Redundant TWSTT Observations

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(Inspired by work of Z. Jiang)

Motivation and Goals

- Improve TAI-generation
- Quantify TWSTT noise by type
  - Site-based noise: property of site
  - Baseline-based noise: property of baseline

TWSTT

- Short-term precision in 100's of ps
  - Higher chip-rate observations would do better
    - Investigations are just beginning
  - Carrier-phase TWSTT could perhaps do much better
    - Developmental effort not now being actively pursued at USNO
- Long-term Precision (accuracy): 1 ns
  - Repeat calibrations by USNO
  - Duplicate USNO-PTB observations
    - Three years
    - At Ku-band, up 4 times /day (now 12 times/day)
    - At X-band, every hour
    - Frequencies use completely different hardware
  - Very short baseline long-term observations at USNO

Diurnal Variations

- TWSTT and GPS can show them
- Can be 1-ns
- Can be reduced
  - Sensitive components indoors, or low-tempco
  - Impedance matching and cable multipath
  - GPS multipath can lead to diurnal variations independent of other effects

Two kinds of link noise

- Baseline-based: property of coupled system pair
  - Reduced by averaging redundant links
- Site-based: property of individual systems
  - Not reduced by averaging redundant links
  - Noise of link given by: $u_{x_{i,j}}^2 = u_{x_i}^2 + u_{x_j}^2$

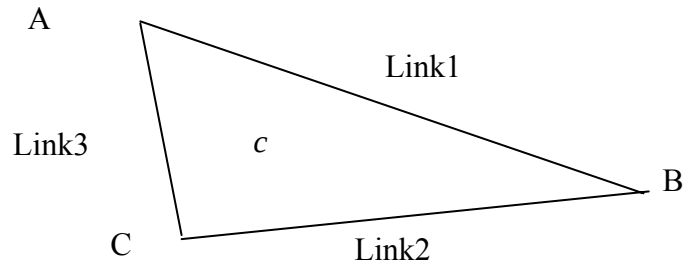
Site and Baseline-based TWSTT Uncertainties

- Site-based
  - Delays in modems, up/down converters, amps, cables…
    - Thermal variations
    - Impedance mismatches
  - Seem to dominate in long-term
- Baseline-based (blb) uncertainties due to
  - Different spread-spectrum codes in different links
  - Clock reference and system jitter between observations
    - Epoch of observations differ by a few minutes
  - Multiplicative bandpass effects
  - Slightly different frequencies in transcontinental links
  - Baseline-dependent calibrations

Two Questions

- Can we infer the noise correlation properties from the data?
- Can we improve time transfer by using redundant links?

Part I: Use Closure to Estimate Baseline-Based Noise



(A-B) + (B-C) + (C-A) = Closure

- Closure= Sum of baseline-based noise around the triangle
  - Site-based noise drops out
- Calibration ensures <Closure>=0
- Variance of Closure = Sum of Variances of Baselines
  - Var(Closure)=Var(A-B)+Var(B-C)+Var(C-A)
  - All Variances are square of RMS
  - Variances >0

Least Squares Fit To All Triangles

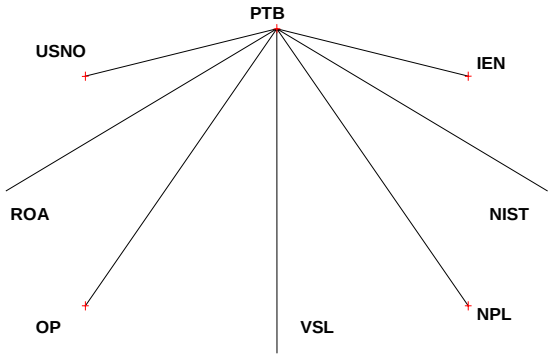


Fig. 1.1-1a Actual TAI pivot single baseline time transfer

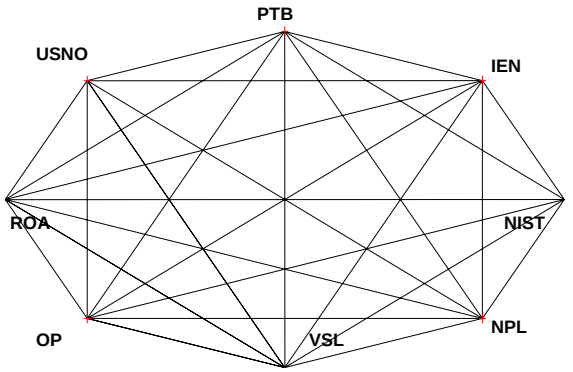


Fig. 1.1-1b Status of the measured TW network in 2005 Feb.

- Parameters for N sites:
  - Variance of each baseline
  - Up to N*(N-1)/2 baselines
- Equations
  - Variance of triangles = Sum of Baseline Variances
  - Up to N*(N-1)*(N-2)/6 triangles
    - Of which only N*(N-1)/2 –N +1 are linearly independent
- Solution exists if N>4

It Didn't Work

- Some derived parameters were nonsense
  - Some baselines had negative variances
  - Which means imaginary Standard Deviations (RMS)
- Inspection of the data tells why
- Baseline-based variances are correlated
  - Which violates the assumption behind least squares
  - Consistent with multiplicative bandpass effects, spread-spectrum leakage, time-slot allocations

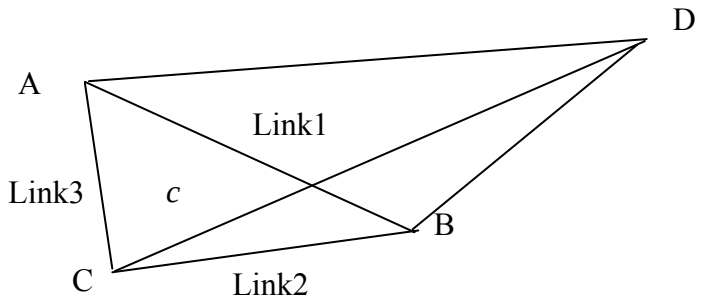


Fig. 2.1.2-1 Closures in a 4 point triangle system

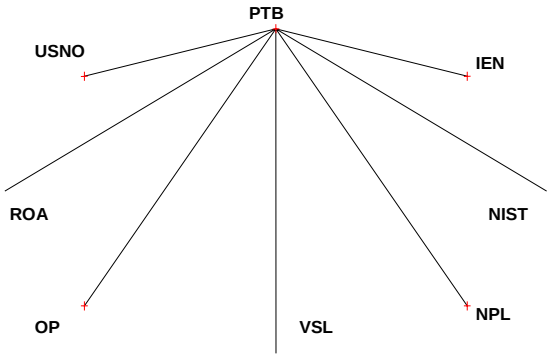
That's OK

- Individual closure RMS's are .3-.5ns
- Baseline-based noise of individual baselines is square root of 3 smaller
  - 200-300 ps
- May try again, modeling correlations between transAtlantic links and inter-European links

Part II.
Can Redundant TWSTT Baselines Improve TAI?

- For non-Asian TAI, BIPM uses only PTB-Lab_k
- Why not use all baselines?
  - Although site-based noise will not be reduced, baseline-based noise will be averaged down
- Example
  - BIPM uses PTB-USNO and PTB-NPL
  - BIPM does not use NPL-USNO
  - Would TAI benefit if the BIPM also used NPL-USNO?

The Two Ways



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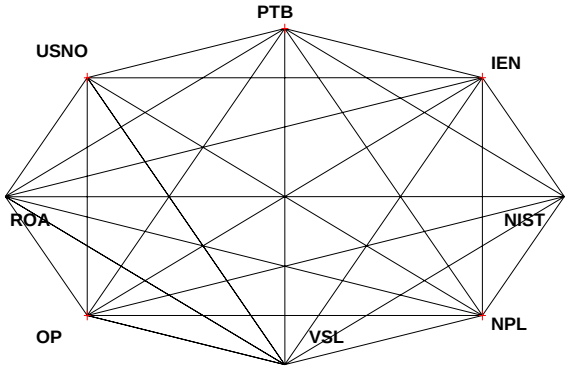

Fig. 1.1-1b Status of the measured TW network in 2005 Feb.

Another Least Squares Fit

1. Consistent calibration
    1. Accept BIPM's calibration of PTB-Lab_k baselines
    2. Calibrate all others to be consistent with PTB-Lab_k
2. Do least squares fit to Lab_k's
    1. Use all baselines, equal weights
    2. Use only data since we began 12 times/day
3. Ask if first and second differences of fitted TA(k)'s are smaller than if just PTB-Lab_k data are used?
    1. Answer was: "no", with PTB as central pivot
    2. Answer was still "no" if central pivot switched to NPL

Stability With and Without Redundant Links

ptb-lab	type	rms	1st diff	2nd diff
ptb-ch	raw	1.352	0.523	0.732
	fit	1.337	0.510	0.717
	diff	0.133	0.193	0.339
ptb-ien	raw	3.040	1.624	2.473
	fit	3.060	1.589	2.397
	diff	0.192	0.238	0.417
ptb-nist	raw	0.921	0.583	0.877
	fit	0.934	0.610	0.915
	diff	0.137	0.184	0.320
ptb-npl	raw	1.026	0.515	0.786
	fit	1.014	0.477	0.699
	diff	0.110	0.170	0.309
ptb-op	raw	2.707	1.238	1.772
	fit	2.689	1.237	1.794
	diff	0.101	0.166	0.291
ptb-sp	raw	2.693	1.700	2.769
	fit	2.646	1.303	1.955
	diff	0.214	0.301	0.510
ptb-usno	raw	1.000	0.564	0.843
	fit	0.987	0.596	0.909
	diff	0.145	0.203	0.366
ptb-vsl	raw	3.219	1.340	1.852
	fit	3.179	1.217	1.593
	diff	0.283	0.426	0.763

Conclusions

- For TAI-generation, TWSTT (and TWSTFT) is dominated by site-based noise
- No significant improvement by using redundant baselines
  - They are still useful as a backup
  - Specific baselines/sites may be benefit
- But this is definitely work in progress
  - I invite you to duplicate, optimize, and come to different conclusions