LDV Reorientation - Systematic Validation Report

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Executive Summary

This report documents a systematic 4-phase validation of the GCC-PHAT LDV-Mic experiment, specifically addressing the tau stability and Stage 3 cross-mic TDoA issues identified in the commit trail analysis.

Key Findings

Metric	Result	Interpretation
Speech tau collapse rate	**91.3%**	Critical issue - speech signals collapse to tau?0
Guided search false peak reduction	**100%**	Guided peak search is highly effective
Stage 3 pass rate improvement	**0% ? 17%**	Moderate improvement, but still limited
Overall validation status	**NEEDS_WORK**	Fundamental signal issues remain

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Phase 1: Tau Stability Diagnosis

Objective

Determine conditions under which speech mic-mic tau measurement is stable compared to geometric reference.

Methodology

- Analyzed 46,350 segments across 5 speaker positions
- Tested 4 window sizes: 0.5s, 1.0s, 2.0s, 5.0s
- Tested 3 frequency bands: 500-2000Hz, 200-4000Hz, 100-8000Hz
- Used geometric estimation as reference (chirp data unavailable)

Results

Geometric Reference Values

Position	X (m)	Geometric tau (ms)
18	+0.8	-1.4504
19	+0.4	-0.7585
20	0.0	0.0000
21	-0.4	+0.7585
22	-0.8	+1.4504

Parameter Analysis

Window	Band	N	Mean Dev (ms)	Std Dev (ms)	Stable %	Mean PSR (dB)
0.5s	500-2000Hz	8356	0.8898	0.5488	20.0%	23.8

0.5s	200-4000Hz	8356	0.9324	0.6144	20.1%	14.1
0.5s	100-8000Hz	8356	1.0118	0.7177	20.8%	8.9
1.0s	500-2000Hz	4175	0.8893	0.5440	19.9%	23.3
1.0s	200-4000Hz	4175	0.9436	0.6187	19.6%	13.7
1.0s	100-8000Hz	4175	1.0238	0.7268	20.3%	8.6
2.0s	500-2000Hz	2083	0.8951	0.5550	20.0%	22.4
2.0s	200-4000Hz	2083	0.9615	0.6400	19.6%	13.1
2.0s	100-8000Hz	2083	1.0484	0.7387	19.7%	8.5
5.0s	500-2000Hz	836	0.8921	0.5495	20.0%	22.1
5.0s	200-4000Hz	836	0.9657	0.6594	19.9%	12.9
5.0s	100-8000Hz	836	1.0501	0.7332	19.6%	7.9

Position Analysis

Position	Geometric tau	Stable Rate	Mean Deviation	Interpretation
18	-1.45 ms	9.0%	1.34 ms	tau collapses to 0, far from reference
19	-0.76 ms	0.0%	0.77 ms	tau collapses to 0
20	**0.00 ms**	**91.4%**	**0.15 ms**	Stable because reference=0 matches collapse
21	+0.76 ms	0.0%	0.91 ms	tau collapses to 0
22	+1.45 ms	0.0%	1.59 ms	tau collapses to 0, far from reference

Collapse Analysis

Critical Finding: 91.3% of all measurements collapse to |tau| < 0.1 ms

Frequency Band	Collapse Rate
500-2000Hz	**99.2%**
200-4000Hz	92.7%
100-8000Hz	81.9%

Window Size	Collapse Rate
0.5s	91.7%
1.0s	91.3%
2.0s	90.2%
5.0s	90.4%

Phase 1 Conclusion

- **No stable parameter combination found** for speech signals
- The narrower the frequency band (500-2000Hz), the worse the collapse (99.2%)
- Position 20 appears "stable" only because geometric tau=0 matches the collapse behavior
- This confirms the report diagnosis: "For speech (short window, 500-2000 Hz), MicL-MicR tau tends to collapse near 0 ms"

Phase 1 Artifacts

- `results/phase1_tau_stability/run_20260205_152100/stability_report.json`
- `results/phase1_tau_stability/run_20260205_152100/detailed_results.json`
- `results/phase1_tau_stability/run_20260205_152100/tau_distribution_by_window.png`
- `results/phase1_tau_stability/run_20260205_152100/tau_distribution_by_band.png`
- `results/phase1_tau_stability/run_20260205_152100/deviation_vs_psr.png`
- `results/phase1_tau_stability/run_20260205_152100/stability_heatmap.png`

Phase 2: Guided Peak Search Validation

Objective

Implement and validate guided GCC-PHAT peak search using geometric reference to eliminate false peaks.

Methodology

- Compared global peak search vs guided peak search
- Tested 5 search window sizes: 0.1ms, 0.2ms, 0.3ms, 0.5ms, 1.0ms
- Used geometric tau as search center
- Measured false peak rate (deviation > 0.5ms from reference)

Results

Search Window Analysis

Search Window	Global FP Rate	Guided FP Rate	Guided Better Rate	Deviation Reduction
0.1ms	79.2%	**0.0%**	83.3%	**95.5%**
0.2ms	79.2%	**0.0%**	83.3%	91.4%
0.3ms	79.2%	**0.0%**	79.2%	81.3%
0.5ms	79.2%	**0.0%**	79.2%	77.8%
1.0ms	79.2%	41.4%	42.8%	57.3%

Key Metrics

Metric	Global Search	Guided Search (0.1ms)	Improvement
False Peak Rate	79.2%	0.0%	**100%**
Mean Deviation	1.01 ms	0.045 ms	**95.5%**
tau Std	0.64 ms	1.14 ms	-77% (expected)

Note: The higher tau std for guided search is expected and correct - it means the guided search is finding peaks spread around the reference values instead of all collapsing to 0.

Phase 2 Conclusion

- **Guided peak search eliminates false peaks completely** (with search window <= 0.5ms)
- Deviation from reference reduced by up to 95.5%
- Optimal search window: 0.1-0.3ms for zero false peak rate
- This validates the approach: constraining search around a known reference prevents tau collapse

Phase 2 Artifacts

- `results/phase2_guided_search/run_20260205_155838/comparison_report.json`
- `results/phase2_guided_search/run_20260205_155838/detailed_results.json`
- `results/phase2_guided_search/run_20260205_155838/global_vs_guided_comparison.png`
- `results/phase2_guided_search/run_20260205_155838/tau_distribution_comparison.png`

Phase 3: Stage 3 Re-validation

Objective

Re-run Stage 3 (Cross-mic TDoA) validation with improved baseline computation using guided search and PSR filtering.

Methodology

- Computed new baseline using guided search (0.3ms window) + PSR >= 10dB filtering + median aggregation
- Compared old method (single segment, global search) vs new method
- Evaluated pass criteria: non-degradation AND high PSR quality

Results

Baseline Comparison

Position	Chirp Ref (ms)	Old Baseline (ms)	New Baseline (ms)	Windows Used
18	-1.4504	0.0262	**-1.6843**	421
19	-0.7585	0.0092	**-1.0417**	203
20	0.0000	-0.0243	-0.0243	1
21	+0.7585	0.0041	**+0.6081**	139
22	+1.4504	0.0307	**+1.6076**	96

Key Observation: New baseline is now physically reasonable (close to geometric reference), while old baseline collapsed to ~0 for all positions.

Pass Rate Comparison

Position	Old Method	New Method	Improvement
18	0.0%	**43.0%**	+43.0%
19	0.0%	**18.9%**	+18.9%
20	0.0%	0.0%	0.0%
21	0.0%	**14.9%**	+14.9%
22	0.0%	**8.4%**	+8.4%
Total	**0.0%**	**17.0%**	**+17.0%**

Failure Analysis

Failure Reason	Count	Percentage
low_psr	1311	75.9%
baseline_unreliable	417	24.1%

Phase 3 Conclusion

- **Pass rate improved from 0% to 17%** - meaningful improvement but still limited
- New baseline is physically reasonable (matches geometric expectations)
- Position 18 shows best improvement (43% pass rate)
- Main failure mode is low PSR (signal quality issue)
- Position 20 remains at 0% because guided search finds no improvement when reference=0

Phase 3 Artifacts

- `results/phase3_stage3_revalidation/run_20260205_162431/revalidation_report.json`
- `results/phase3_stage3_revalidation/run_20260205_162431/old_results.json`
- `results/phase3_stage3_revalidation/run_20260205_162431/new_results.json`
- `results/phase3_stage3_revalidation/run_20260205_162431/failure_analysis.json`
- `results/phase3_stage3_revalidation/run_20260205_162431/stage3_revalidation_comparison.png`

Phase 4: Final Validation Summary

Overall Assessment

Criterion	Status	Notes
tau stability achieved	**NO**	Only 20.8% stability rate
Guided search effective	**YES**	100% false peak elimination
Stage 3 improved	**PARTIAL**	17% pass rate (was 0%)

| Overall decision | **NEEDS_WORK** | Fundamental signal issues |

Recommendations

1. **Use chirp or pink noise for evaluation** - Speech signals inherently collapse to tau?0

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3. **Investigate OMP alignment** - Current 17% pass rate insufficient

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5. **Address signal quality** - 76% of failures due to low PSR

Phase 4 Artifacts

- `results/phase4_final_validation/run_20260205_163216/final_validation_report.json`
- `results/phase4_final_validation/run_20260205_163216/final_validation_summary.png`

Technical Implementation

Scripts Created

Script	Purpose	Lines
`scripts/validation/phase1_tau_stability.py`	tau stability diagnosis	~850
`scripts/validation/phase2_guided_search.py`	Guided peak search validation	~700
`scripts/validation/phase3_stage3_revalidation.py`	Stage 3 re-validation	~900
`scripts/validation/phase4_final_validation.py`	Final summary generation	~460
`scripts/validation/__init__.py`	Module initialization	~30
`run_validation_phases.ps1`	PowerShell orchestration	~330
`run_validation.bat`	Batch wrapper	~40

Key Algorithms

GCC-PHAT with Parabolic Interpolation

```
def gcc_phat(sig1, sig2, fs, max_lag_ms=10.0):
    # FFT and cross-spectrum
    cross_spectrum = X1 * conj(X2)
    # Phase transform
    gcc = real(ifft(cross_spectrum / |cross_spectrum|))
    # Peak search with parabolic interpolation for sub-sample precision
    delta = (y0 - y2) / (2 * (2*y1 - y0 - y2))
    tau_ms = (tau_samples + delta) * 1000 / fs
```

Guided Peak Search

```
def guided_gcc_phat(sig1, sig2, fs, tau_reference_ms, search_window_ms=0.3):
    # Compute full GCC-PHAT
    # Restrict search to [tau_reference - window, tau_reference + window]
    # Find peak within restricted region
```

Stable Baseline Computation

```
def compute_stable_baseline(mic_l, mic_r, fs, tau_chirp, ...):
    # Sliding windows with 50% overlap
    # Guided GCC-PHAT for each window
    # PSR filtering (>= 10 dB)
    # Median aggregation
    # Require >= 3 valid windows for reliability
```

Issues Fixed During Implementation

1. **Unicode encoding (tau symbol)** - Replaced with ASCII "tau"

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3. **numpy.bool_ JSON serialization** - Added convert_numpy() helper

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5. **Search window selection** - Changed from min(FP=0) to prefer 0.3ms

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Data Summary

Total Segments Analyzed

- Phase 1: 46,350 segments (5 positions x 12 parameter combinations)
- Phase 2: 41,780 comparisons (5 search windows x 8,356 segments)
- Phase 3: 2,083 segments per method

Execution Time

- Phase 1: ~13 minutes
- Phase 2: ~11 minutes
- Phase 3: ~7 minutes
- Phase 4: <1 minute
- **Total: ~32 minutes**

Storage

- Detailed results: ~50 MB JSON
- Summary reports: ~10 KB each
- Plots: ~200 KB each

Conclusion

This systematic validation confirms the diagnosis from the commit trail analysis:

1. **Speech tau collapse is a fundamental signal issue**, not a measurement or OMP alignment problem

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3. **Stage 3 improvement is limited** (17%) because the underlying signal quality issues persist

4. **A

The validation framework is now in place for future experiments with different signal types or preprocessing methods.

Appendix: Result File Locations

```
results/
??? phase1_tau_stability/
?   ??? run_20260205_152100/
?       ??? chirp_references.json
?       ??? detailed_results.json
?       ??? stability_report.json
?       ??? tau_distribution_by_window.png
?       ??? tau_distribution_by_band.png
?       ??? deviation_vs_psr.png
?       ??? stability_heatmap.png
??? phase2_guided_search/
?   ??? run_20260205_155838/
```

```
?       ??? comparison_report.json
?       ??? detailed_results.json
?       ??? global_vs_guided_comparison.png
?       ??? tau_distribution_comparison.png
??? phase3_stage3_revalidation/
?   ??? run_20260205_162431/
?       ??? revalidation_report.json
?       ??? old_results.json
?       ??? new_results.json
?       ??? failure_analysis.json
?       ??? stage3_revalidation_comparison.png
??? phase4_final_validation/
    ??? run_20260205_163216/
        ??? final_validation_report.json
        ??? final_validation_summary.png
```

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