Synchronization of Radiometers on Spatially-Separated Platforms

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Spatial Separation Context

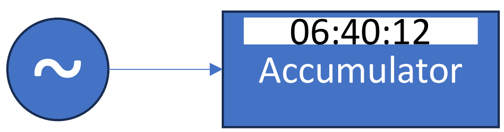
- Distance and/or motion of platforms sufficiently disparate that tethered connection between them is not feasible, e.g.,
  - Formation of aircraft
  - Constellation of spacecraft

Need for Synchronization

- Recommended Practices document proposes correlation among radiometers as the preferred approach
  - Sampling Rates must be synchronized among multiple platforms
    - Lack of frequency synchronism leads to correlation loss and temporal broadening
  - Times must be tagged to a common standard to attribute the thermograph to its geographical location.
    - Lack of time synchronism leads to smearing/blurring of the thermograph
- Both effects are linked to synchronization of on-board clocks

Components of a Clock

- The simplest concept of a clock is described in terms of two components
  - Isochronous* oscillator
  - Accumulator that counts cycles of the oscillator



* Temporal phase profile is linear

Intervals between Isochronous Events

- Time lapse between consecutive cycles of emission from an atom
  - 1/9,192,631,770 s for Cesium atom
- Time lapse between consecutive leading edges of a highly stable rectangular waveform generator
- Time lapse between two identical states of Kepler motion of Earth around the sun, the state being defined by (R, $\dot{R}$, $\ddot{R}$, ϕ, $\dot{\phi}$, $\ddot{\phi}$)

Impairments to Isochronism

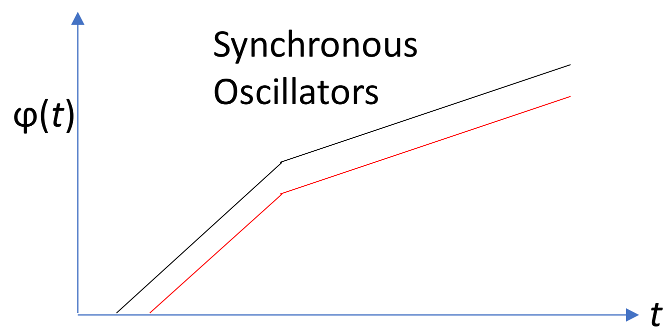
- Oscillators in nature or man-made are approximately isochronous
  - Atoms recoil during emission (Doppler broadening), interact with other atoms, perturbed by electric fields, etc.
  - Waveform generators affected by random fluctuations in phase, or equivalently jitter in time
  - Earth's motion perturbed by presence of other bodies, and its own rotation

Isochronism is a property of a single oscillator

Synchronism

- Synchronism applies to two or more oscillators or clocks.
  - Two oscillators with phase characteristics $\varphi_i(t)$ and $\varphi_j(t)$ are synchronous if and only if $\frac{d(\varphi_i - \varphi_j)}{dt} = 0$ at all times.

  [Note: Oscillators i and j need not be isochronous, but the phases must track in time so that $\varphi_i(t) - \varphi_j(t)$ = constant for all time]
  - Two clocks are synchronous if their oscillators are synchronous AND $\varphi_i(t) - \varphi_j(t) = 0$.



Benefits of Isochronous Operation

- Although isochronous operation is not necessary for synchronism, it has significant benefits
  - Spectral characteristics best suited for frequency reference
  - Samples at equally-spaced instants of time compatible with analytical methods developed for that purpose (e.g., Fourier and Laplace analysis)
  - Compensations for small deviations from isochronism, e.g., slowly varying Doppler shifts more easily accomplished

Plesiochronous Systems

- Practical systems are neither perfectly isochronous nor synchronous.
  - Nominally isochronous and synchronous, e.g., oscillators in free-running state may differ in frequency by parts per million or even several parts per billion.
  - Deviations from isochronism synchronism constrained within specified bounds by proper design. Algorithms operate on sampled data to estimate deviations and correct the clocks for such deviations.
    - Common in digital communication systems where carrier-phase and symbol timing loops estimate deviations and compensate for them during the signal demodulation process.

Plesiochronous Definition

- $\frac{d(\varphi_\mathrm{i}-\varphi_\mathrm{j})}{dt} \ll \frac{d\varphi_\mathrm{i}}{dt}$ and $\frac{d\varphi_\mathrm{j}}{dt}$; $\frac{d(\varphi_\mathrm{i}-\varphi_\mathrm{j})}{dt} = k_\mathrm{i}\frac{d\varphi_\mathrm{i}}{dt} = k_\mathrm{j}\frac{d\varphi_\mathrm{j}}{dt}$; $k_\mathrm{i}, k_\mathrm{j} < 10^{-6}$
- $|\varphi_\mathrm{i}(t) - \varphi_\mathrm{j}(t)| \leq \Delta\varphi_\mathrm{B}$

[1] S.P. Ferguson, *Tutorial: The Synchronous Digital Hierarchy*, IEE Colloquium on What's New in Telecommunications?, London, UK, January 1994

[2] G.D. Richardson, P.C. Smith, *Transmission of Synchronous Digital Hierarchy Signal by Radio*, IEEE International Conference on Communications, Atlanta, GA, USA, April 1990

[3] Atsushi Imaoka, Masami Kihara, *Time Signal Distribution in Communication Networks Based on Synchronous Digital Hierarchy*, IEEE Transactions on Communications, Vol. 45, No. 2, February 1997

Challenges for WG - General

- Standard algorithms apply to deterministic events
  - Need to adapt formulation to random (probabilistic) events
- Standard technique apply to receivers on one platform – feasible to tie all operations to a single time & frequency reference
  - Multiple platforms have independent LOs and sampling clocks which need phase locking and time synchronism to a common but necessarily remote reference.
    - Pro: Phase noise is uncorrelated among LOs and suppressed by cross-correlation, and remote separation of receivers eliminates crosstalk
    - Con: Cross-correlation loss and broadening due to plesiochronous sampling mismatch in clock times and delays and gain between antennas and samplers on different platforms.

Challenges for WG – Processing Sequence

- Where and how do we apply Doppler compensation?
- Time-domain cross-correlation with plesiochronous clocks
- Frequency-domain cross-correlation with plesiochronous clocks
  - Perform FFT on each receiver output (with reference to whose clock?)
  - Convolve FFTs pairwise (what is the degradation in correlation gain due to mismatch in sampling clocks?)
  - Perform inverse FFT on convolved pair