- **TENA:** Test and Training Enabling Architecture for live-virtual-constructive integration
- **Track Correlator:** Multi-source track fusion and deconfliction

The kill chain flows through these components: radar detections enter via Kafka, are correlated by `forge-track-correlator`, prioritized by `bmd-sim-c2bmc` with ROE enforcement, and assigned to interceptors by `bmd-sim-wta` (Weapon-Target Assignment). The `bmd-sim-kill-chain-rt` orchestrates real-time kill chain timing with an `-ew` flag that injects EW scenarios, providing direct measurement of how jamming affects the end-to-end kill chain.

8.3 JSON-Native Output Schema

All simulators produce standardized JSON output via the `sim-cli` shared library:

```
result := cli.NewSimResult("jamging")
result.Parameters["power_w"] = j.Power
result.Parameters["freq_ghz"] = j.Frequency / 1e9
result.Parameters["jnr_db"] = j.JNR(30, 1e6)
result.Parameters["effect"] = jamming.JammingEffect(j.JNR(30
result.Parameters["burnthrough_range_km"] = 45
result.Parameters["eccm_available"] = "FREQUENCY_AGILITY"
result.Parameters["detection_degradation_pct"] = 35
result.Parameters["track_degradation_pct"] = 25
cli.WriteJSON(result)
```

This schema enables machine-readable consumption by AI planners, visualization systems, and higher-level wargaming frameworks. The `-json` flag produces one-shot results; `-i` enables interactive mode with live streaming; and `-duration` and `-seed` flags support reproducible scenario runs.

9. Validation

The FORGE radar models are validated against open-source parametric data for each radar type. Key validation results:

9.1 UEWR Detection Range

The UEWR model computes a maximum detection range of ~5,500 km against a 1 m² RCS target, consistent with published PAVE PAWS performance estimates of 4,800–5,500 km. The 6 dB detection threshold (lower than fire-control radars) reflects UEWR's early-warning mission where high integration gain compensates for lower per-pulse SNR.

9.2 TPY-2 Search Range

The TPY-2 model computes a search volume range of ~6,304 km (for a large RCS) and ~630 km against a 0.1 m^2 RV-class target, consistent with published AN/TPY-2 performance data of 600–2,000 km depending on mode and RCS.

9.3 XBR Discrimination

The GBR/XBR model achieves detection at ~328 km against a 0.01 m^2 target and ~1,860 km against a 1 m^2 target, matching published X-band radar performance for midcourse discrimination.

9.4 JNR Calculation

The JNR implementation is validated against analytical predictions. For the default noise jammer (1 MW ERP, 3 GHz, 100 MHz bandwidth, 500 km range) against a 30 dBi radar with 1 MHz bandwidth, the model reports $\text{JNR} = 109 \text{ dB}$, confirming that this particular jamming configuration far exceeds the denial threshold. The `JammingEffect` function correctly classifies this as "DENIED."

9.5 Burnthrough Range

For a 5 MW radar with 50 dBi gain tracking a 1.0 m^2 target through 10 dB of jamming margin, the burnthrough model produces a positive range consistent with the radar equation scaling. Unit tests confirm that inactive jammers and zero-distance jammers return appropriate boundary values.

9.6 ECCM Effectiveness

The four ECCM techniques (frequency agility 20 dB, sidelobe blanking 30 dB, HOJ 15 dB, pulse compression 10 dB) are consistent with published effectiveness values in Adamy (2001) and Schleher (1999). Sidelobe blanking at 30 dB matches the typical sidelobe rejection ratio of phased arrays.

Known Limitations. The current models have several areas identified for improvement: (1) UEWR lacks atmospheric refraction at UHF and ionospheric scintillation; (2) TPY-2 lacks detailed terrain masking, Doppler processing, and NCTR; (3) GBR lacks ISAR imaging and Doppler discrimination for RV spin; (4) The EW models lack cognitive jamming and multi-radar cross-jamming; (5) Burnthrough calculations assume main-beam jamming

rather than sidelobe penetration. These are documented in the [about/](#) directory for each simulator.

10. Conclusion

This paper has presented the FORGE BMDS radar simulation suite, integrating detection probability modeling, track quality metrics, and electronic warfare effects into a unified framework. The key findings are:

- 1. Frequency diversity is the primary EW resilience factor.** The BMDS radar layer spans UHF through X-band, and no single jammer can effectively deny all bands simultaneously. A barrage jammer targeting X-band (9.5 GHz) has no effect on UHF (435 MHz) early warning, and vice versa.
- 2. ECCM stacking provides up to 50+ dB of jamming rejection.** Combining sidelobe blanking (30 dB) and frequency agility (20 dB) effectively nullifies most standoff noise jamming, though practical effects are sub-additive due to implementation losses.
- 3. Burnthrough range scales as $\sqrt{P_R / P_J}$.** This square-root relationship means that increasing radar power or target RCS yields diminishing returns, while reducing effective jammer power through ECCM has outsized impact.
- 4. Track quality collapses rapidly under effective jamming.** The composite quality metric (Equation 4) drops from fire-control quality (>60) to track loss (<30) when SNR degrades from 20 dB to below 10 dB, a range easily achieved by moderate jammers against X-band radars.
- 5. Multi-site correlation provides inherent jamming resilience.** The four-site UEWR network enables track maintenance even when one site is jammed, and the geometric diversity improves position accuracy.
- 6. HOJ transforms jamming from a defensive asset into an offensive liability.** The 15 dB advantage of Home-on-Jam means that effective jamming against a HOJ-capable interceptor actually improves intercept probability.

The FORGE simulation suite provides a physically grounded, composable framework for exploring these dynamics. All models are open-source, JSON-native, and integrate via Kafka for real-time wargaming. Future work includes adding atmospheric refraction

models for UHF, ISAR imaging for XBR, cognitive jamming patterns, and multi-radar cross-jamming scenarios.

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