State of the art in High-Stability Timing, Phase Reference Distribution and Synchronization Systems

Mario Ferianis - Sincrotrone Trieste S.c.p.A, Italy - WE3GRI02
Recent advances in **high-stability electronic** and **electro-optic timing** and **synchronization** systems are presented. These systems have been proposed for several **new FEL facilities**, and are in development at several labs.

Several basic technical implementations are in development, some based on **pulsed mode-locked laser** technology, others using **CW systems**. There are numerous technical choices with regard to the **stability**, **synchronizability**, capability of multi-drop operation, availability of inherent diagnostic information, complexity of transmitters vs. receivers, use of **commercial vs. custom-designed** components, etc.

This talk presents an **overview of the basic timing and synchronization requirements** in accelerator systems, and reviews the state of the art. Contrasts are made between the **CW** and **pulsed optical distribution** approaches.

The technology in development to distribute a **38GHz phase coherent LO** at the ALMA radio telescope is highlighted as a related technical system in development.
Jitter and drift in 4GLS

Timing & Synchronization (T&S) systems

- In 4th Generation Light Sources (4GLS) the required jitter is as low as $<10 \text{fsec}_{\text{RMS}}$ (it is few ps in 3GLS)
- In 4GLS T&S systems we have:
  - Timing generates the Bunch Clock
  - Phase Reference represents the Ref. at the bunch level
  - Distribution delivers to the end user the two above
- The jitter of a periodic signal can be defined as the measurement of its time fluctuations, measured over a certain observation time and wrt a phase reference
- It is relative to fast fluctuations which may occur at various frequencies
- In the frequency domain, it is referred to as: Phase Noise
- Drift is related to slow time fluctuations of the signal wrt the reference
- In a T&S system, drift may be caused by changes in:
  - propagation time (temperature dependant) in the distribution system
  - reference frequency (stability of the master oscillator)
- Drift is related to the stability of the T&S system

recent book: Phase Noise and Frequency Stability in Oscillators
E. Rubiola, FEMTO-ST Institute, Université de Franche Comté, Besançon
Need to address specific events...

2009 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium
20 to 24 April 2009


Courtesy of Jesse Searls, Poseidon S.I. Ltd
Layout of a fsec T&S system

μ-wave Reference Oscillator

Master Timebase /Event Gen.

Timing: set of triggers

Phase Reference distribution

Timing User #1

Timing User #2

Timing User #3

Phase Reference distribution

Feedback path

Gun

Lasers

Accelerator

Feedbacks

LLRF, etc

Diagnostics

Experiments

Laser, HV diags

Timing User #N

Timing User #N-1

Receivers

Transmitters
To develop fsec T&S systems: moving to Optical / O/E techniques

A fsec Timing & Synchronization system has:
- to meet the **demanding specifications:**
  - jitter
  - drift
  - **T&S clients distributed over the whole facility** (extension ≥ km)
  - **to be remotely controllable** (*Control System integrated*)
  - **rad-hard** (at least for some sub-systems)
- to **reliably operate:** T&S systems are deployed in Facilities (24h-7d)
  - need to use engineered sub-systems:
    - (true for Telecom components; table-top sub-systems ?)
  - **cost** could also be an issue (*Fiber Optics are cheap, fsec are not*)
  - to be “easily” **upgradable** (considering here also system **maintenance**)
  - to make our job easier, these systems typically operate in a protected, quiet
    (vibration free) and **temperature controlled** (ΔT≤1°C_{pk-pk}) environment
To measure & characterize a fsec T&S system

- time domain is not sufficient (…scopes only for coarse measurements)
  although current samplings (and associated photodiodes) go up to 100GHz…

- frequency domain allows higher resolution (Phase Noise Spectrum)
  we implicitly agree on averaged measurements, no Real Time SP. AN.

- take your Reference signal (aka Carrier), typically $f_c \approx$ GHz

- plug it in into a Spectrum Analyzer and:
  - select a sufficiently small Span & Resolution Bandwidth (1MHz & 10Hz)
  - you can observe your carrier and its Sidebands which (from Signal Theory) are a clear and high sensitivity signature of your Carrier quality
  - if you see two peaks, symmetrically located around your Carrier:
    you are in troubles: AM detected!
  - being more clever with your Reference Oscillator you will see a central peak with symmetrical slopes on each side: where are now my fsec?
The Carrier and its spectrum

\[ V(t) = (V_0 + \Delta V(t)) \cdot \cos(\omega_o t + \Delta \varphi(t)) \]

The single-sideband phase noise is mathematically defined as the power spectral density of the phase fluctuations:

\[ L(f) = \int_{-\infty}^{+\infty} e^{-j2\pi f \tau} \Delta \varphi(t + \tau) \Delta \varphi(t) \, d\tau \]

\[ \Delta \varphi(t) = \omega_o \cdot \Delta t(t) \]

"Phase Noise and Jitter", N. Roberts, ZARLINK semicond.
EE Design, July 14 2003
From phase noise to jitter

To extract the RMS timing jitter occurring in a certain frequency range from the phase noise

It is a complex spectrum over positive and negative frequencies, so it has to be taken twice if we integrate only over the positive frequency range

\[
\Delta t_{rms}(f_1, f_2) = \frac{1}{\omega_0} \sqrt{\int_{f_1}^{f_2} L(f) \, df}
\]

Area under curve yields jitter


“Phase Noise and Jitter”,
N. Roberts, ZARLINK semicond.
EE Design, July 14 2003
Reference 3GHz Oscillators

Ref. INWAVE gmbh 0.01ppm

Ref. Poseidon Scientific Instruments Ltd.

11fsec_{RMS} [100Hz-10MHz]

500Hz 90dB
Which is the physical meaning of a phase noise component for a high frequency signal (i.e. carrier, Phase Reference)

- Let's represent it as \( R(t) = A_R \sin(2 \pi f_R t + \varphi_R) \) by using the vector notation
- It is a vector, rotating at \( \omega_R = 2 \pi f_R \)
- Let's add to it a phase noise components \( N(t) = A_N \sin(2 \pi f_N t) \)
- For each value of \( N(t) \) we obtain the resultant \( R^{+N}(t) \) by applying vector sum
- \( R(t) \) is oscillating around its nominal angle at \( f_N \) and by \( \pm \varphi_N \)
- The value of \( \varphi_N \) depends on the ratio \( A_N / A_R \); proportional pk-pk jitter of \( R(t) \)
- The rate at which \( R(t) \) moves depends on \( f_N \); i.e. the offset frequency in the phase noise spectrum
considerations on phase noise

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Artist view: amplitude changes not shown!!!
considerations on phase noise

how does a 100Hz phase noise component affect a RF signal?

- let’s plug in some numbers... $f_R = 3$ GHz; $f_N = 100$ Hz;
- from phase noise measurements, we get relative amplitudes: $A_R / A_N = 80$ dB (typical)
  - $\phi_N [rad] \equiv A_N / A_R = 0.0001$ rad
  - $\tau_R = 330$ ps; $\phi_N = 0.0057$ deg = 5.309 fsec
    
    $\left(2\pi \times 3.10^9 \times 5.309 \times 10^{-15} = 1.10^{-4}\right)$

by how much does the phase of a noisy Phase Reference signal change in few $\mu$s?

- (the time of flight of FERMI@Elettra is few $\mu$s)
  - $\tau_N = 10$ ms; consider 2$\mu$s around zero crossing
  - phase deviation $\Rightarrow$ 0.00667 fsec!!!
  - The peak value (5.309 fsec) is reached after 2.5 ms

<table>
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<th>$\varphi$</th>
<th>$F_N$</th>
<th>$t$</th>
<th>$f(t)$</th>
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<td>[Hz]</td>
<td>[sec]</td>
<td>[fsec]</td>
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The Phase Reference:

**fsec T&S system clients & requirements**

- In order to properly operate, all the relevant systems (T&S clients) have to share a common phase reference.
- The client sensitivities to jitter are not all equal though.

$$Jitter_{total} = \sqrt{jitter^{2}_{REF} + jitter^{2}_{DEV}}$$

<table>
<thead>
<tr>
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<tr>
<td>REF</td>
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<tr>
<td>accelerating sections (S-band &amp; L-band)</td>
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<tr>
<td>harmonic linearizer (X-band)</td>
<td>&lt;70 fsec_{RMS}</td>
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<table>
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<tbody>
<tr>
<td>photo-injector</td>
<td>&lt;100 fsec_{RMS}</td>
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<tr>
<td>laser heater</td>
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<tr>
<td>seed</td>
<td>&lt;15 fsec_{RMS}</td>
</tr>
<tr>
<td>user</td>
<td>&lt;15 fsec_{RMS}</td>
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<th>Diagnostics</th>
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</thead>
<tbody>
<tr>
<td>Bunch Arrival Monitors (BAMs)</td>
<td></td>
</tr>
<tr>
<td>Electro-Optical Sampling (EOS) stations</td>
<td>&lt;15 fsec_{RMS}</td>
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</table>
### The Phase Reference: jitter budget

<table>
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<tr>
<th>absolute</th>
<th>relative (1-2) $\cdot fsec_{RMS}$</th>
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<tbody>
<tr>
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<td>0</td>
</tr>
<tr>
<td>10</td>
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<td>10</td>
<td>17.3</td>
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<tr>
<td>10</td>
<td>20.0</td>
</tr>
</tbody>
</table>
Phase Reference systems

- To generate and to distribute the phase information
- Jitter $<10\text{fsec}_{\text{RMS}}$
  - the bandwidth (BW) over which jitter is defined depends on the time structure of the beam:
    - [10Hz - 10MHz] for long macro-pulses
    - [100Hz - 10MHz] for pure single bunch
- Drift $<10\text{fsec}_{\text{RMS}}$
- Frequency 100s MHz to GHz range
- State of the art solutions are based on Optical clock
- RLE@MIT – Cambridge, MA (prof. FX Kaertner group):
  - PULSED OPTICAL PHASE REFERENCE SYSTEM
- CBP @ LBNL – Berkeley, CA (J.M. Byrd, R. Wilcox et al.)
  - CW OPTICAL PHASE REFERENCE SYSTEM
Phase Reference systems

- Why OPTICAL?
- What is PULSED and what is CW?

**OPTICAL**
- the key issue is not only the generation of a phase reference signal with fsec jitter, but also distributing it over the whole Facility without spoiling the Reference Oscillator jitter
- **Optical Oscillators** (*soliton* fiber lasers) are typically performing better than μ-wave oscillators in the BW of interest (>1kHz)
- Optical link stabilization techniques have been demonstrated and implemented able to keep jitter ≤10fsec\textsubscript{RMS}
- **Electro optical diagnostics** have been implemented; making full use of the Optical Reference, these can provide resolution <10fsec as well
how does it work?

- the phase information is *encoded* into the repetition rate of a soliton fiber laser which is phase locked to a µ-wave reference for improved jitter (low frequencies end) and drift
- a train of optical pulses is sent over single mode optical fibers (rep rate ∼100sMHz)
- the propagation over the fiber links is stabilized by means of active loops adopting a x-correlator as *phase detector*
- ideally suited for *synchronization* of remote laser oscillators
- *direct seeding* of remote optical amplifiers is under investigation
- extraction of an harmonic RF electrical signal at the remote stations has been implemented as well
- *longitudinal diagnostics* have been implemented for Bunch Arrival Time Monitor with res <10fsec_{RMS}
- aiming at: *single oscillator* facility
... there are also Continuous Wave (CW) T&S clients: the accelerating structures and the associated RF plants

- **CW OPTICAL PHASE REFERENCE**
  - The Optical Link is stabilized making use of the Optical Mixing concept, applied to the Optical carrier and its 100MHz frequency shifted replica ($f_{CAR} = 190$THz @1560nm)
  - As heterodyning preserves phase relationships:
    1 degree at optical = 1 degree RF
    1 degree at 110 MHz = 0.014 fsec at optical
  - Gain $10^3$ leverage over RF-based systems in phase sensitivity
  - RF is sent over the stabilized link
  - System has been optimized through the years; it is integrated into the Low Level RF (LLRF) system used to locally (at each plant) stabilize (in amplitude and phase) the accelerating field seen by the particles
Pulsed Optical Phase Reference: stabilized link

- Mode-locked laser
- Isolator
- PZT-based fiber stretcher
- Fiber link ~ several hundreds meters to a few kilometers
- Faraday rotating mirror

Timing Comparison Cross-corelator

PPKTP: periodically poled Potassium Titanium Oxide Phosphate (KTiOPO4)

to detector 2
group delay between orthogonal polarizations

dichroic mirror reflecting fundamental transmitting fundamental

dichroic mirror reflecting fundamental transmitting SHG

to detector 1

Courtesy of: prof. F.X. Kaertner RLE/MIT; F. Loehl DESY

Mario Ferianis WE3GRI02 PAC09 May 4-8, 2009
Pulsed Optical Phase Reference: stabilized link

Mode-locked laser → isolator → fiber stretcher → PZT-based fiber stretcher → Faraday rotating mirror

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dichroic mirror

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Mode-locked laser

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Courtesy of: prof. F.X. Kaertner RLE/MIT; F. Loehl DESY
Pulsed Optical Phase Reference:
two-links out of loop jitter measurement

Two link stabilization system. The outputs of 2 separate stabilized links are recombined for an out-of-loop drift measurement with a third PPKTP cross-correlator.

The transfer function (s-curve), for the PPKTP cross-correlator is the calibration for the measurement sensitivity of the X-correlator. It is performed by modulating the piezo to provide a time-varying delay to one link.
Pulsed Optical Phase Reference: two-links out of loop jitter measurement

Courtesy of: J. Cox RLE/MIT; F. Rossi ELETTRA
The results obtained for the 2 link measurement. The upper plot shows the drift of the fiber link which the system compensates for over 18 hours, as revealed by monitoring the position of the free-space motorized delay. The lower plot shows the out-of-loop drift as measured by X-correlator between both links. The drift is 18 fs\text{\textsubscript{RMS}} over 3 hours.

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Courtesy of: J. Cox RLE/MIT; F. Rossi ELETTRA
CW Optical Phase Reference: link stabilization

- Optical carrier at 1560nm
- Frequency shifted (2x55MHz) & back reflected at the far end

Courtesy of R. Wilcox LBNL
CW Optical Phase Reference: link stabilization

- Final version: no more piezo for length correction
- The delay is sensed and locally added at each remote station

Courtesy of J. Byrd and R. Wilcox, LBNL
CW Optical Phase Reference system:
RF transmission at 2850MHz

- Comparison of RF phase transmission through 2m fiber and 200m or 2km
- Fiber in loose coils in lab, with +/- 2 degree C air temperature stability
- Periodic error in 2km data is air conditioning cycle
- In 2km case, 15fs RMS for first 48 hours

200m, 8.4fsec_{RMS} over 20h

2km, 20fsec_{RMS} over 20h

Courtesy of J. Byrd and R. Wilcox, LBNL
CW Optical Phase Reference system: tested on field at LCLS

- 4 lines, expandable to 16
- <100fs_{RMS} error over 24h
- Continuous operation over one week
- Deliver signals capable of synching mode locked lasers: 0dBm, 2850 (RF), 476 and 68MHz

Courtesy of J. Byrd and R. Wilcox, LBNL
Pulsed Optical Phase Reference:
1st deployed on field at FLASH (DESY)

- The most complete Optical Timing system implemented so far
- Dual MLO for improved redundancy; *short link* Option
- fully integrated diagnostics: BAM, Energy BPM

**Laser building**
EO, HHG and ORS

**Experiments**
FLASH

BAM
Beam arrival monitor
L2L
Laser to laser synchronization
Seed
Direct laser seeding
L2RF
High precision down converter
L2L
Laser to RF conversion

**Acknowledgment**
Courtesy of H. Schlarb, DESY

Mario Feriani
WE9GRI02
PAC09
May 4-8, 2009
Pulsed Optical Phase Reference:
Bunch Arrival Monitor at FLASH (DESY)

- Based on an original idea that makes full use of the Optical timing
- Amplitude of the Ref. laser pulses is modulated according to the relative timing

![Diagram showing laser pulses from fiber link, EOM, ADC, and beam pick-up]

A fssec relative timing measurement is transformed into an amplitude measurement (ADC)

Courtesy of F. Loehl, DESY
Pulsed Optical Phase Reference:
Bunch Arrival Monitor at FLASH (DESY)

- 1st Front End prototype installed in tunnel

2nd prototype is underway with new optical delay lines with improved reliability

Courtesy of F. Loehl, DESY
Pulsed Optical Phase Reference:
Bunch Arrival Monitor at FLASH (DESY)

- two BAMs tested at two different locations along the accelerator
- distance BAM 1 to BAM 2 = 60m

Courtesy of F. Lochl, DESY
Pulsed Optical Phase Reference:
Bunch Arrival Monitor at FLASH (DESY)

Arrival time correlation between two BAMs

Courtesy of F. Lochl, DESY
Pulsed Optical Phase Reference:
Bunch Arrival Monitor at FLASH (DESY)

Arrival time correlation between two BAMs

Single bunch resolution of entire measurement chain (laser, links, BAMs) $< 6\text{fs}_{\text{RMS}}$

uncorrelated jitter over 4300 shots: 8.4 fs (rms)

Courtesy of F. Lochl, DESY
In order to keep track of the developments and of T&S installation activities, in March ‘08 the 1st T&S Workshop has been held at Sincrotrone Trieste.

The 2nd T&S Workshop has been held in March ‘09 @ICTP Miramare (Italy) organized by INFN/LNF.

It is a “traditional” event where experts meet and discuss.

Tutorial on Optical Synchronization held at DESY IRUV-X FP7 (OCT ‘08)
In the framework of an ST collaboration contract with I-tech and Ljubljana Univ. (SLO), a prototype link has been built and is currently being tested for the transmission over stabilized FO link of a Reference 3GHz signal.

*Patent Pending*

Original sketch, April 2008

Courtesy of prof. M. Vidmar, UNI LJ (SLO)
Absolute jitter of the transmitted 3GHz carrier: 22fsec\textsubscript{RMS} [100Hz -10MHz]
Optical cabling

- High quality single mode fiber optics are available
- Length are limited, if compared to telecom links (>100km)
- Systems are available to simplify the installation to the facility:
  - bundles of fibers (up to 12 / bundle) are blown in thin pipes (>1km)
- Successive upgrades / FO replacements feasible at low impact

D=3mm

www.prysmian.com
Measurements on optical fibers

- Prior to installation in the accelerator, measurements have been carried out to qualify the optical fibers.
- Polarization Mode Dispersion has been measured on a 8 fiber bundle (L=500m) by prof. A. Galtarossa (Lab. di Fotonica, (DEI) Uni. Padova).

**Differential Group Delay (DGD)**

\[
PMD_c = \frac{DGD}{\sqrt{L}} \left[ \text{ps}/\sqrt{\text{km}} \right]
\]

![Graph showing 8 fibers with a bundle and DGD as a function of wavelength.]

- 0.25dB/div
- 0.185dB/km
Coaxial vs. Optical cabling

- At PSI, for the FEL/LEG test stand the program is:
  - to start with a high performance coaxial system (well known technology, fallback) using an electrical Master Oscillator
  - to start then an Optical Master Oscillator
  - to implement fiber based optical distribution to improve performance, functionality and flexibility

- Rather than a coaxial cable, it is a coaxial assembly to provide thermal control over the cable:
  - temp. sensors located in cable
  - heater control loop
  - 45 €/m
  - long term drift <50 fsec

Courtesy of S. Hunziker (PSI, CH)
Beyond Accelerators … ALMA

ALMA, the Atacama Large Millimeter/ submillimeter Array, will be a single research instrument composed of up to 80 high-precision antennas, located on the Chajnantor plain of the Chilean Andes in the District of San Pedro de Atacama, 5000 m above sea level.
One of the major challenges for ALMA is distributing the reference signal to the antennas, which may be as much as 16km apart, with sufficient precision to keep the local oscillators synchronized to an accuracy of much better than a radian of phase, even at the highest observing frequencies.

The limit on noise in the timing is 38 fsec on short time scales with drifts of only 13 fsec allowed on times of 20 to 300 seconds.

An advanced photonic system has been developed to achieve this.

The reference signal, typically at a frequency of about 100 GHz, is distributed on optical fibers as the beat between two tunable lasers, a “slave” laser locked to an ultra-stable “master”.

The Atacama Large Millimeter/ submillimeter Array
Richard E. Hillsa and Anthony J. Beasley ALMA
• This beat is detected by a photo-mixer at each receiver cartridge and used to lock the local oscillator. A small sample of the laser light is taken off at the receiver, shifted in frequency by 50 MHz and returned to the central laboratory.
• The optical path in each fiber is then monitored and changes due to thermal expansion or mechanical movements can be compensated by means of a “line-stretcher” in which a coil of fiber is stretched under control of a servo loop.
• This scheme has been extensively tested and production of the various parts of the system is now underway.

The Atacama Large Millimeter/submillimeter Array
Richard E. Hillsa and Anthony J. Beasley ALMA
Thank you for your attention

...time for Questions