VDI PHASE SLOPE DISCRIMINATION PROCESS

Multi-Frequency Analysis for Metal Target Identification

STEP 1: INPUT - Multi-Frequency IQ Analysis

Multi-Tone IQ Demodulation
(1-24 frequencies, 1000-20000 Hz)

↓

For each frequency:
- **Amplitude (signal strength)**
- **Phase (degrees)**
- **I/Q components**

```
VDICalculator.kt:53 - calculateVDI(analysis: List<ToneAnalysis>)
```

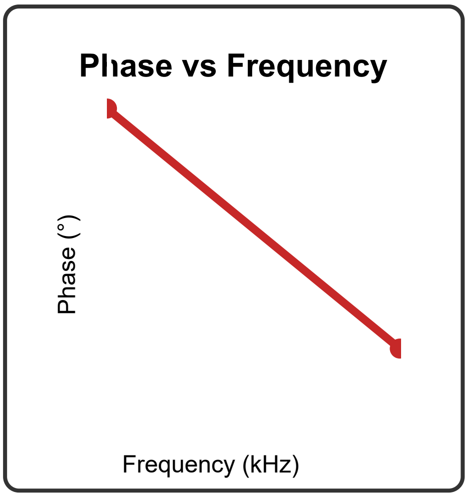
STEP 2: PHASE SLOPE CALCULATION

```
Phase Slope Formula:

phaseSlope = (phase_highest_freq - phase_lowest_freq) /
(freq_diff / 1000)

Units: degrees per kHz
```

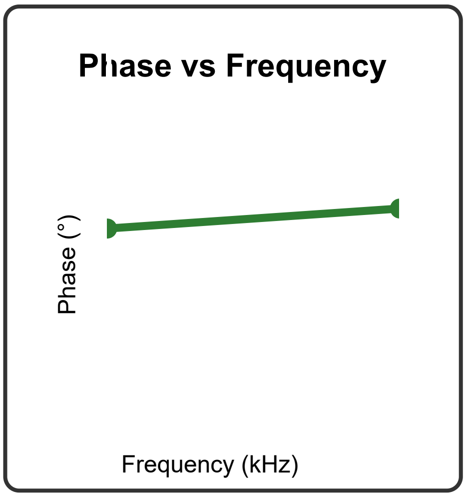
```
VDICalculator.kt:84 - calculatePhaseSlope()
```

FERROUS Example (Iron Nail)

NON-FERROUS Example (Copper Coin)



Phase Slope: -8.5 deg/kHz
Freq: 1 kHz → Phase: +30°
Freq: 20 kHz → Phase: -130°
Slope = (-130 - 30) / 19 = **-8.4 deg/kHz**



Phase Slope: -0.5 deg/kHz
Freq: 1 kHz → Phase: +10°
Freq: 20 kHz → Phase: +0°
Slope = (0 - 10) / 19 = **-0.5 deg/kHz**

STEP 3: CONDUCTIVITY INDEX CALCULATION

```
Conductivity Index Formula:

lowFreqAmp = average(first 1/3 of frequencies)
highFreqAmp = average(last 1/3 of frequencies)

conductivityIndex = (highFreqAmp / lowFreqAmp) / 2.0

Range: 0.0 (low conductor) to 1.0 (high conductor)
```

```
VDICalculator.kt:101 - calculateConductivityIndex()
```

Physical Basis: High conductivity metals (copper, silver) respond well to high frequencies. Low conductivity metals (aluminum foil, iron) attenuate at high frequencies.

STEP 4: PHASE CONSISTENCY CHECK

```
Phase Consistency Formula:

stdDev = standard_deviation(all phase measurements)
consistency = 1.0 - (stdDev / 90°)

Range: 0.0 (inconsistent/noisy) to 1.0 (very consistent)
```

`VDICalculator.kt:122 - calculatePhaseConsistency()`

Purpose: Measure confidence in the reading. Solid single targets have consistent phase. Multiple objects, ground minerals, or noise create inconsistent phase readings.

STEP 5: RAW VDI CALCULATION

Phase Slope < 0?
(Ferrous)

↓ YES

```
normalizedSlope = phaseSlope
/ -10.0
(clamp 0.0 to 1.0)

VDI = 30 × (1 -
normalizedSlope)

Range: 0-30 VDI
```

Phase Slope ≥ 0?
(Non-Ferrous)

↓ YES

```
Use conductivityIndex

VDI = 30 +
(conductivityIndex × 69)

Range: 30-99 VDI
```

Amplitude Adjustment
Strong signal (>0.5): +5 VDI
Weak signal (<0.1): -5 VDI

`VDICalculator.kt:140 - calculateRawVDI()`

STEP 6: VDI SCALE & TARGET CLASSIFICATION

0 30 45 50 65 70 99

FERROUS LOW CONDUCTOR GOLD RANGE HIGH CONDUCTOR

VDI Range	Target Type	Phase Slope	Examples
0-30	FERROUS	< -3.0 deg/kHz	Iron, steel, nails, bottle caps
31-45	LOW CONDUCTOR	-3.0 to 0 deg/kHz	Aluminum foil, small aluminum pieces
46-65	MID CONDUCTOR	~0 deg/kHz	Pull tabs, brass, zinc pennies
50-70	GOLD RANGE	-1 to +1 deg/kHz	Gold jewelry, rings, chains
70-99	HIGH CONDUCTOR	~0 to +1 deg/kHz	Copper coins, silver, large targets

```
VDICalculator.kt:174 - classifyTarget()
```

STEP 7: CONFIDENCE CALCULATION

```
Confidence Score Formula:

amplitudeScore = clamp(avgAmplitude, 0.0, 1.0)
confidence = (amplitudeScore × 0.3) + (phaseConsistency × 0.7)

Range: 0.0 to 1.0
• 0.8-1.0: High confidence
• 0.5-0.8: Medium confidence
• 0.3-0.5: Low confidence
• 0.0-0.3: Very low (returns UNKNOWN)
```

```
VDICalculator.kt:197 - calculateConfidence()
```

Note: Phase consistency is weighted 70% because it's the most reliable indicator of a solid, single target versus trash, multiple objects, or ground minerals.

FINAL OUTPUT: VDIResult

VDIResult Data Class

↓

```
Output Structure:

• vdi: Int (0-99)
• confidence: Double (0.0-1.0)
• targetType: TargetType enum
• phaseSlope: Double (deg/kHz)
• conductivityIndex: Double (0.0-1.0)
```

Example Output: Iron Nail

VDI: 12
Confidence: 0.85 (High)
Type: FERROUS
Phase Slope: -8.5 deg/kHz
Conductivity: 0.15
Description: "Ferrous (Iron/Steel) | Confidence: High"

Example Output: Copper Penny

VDI: 78
Confidence: 0.92 (High)
Type: HIGH_CONDUCTOR
Phase Slope: -0.5 deg/kHz
Conductivity: 0.85
Description: "High Conductor (Cu/Ag) | Confidence: High"

KEY PHYSICS INSIGHTS

Why Phase Slope Discriminates Metals:

- **Ferrous metals (iron, steel):** High magnetic permeability causes phase to shift dramatically with frequency. The eddy currents and magnetic properties create a steep negative phase slope.

- **Non-ferrous metals (copper, silver, gold):** Only eddy currents (no magnetic effects) result in relatively flat phase response across frequencies.
- **Conductivity matters:** High conductors maintain strong signals at high frequencies. Low conductors attenuate quickly at high frequencies.

Why Multi-Frequency Analysis Works:

- Single frequency can't distinguish between different metals - they all look like "metal detected"
- By comparing phase and amplitude across multiple frequencies, we can characterize the target's electromagnetic properties
- This is similar to how X-ray CT uses multiple angles to create a 3D image - we use multiple frequencies to "see" the metal's electrical properties