Report of Study Group II On the Optimization of Time Transfer Links

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Meetings of CCTF and Working Group on TAI

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Outline

- Introduction
- Review of Uncertainty Analysis
  - Theory
  - Crossover Sites
  - Virtual Pivot
- Use of Redundant Links
  - GPS links under AV and CV
  - TWSTFT links
- Recommendations

Background

- Time Transfer for TAI achieved via
  - GPS multi-channel common view
  - GPS single-channel common view
  - GPS dual-frequency P3
  - Ku-band TWSTFT
  - X-band TWSTFT
  - Other means
- All-in-View (AV) currently not used

Study Groups

- At request of Patrizia Tavella, Chair of WG on TAI
- Study Group 1
  - Analyze advantages and disadvantages of two GPS techniques
    - All-in-View (AV)
    - Common View (CV)
- Study Group 2
  - Study means of linking clocks for TAI
    - Reducing uncertainties
    - Improving robustness
- Prepare recommendations for these meetings

Current Link Configuration

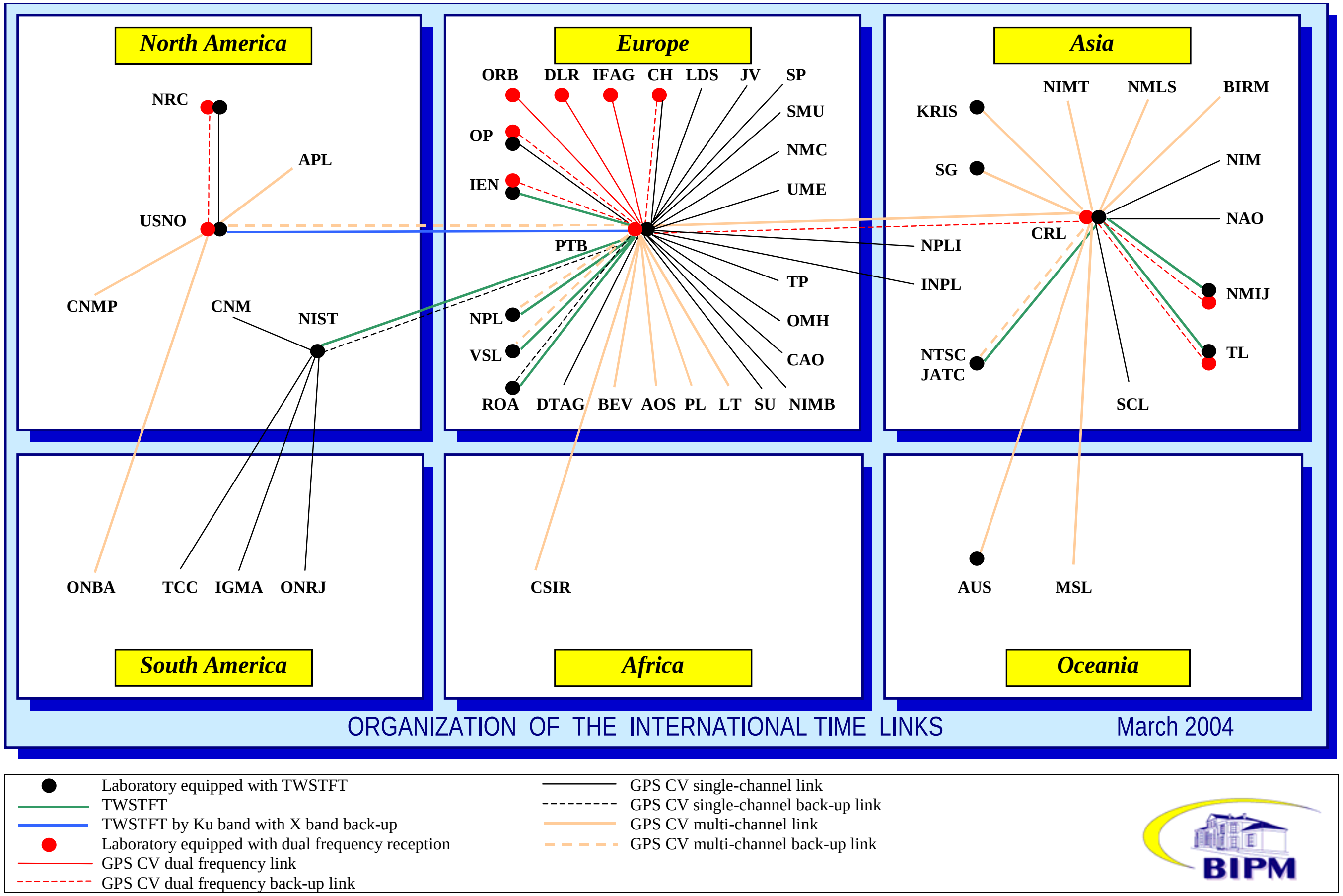


Fig. 2 The TAI/Circular T time links

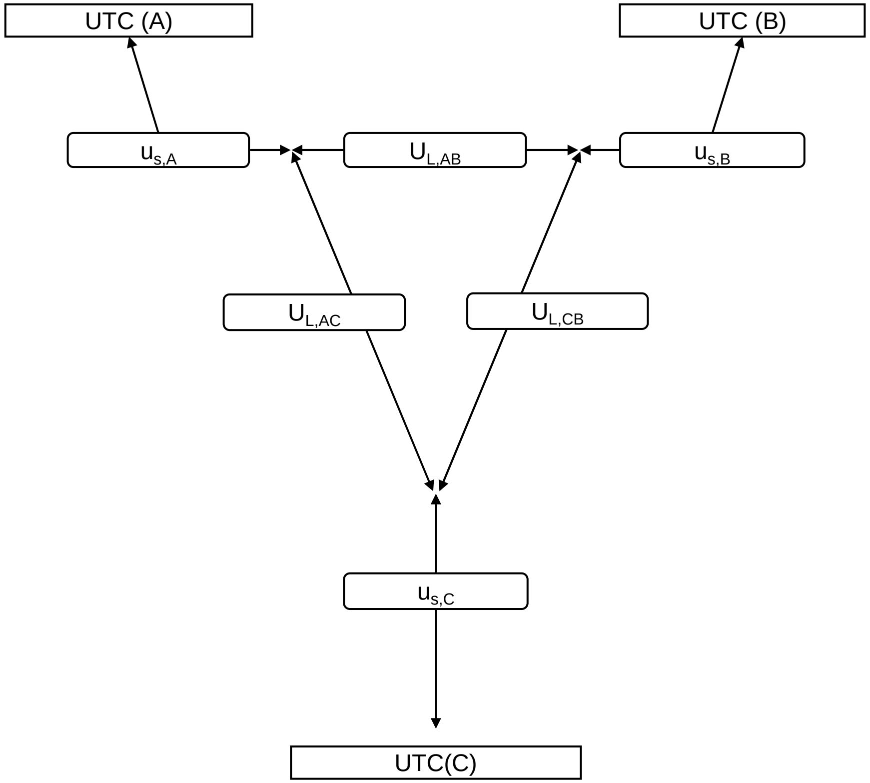
Two Definitions

- Pivot Site
  - A site linked to at least two other sites for TAI-Generation
- Crossover Site
  - A pivot site for which at least two of the links use different time transfer systems

Recent Work on Uncertainties

- Uncertainty is less for highly weighted labs
- Uncertainty is less for low-noise time-transfer systems
- Site-based and link-based Uncertainties have different impact
  - Site-based uncertainties affect only that site
    - Independent of topology
    - Not reduced by averaging redundant links
    - Act like link-based if two different time-transfer systems used at the site (crossover sites)
  - Link-based uncertainties affect all sites
    - Topology-dependent
    - Reduced by averaging redundant links

Site and Link-based Uncertainties



TWSTFT Uncertainties

- Mostly site-based
  - Delays in modems, up/down converters, amps, cables …
- Link-based uncertainties due to
  - Slightly different frequencies in transcontinental links
  - Different spread-spectrum codes in different links
  - Reference and system instabilities between observations (times differ by a few minutes)
  - Multiplicative bandpass effects
  - link-dependent calibrations
- Closure studies: uncertainties=700 ps/sqrt(3)
  - Closure = signed sum of measured clock differences between 3 labs A, B, and C
  - Closure sum = (A-B) + (B-C) + (C-A)

GPS Uncertainties: Largely Site-based

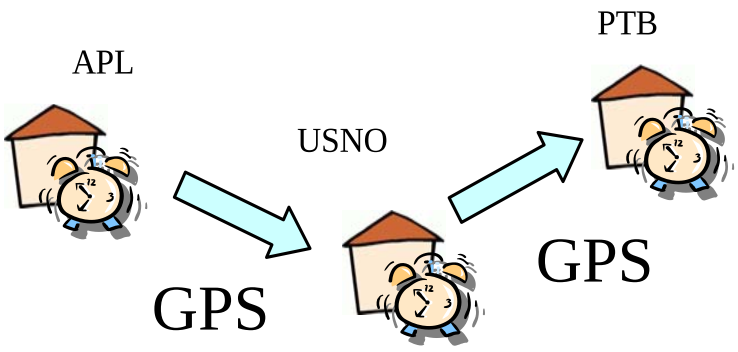
- Every uncertainty depends only upon site, or is global
  - Receiver instabilities
  - GPS or IGST instabilities for All-in-View
  - Ionosphere model errors (maps/Klobuchar)
  - Multipath
- **Link-dependent uncertainties are generated by link-dependent sampling in time and az/el**
  - Jiang and Petit, in BIPM TM132
    - CV closure uncertainties up to 1 ns/sqrt(3)
    - AV closure uncertainties 350 ps/sqrt(3)
- All calibration uncertainties (type B) are site-based

Link-based Uncertainties and Biases

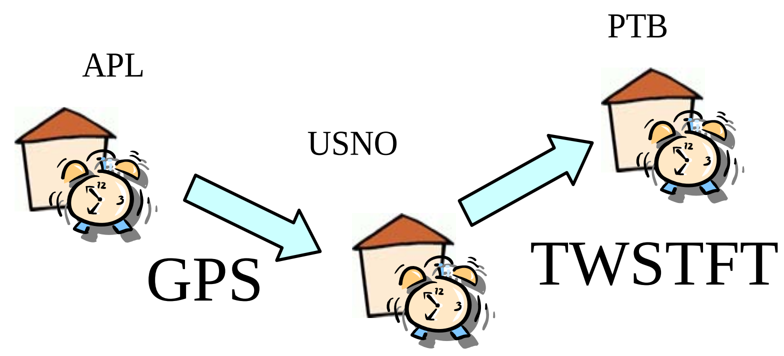
- Effect on UTC-UTC(k) is topology-dependent
  - A bias “B” between GPS and TWSTFT at a crossover site forces all sites linked by GPS to be “B ns” off from those linked by TWSTFT
    - Biases up to 10 ns have been observed in the past
  - Uncertainties also propagate in a similar manner (rss)
- Raising the uncertainty assigned to a lab with a primary frequency standard could lower that standard’s weight in steering EAL to TAI
  - Solution is to optimize EAL-generation

Problem area: “Crossover Sites“

- Different time-transfer systems for different links
- Site-based uncertainties become effectively link-based



APL-PTB not affected by USNO



APL-PTB is affected by USNO

Link-based Noise is Worse Than Site-based

- Link-based noise propagates down a chain
- Site-based noise affects the lab only
  - Except when it is converted to link-based
    - As at crossover sites
- Example: assume all labs and links are identical and the links form a straight chain.
- Consider lab k at one end of the chain
  - Let U=uncertainty of *UTC – UTC*(k), u=link uncertainties
  - If u is link-based, $U_{link} = u\sqrt{(2N-1)*(N-1)/(6N)}$
  - If u is site-based $U_{site} = u\sqrt{(N-1)/(2N)}$
  - Ratio of above is $U_{link}/U_{site} = \sqrt{(2N-1)/3}$
- For the current star-pattern and weights used by the BIPM to make TAI, but assuming equal link and site uncertainties, the difference would be 50%

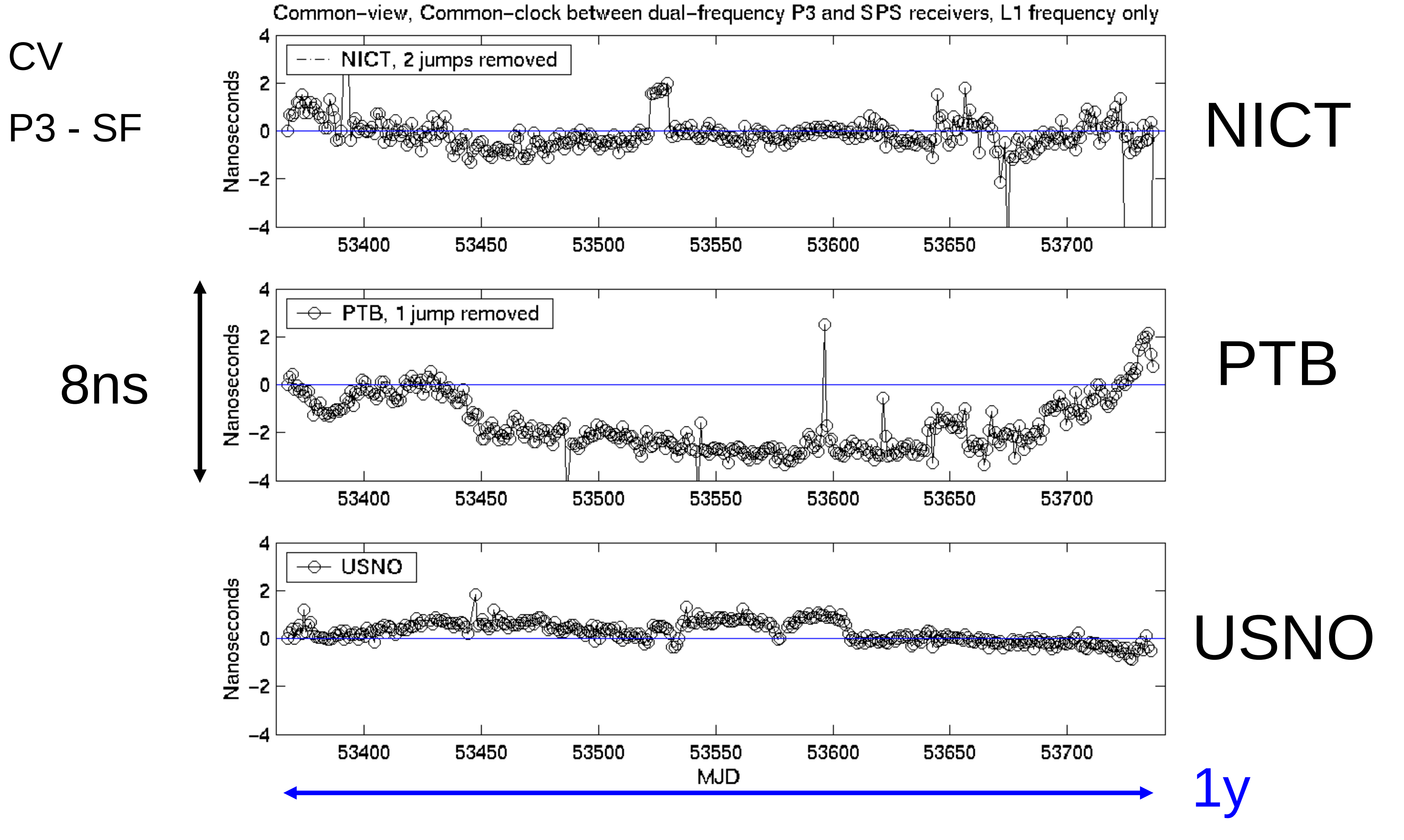
Virtual Pivots

- A pivot lab is linked to >1 lab in TAI generation
  - A virtual pivot is a pivot with zero weight
  - Could also use a reference timescale
    - GPST, IGRT, and IGST are examples
- TAI is largely insensitive to “site-based noise” in virtual pivot’s timescale
  - Some would be converted to link-based if there are data gaps
  - In extreme case can generate A-B if even if Lab A and Lab B have no overlapping data
  - The Vondrak smoothing also creates link-based noise
- To the extent there is link-based noise, TAI would be degraded

Ideal Crossover Site

- At least two independent TWSTFT and >= 2 independent GPS systems
  - state-of-the-art
- Maser-based timing reference
- Environmental impact minimized
  - Low tempco components
  - Short exterior cabling
  - No obvious diurnals in the data
- Minimal multipath - cable and az/el
- Monitoring of key components
  - Continuously monitored electronically
  - Human oversight and human hindsight

Recent GPS Receiver Variations



How to use multiple GPS receivers

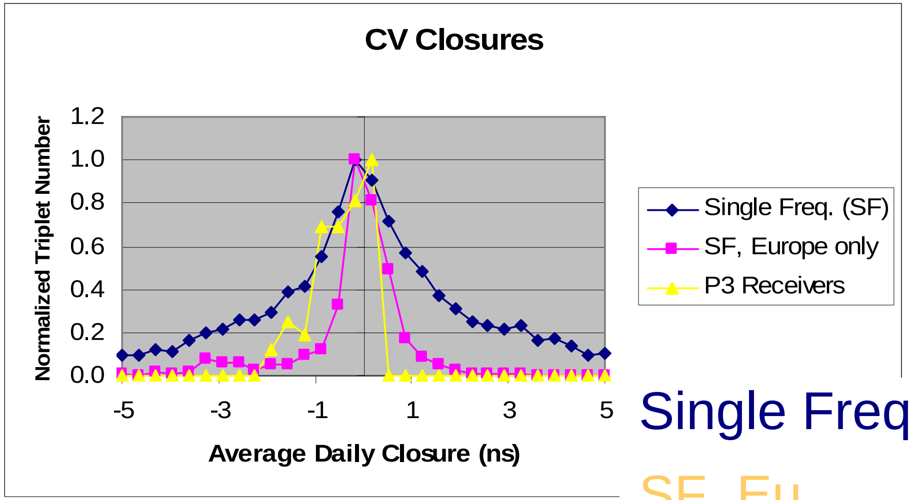
- At a non-crossover site, use best one for TAI
  - Otherwise you create a crossover
    - Which adds link-based noise
  - Use ensemble to correct bias variations
- At a TWSTFT/GPS crossover site
  - It's irrelevant if TWSTFT delay varies
  - Using the best GPS receiver optimizes
    - But only if other receivers are used compute average reciever bias
- Special issues in comparisons between different receiver models are discussed in next slide

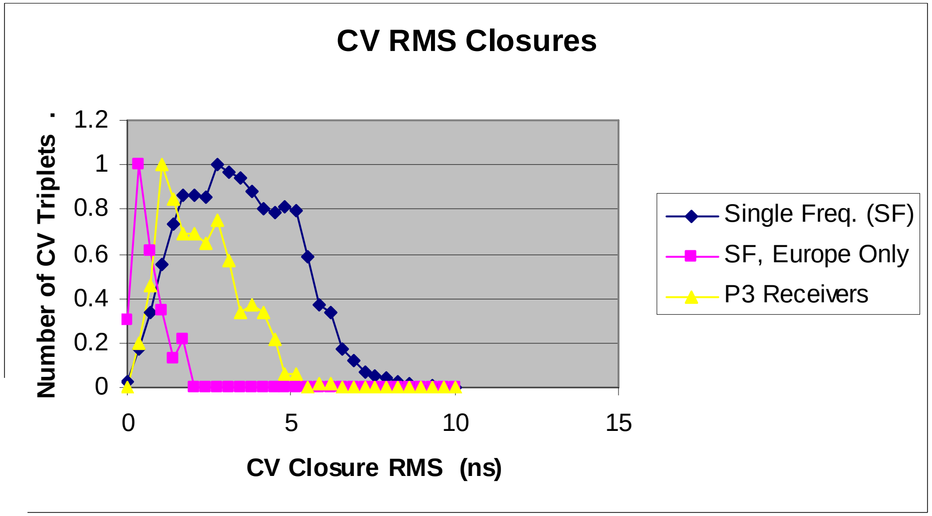
Using Redundancies

- How much do we gain by averaging redundant GPS CV links?
- How much we gain by averaging redundant GPS AV links?

  (200 ps RMS at most – see Jiang and Petit)
- How much do we gain by averaging redundant TWSTFT links?
- What about reducing crossover site biases?

Benefits of Averaging CV





Single Freq.

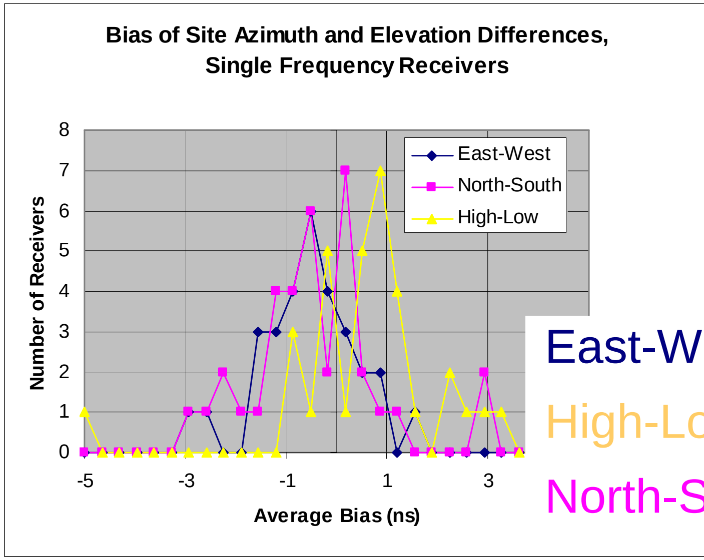
SF, Eu

P3 receivers

CV's link-based noise is reduced

It exists because CV does not sample all sky angles equally

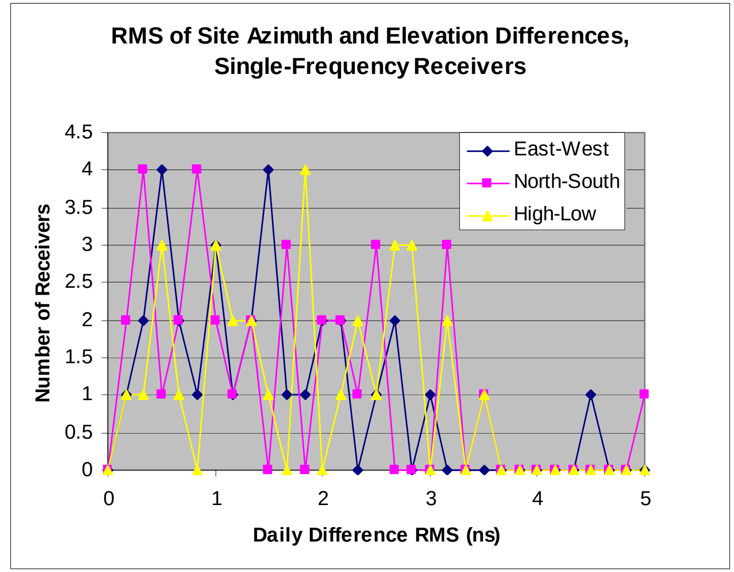
GPS and the Angle of Observation

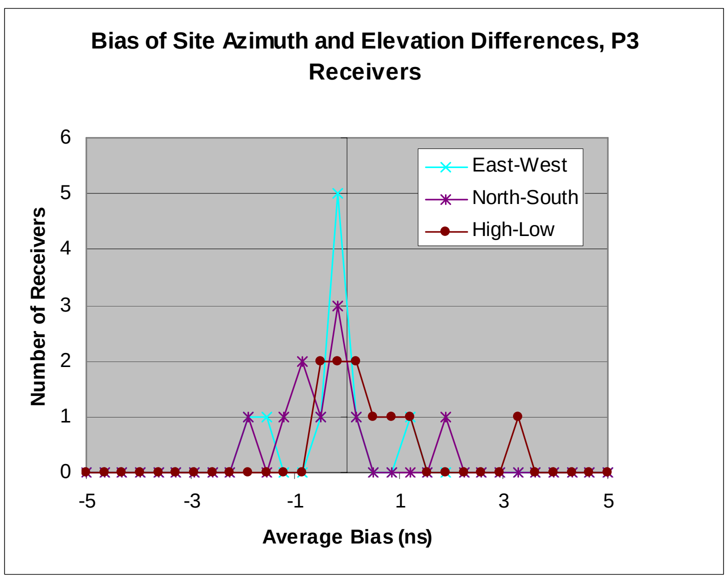


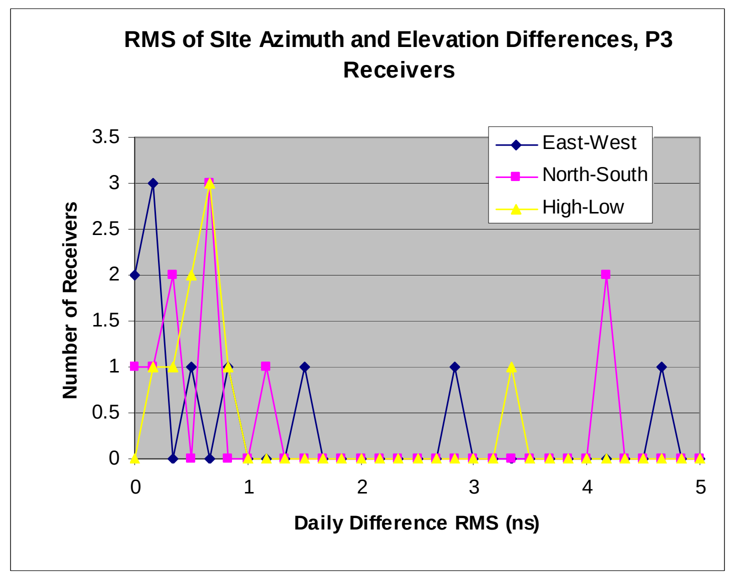
East-West

High-Low

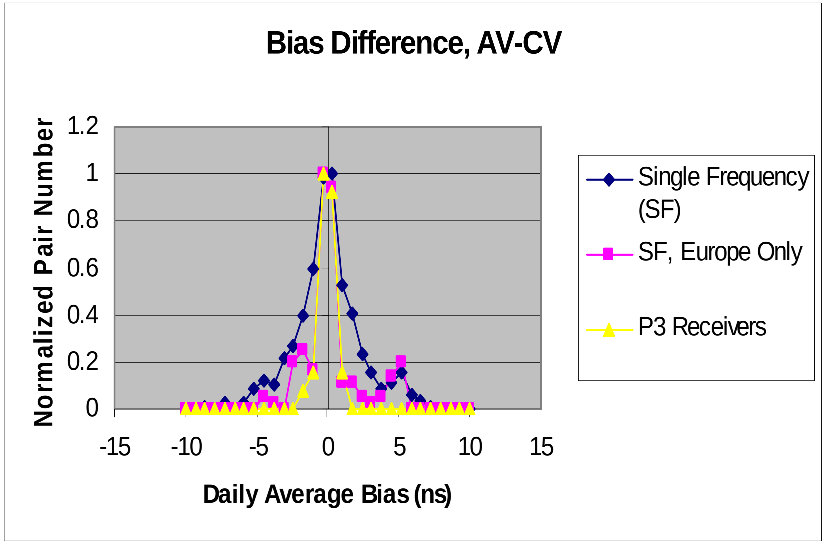
North-South

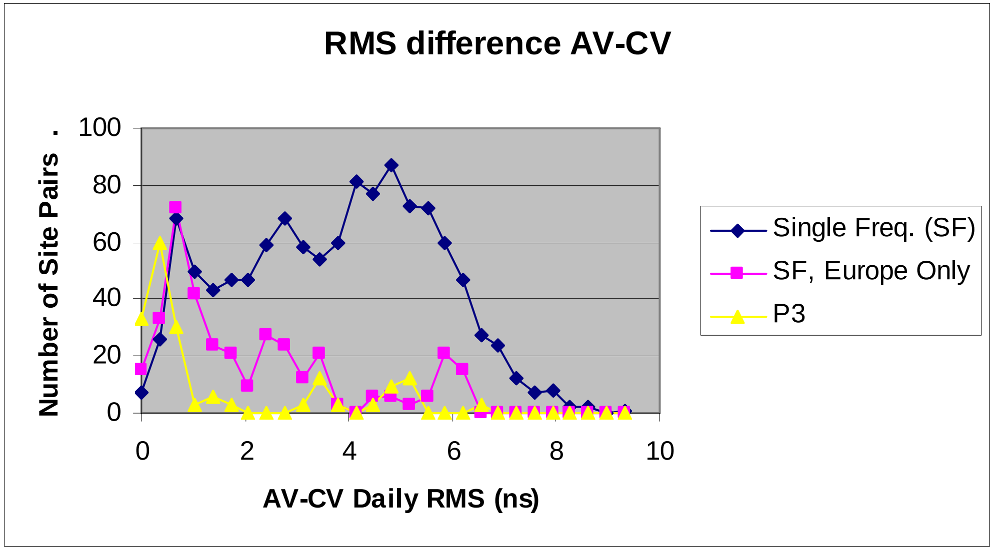






What about GPS AV and CV?

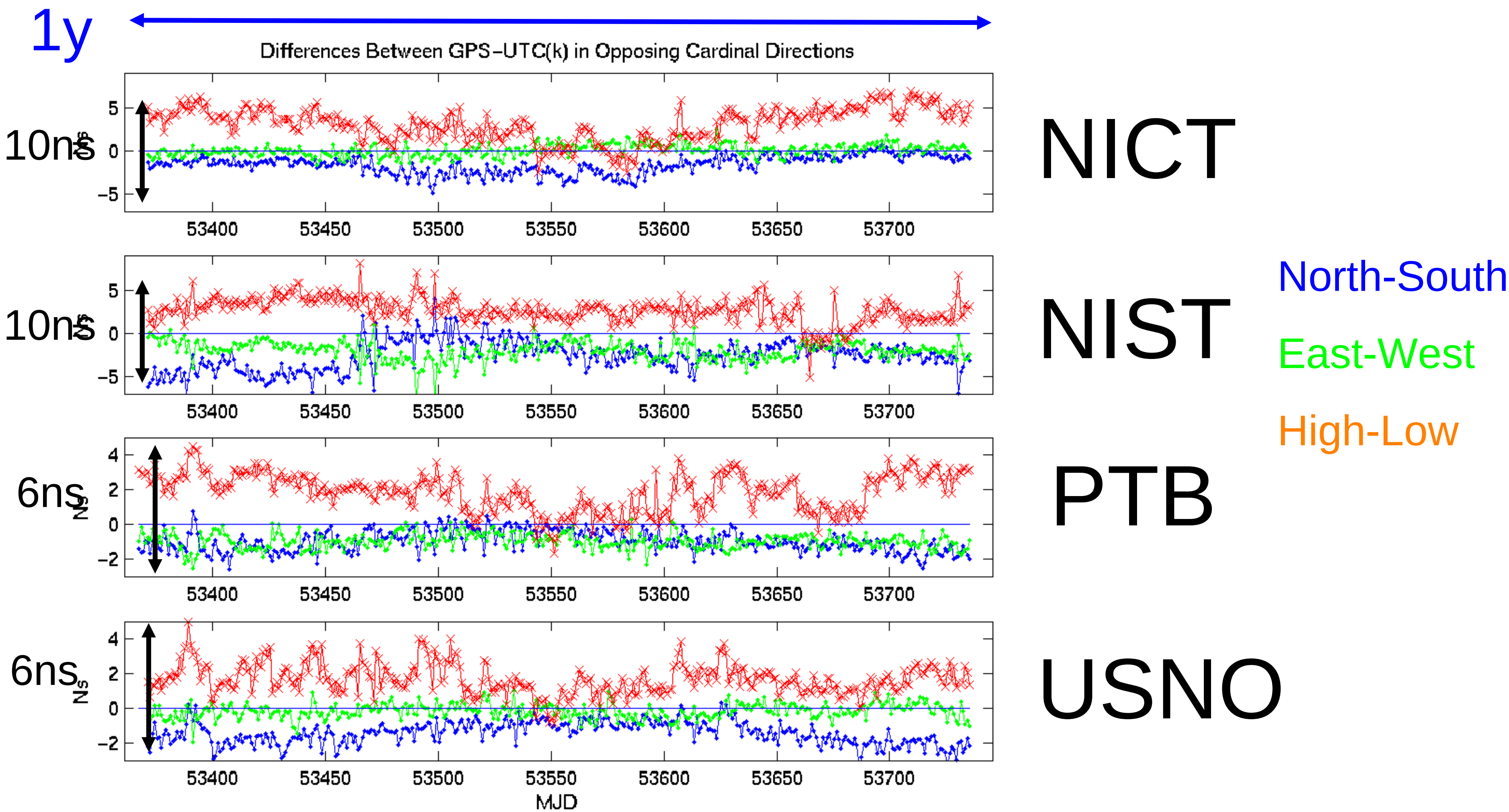




Longest links show largest differences

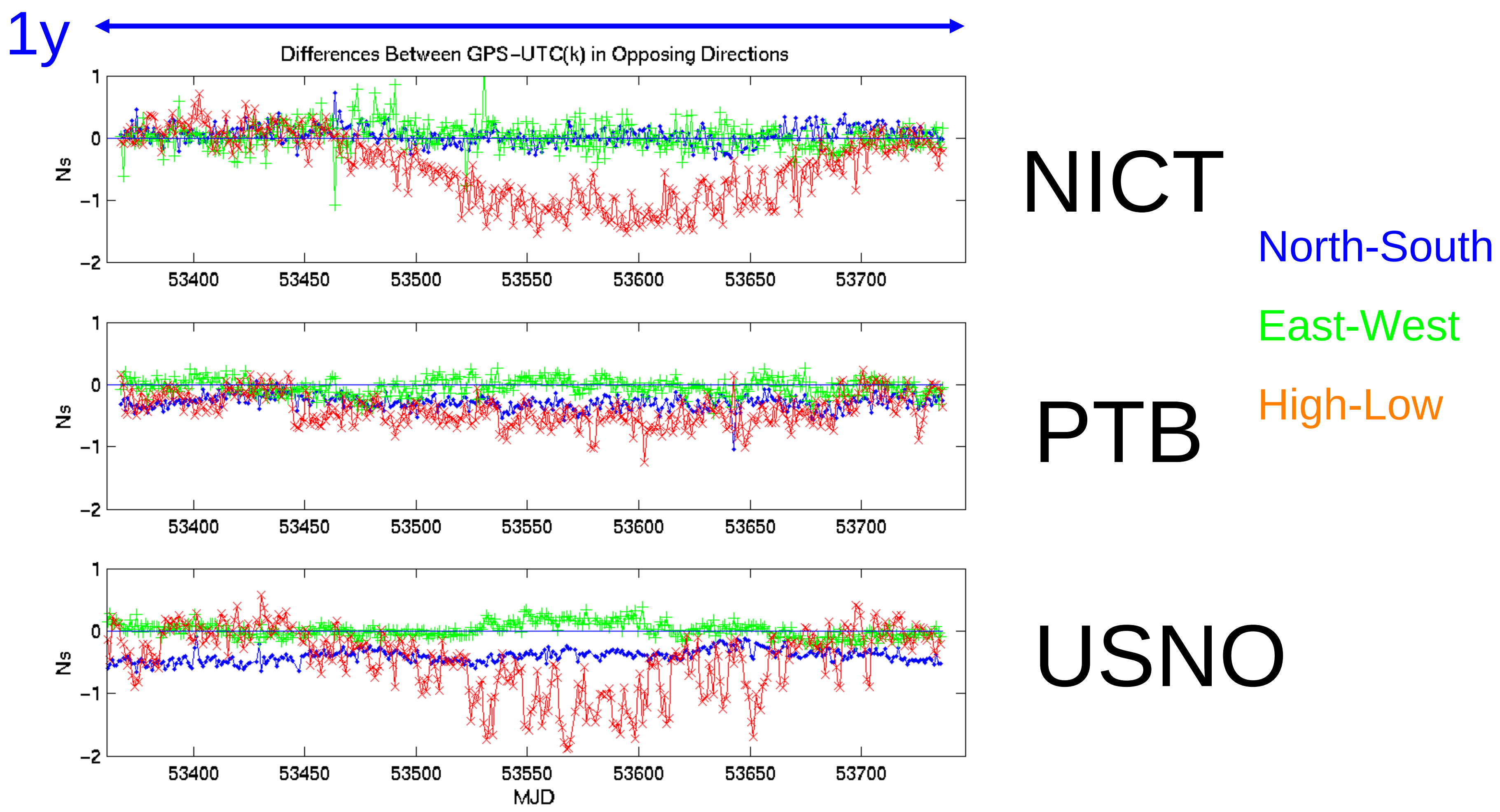
Directional Asymmetries in Data of Crossover Site Single Frequency Receivers

Plot Vertical Scales: 16 ns



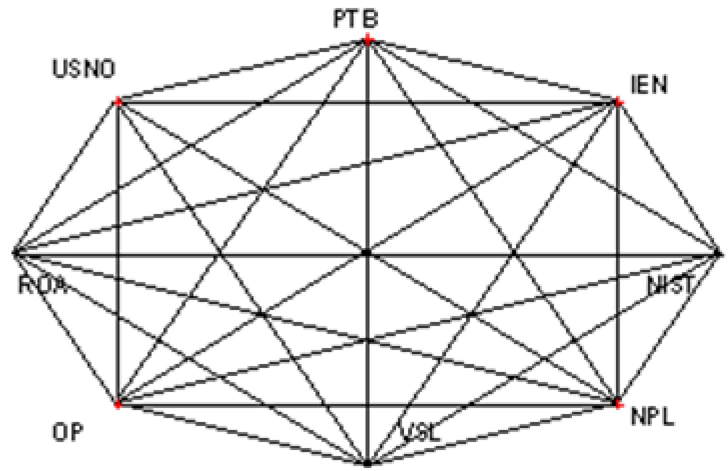
Directional Asymmetries in Data of Crossover Site Geodetic (P3) Receivers

Plot vertical scales: 3 ns



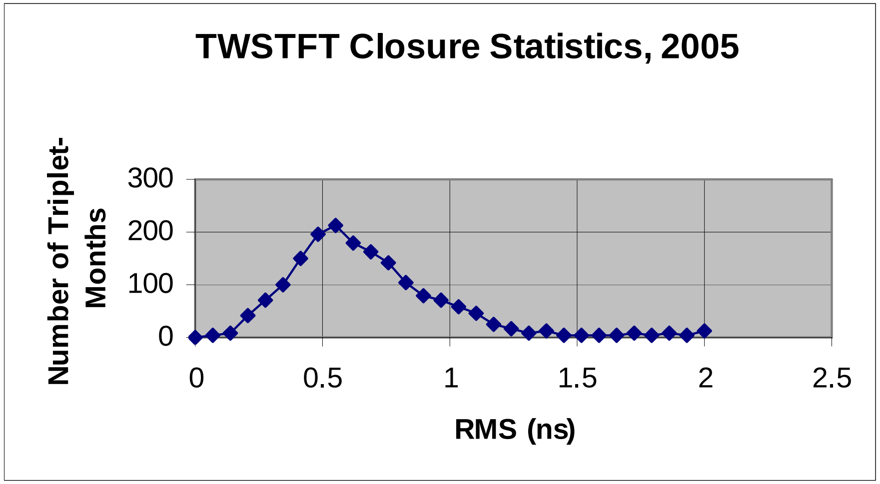
TWSTFT Links

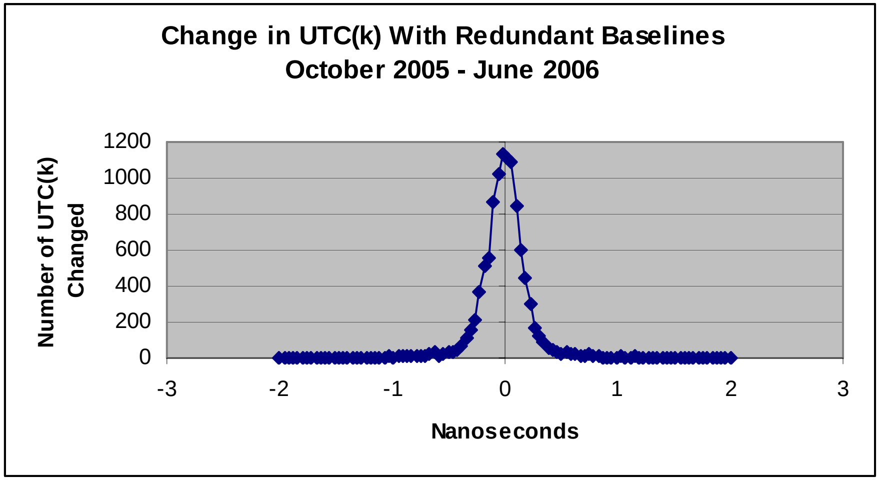
Minimal Set



Fully redundant

Fit is Consistent with Expectations





Conclusion: Benefit <400 ps

Redundancy and Crossovers

- Redundant TWSTFT and GPS links
  - Except for GPS CV, benefits of averaging are highly subnanosecond
  - It is one way to identify bad data
    - But that should be done before TAI generation
- If BIPM switches to AV, biases at crossover sites are only remaining bias issue

Crossover Biases

- Minimize number of crossover sites
  - Usually minimizes link-based noise
  - Lab and/or BIPM check with redundant receivers
  - Minimizes the effects of unremoved biases
- Ways to use redundant systems for bias identification/removal
  - Zero baseline CV at each lab
  - Double differences between GPS and TWSTFT
  - Average using network of sites
    - Could also do this to compute TAI
    - Drawback is complexity
    - Details follow

Least Squares Fit to Crossover Biases

- Bias between TWSTFT and GPS systems
  - One bias parameter per crossover site
  - Sum of bias parameters constrained to be 0
  - Possible extension: extra bias parameters if a crossover site has >2 independent systems
- Solution yields the link values that form input to ALGOS
- Could generalize to included redundant GPS CV links, etc.

Receiver-dependent Biases

- Correlator spacing, receiver filter bandwidth, and receiver transfer function can affect GPS biases
  - Hegarty et al, PTTI 2004, pp. 307-318
    - Same article in GPS World, January 2006
- Result in a satellite-dependent bias between receivers of different make.
  - This must be accounted for.

Timing Group Delay and GPS Receivers

- Timing Group Delay is bias between the two GPS frequencies (L1 and L2)
  - It is broadcast by the satellites
  - Single-frequency receivers use it as part of the ionosphere correction
  - It is not yet consistent with the USNO absolute calibration of dual frequency receivers
  - Shows as a 10 ns bias in GPS in Circular T
- May be a problem in P3 vs. single-frequency ionosphere-corrected data

SG II Recommendations

- Minimize number of crossover sites
  - Ensure data quality through redundancy
  - Biases between different receiver types can be significant
    - Best resolved in short baseline CV at each site
- Virtual pivots not recommended
  - They add some noise.
- All-in-View is recommended
  - Consistency with calibration is one reason
- Use of redundant links not promising
  - Develop carrier phase GPS instead