STATE OF THE ART IN HIGH-STABILITY TIMING, PHASE REFERENCE DISTRIBUTION AND SYNCHRONIZATION SYSTEMS

M. Ferianis, Sincrotrone Trieste S.C.p.A. ELETTRA, Trieste, Italy

Abstract

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 38 GHz phase coherent LO at the ALMA radio telescope is highlighted as a related technical system in development.

INTRODUCTION

New 4[th] Generation Light Sources (4GLS) currently in operation, construction or design at several National Laboratories are posing demanding requirements on the associated Timing and Synchronization (T&S) systems, identified as femto-second (fsec) T&S systems. 4GLS are typically Free Electron Lasers (FEL) driven by single pass Linear Accelerators (LINAC). Such demanding requirements on jitter (<10fsec$_{RMS}$), and drift, originate from the adopted scheme for the generation of the electron beam and the FEL radiation.

The typical bunch length (τ_B<50fsec$_{FWHM}$), achievable in single pass accelerators thanks to the beam longitudinal manipulation techniques, the required beam quality (6-D emittance) and the radiation generation (seeding) and exploitation (time resolved / pump-probe experiments) schemes call for an ultimate jitter of <10fsec$_{RMS}$. This ultra-low jitter value is typically required either between the electron bunch and the seed laser pulse or between the FEL pulse and the User laser pulse. To achieve this goal, the whole accelerator components need to share a Phase Reference with <10fsec$_{RMS}$ jitter and drift.

LAYOUT OF A T&S SYSTEM

In 4GLS, the time position of the bunch is identified by the combination of the timing pulse and the slope of the Phase Reference signal, the former representing the Bunch Clock, coarse (<10ps$_{RMS}$) bunch position, the latter identifying the expected bunch phase (fine, <10fsec$_{RMS}$).

A generic layout of a T&S system is presented in Fig. 1 where no precise reference is made to existing systems; only the key components of such a T&S system are indicated. The accelerator and beam line systems (defined as: *timing users*) that need to be synchronized are schematically represented in Fig. 1.

The T&S system is made of the following sub-systems:

- µ-wave reference oscillator (RMO)
- Reference Phase oscillator (RPO)
- Phase Reference optical distribution system, which includes optical transmitters (TX) and receivers (RX)
- Master time base (MTB) with its distribution system
- Active stabilization loops (feedback systems)
- Diagnostics to feed the stabilization loops

The loops are part of the synchronization systems.

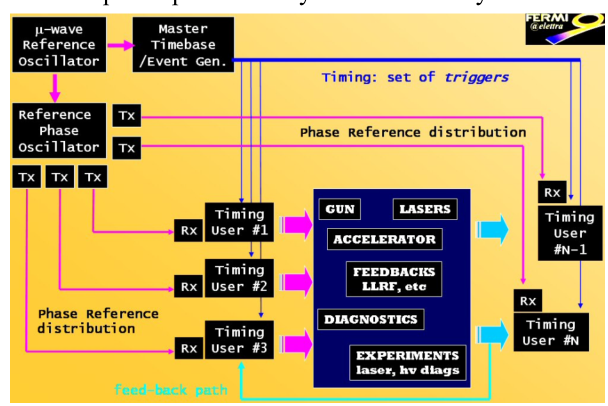

Figure 1: Layout of a T&S system.

The *RMO* provides the phase reference to the RPO and to the MTB, both linked to it over short (L<1m) and temperature stabilized (ΔT<0.1^{o}C$_{pk\text{-}pk}$) coaxial lines.

The *RPO* is phase locked to the RMO; it accomplishes several key tasks like:

- improving the high end of the phase noise spectrum (see later for definition) of the RMO
- converting the physical layer of the RMO output from electrical into optical, in order to make it suitable for fsec stable transmission over actively stabilized long (D<1km) optical links
- to provide an adequate number of fsec phase stable replicas of the Phase Reference (a typical value for 4GLS could range between 16 and 32).

The last bullet pin points a key issue of T&S systems: any slow (<100Hz) jitter component, present either in the RMO or in the RPO, is cancelled out being common mode to all timing users. The statement is true provided these are properly phase locked to the Phase Reference in the bandwidth of interest (BW<1kHz).

The *Phase Reference Distribution System* delivers to the timing users the same phase reference, within 10fsec$_{RMS}$. It is based on optical concepts and it makes use of optical components and cables as these allow for a stabilization of the propagation time through the link at the <10fsec$_{RMS}$ level which would not be possible if using copper coaxial lines, even if temperature controlled (50fsec$_{RMS}$ can be considered as state of the art value for coax. [1]).

The *MTB* generates, synchronously with the RMO, the Bunch Clock and other auxiliary signals needed for a stable and reproducible operation of the facility. The Bunch Clock is the *clock* driving the Bunch Number which allows for unique bunch identification. It is distributed to all the systems to allow time alignment of the acquired data for an off-line co-related data analysis. The MTB and its distribution system have much more relaxed jitter requirements (<10 ps$_{RMS}$). It is reasonable to adopt optical fibres also for the Bunch Clock distribution as these typically came as *multi-fibre cables*. Part of the distribution system components (optical cables and receivers) are outside the Timing Room as most of the timing users are typically remotely located, like:

- the RF plants, implementing local Low Level RF (LLRF) loops to stabilize amplitude and phase
- the laser systems, locking to the electron bunch / FEL pulse
- diagnostics stations (bunch length and bunch arrival monitors) used as error signals
- loop processors to globally act on the beam

BASIC REQUIREMENTS OF A FEMTOSECOND T&S SYSTEM

Fsec T&S systems have to meet demanding specifications in terms of:

- jitter
- drift
- serving the whole facility
- being remotely controllable
- rad-hard (some parts are located in the tunnel)

T&S systems need also to be reliable, being deployed to facilities operating on a 24h-7d basis.

Costs have to be evaluated as well: fibre optics (FO) are cheap, getting fsec out of them it is not. A T&S system should be also easy to maintain and to upgrade coping with future needs. It is worth mentioning here that T&S systems are typically installed in quiet (vibration free) and temperature controlled ($\Delta T<1^{o}C_{pk}$) environment which helps in achieving ultimate performances.

MEASUREMENT OF A FEMTO-SECOND T&S SYSTEM

Dealing with fsec T&S systems calls for a technological upgrade as conventional high speed electronic circuits and coaxial distribution systems are typically limited to a jitter of ≤100fsecRMS and even larger drifts. Furthermore, to achieve fsec measurement resolution, time domain techniques are not adequate; frequency domain techniques provide a higher resolution. These are averaged measurements which is acceptable for high stability systems like T&S systems are. Let's consider a sinusoidal signal, also known as carrier, expressed as:

$$V(t) = (V_0 + \Delta V(t)) \cdot \cos\left(\omega_o t + \Delta\varphi(t)\right)$$

Here both amplitude (ΔV) and phase (Δφ) fluctuations are indicated. The jitter of a periodic signal can be defined as a measurement of its *fast time fluctuations*, measured over a certain observation time and with respect to a phase reference. In frequency domain it is referred to as phase noise.

Drift is related to *slow time fluctuations* of the signal with respect to the reference; in a T&S system, drift may be caused either by temperature dependant changes in propagation time over the distribution lines or by variations of the reference frequency, depending the latter on the stability of the master oscillators. The phase noise of a signal is defined as the power spectral density of its phase fluctuations:

$$\mathrm{L(f)} = \int_{-\infty}^{+\infty} e^{-j2\pi f\tau} \left\langle \Delta\varphi(t+\tau)\Delta\varphi(t)\right\rangle d\tau$$

By integrating the phase noise over a frequency interval the timing jitter is obtained:

$$\Delta t_{rms}(f_1, f_2) = \frac{1}{\omega_o}\sqrt{2\int_{f_1}^{f_2} L(f)df}$$

The offset from the carrier frequency in the phase noise plot is called *offset frequency*.

CONSIDERATIONS ON PHASE NOISE

To understand the physical meaning of the phase noise and of the offset frequency, let's represent the carrier R (t) and the phase noise N (t) in vector notation (see Fig. 2)

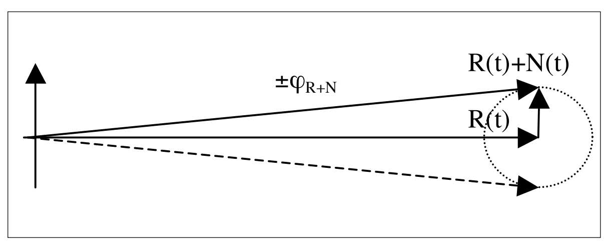

Figure 2: Vector representation of signal R (t), rotating at angular frequency ω_R, and phase noise N (t), rotating at angular velocity ω_N.

The peak to peak oscillations of the sum vector R (t) + N (t) around the phase of reference R (t), by $\pm\varphi_{R+N}$, represent the jitter. Let's consider a reference signal R(t) at a frequency of 3GHz; let the frequency of the noise N (t) be 100Hz and the amplitude ratio A_R/A_N equal to 80dB. We obtain a peak phase oscillation of 5.3fsec which is a small value, but not negligible for fsec T&S system.

To quantify the impact of the various phase noise components on the carrier, let's calculate how much does the carrier phase change during the time of flight of an average 4GLS, defined as the time over which the charges and the photons are travelling down the accelerator to the experimental stations. For a single bunch machine like FERMI@Elettra [2] with a total (accelerator plus beam lines) length L<300m, the time of flight τ_F is smaller than 1μs. In the above numerical example, considering a time window of total 2μs around the zero crossing (steepest slope) of the noise component (f_N=100Hz) the effective carrier phase deviation is equal to 0.006fsec being the maximum deviation of 5.3fsec reached only after 2.5ms. This is a really negligible value. In summary, the phase noise integration interval for the jitter calculation has to be evaluated considering both the time structure of the beam and the physical extension of the machine.

PHASE REFERENCE SPECIFICATION

The timing users that need to be synchronized are not all equally sensitive to jitter [3], in terms of effect on the beam. It is generally accepted to define the total jitter of the T&S user as the quadratic sum of the reference jitter (at the delivery point) and of the jitter of the timing user itself.

$$Jitter_{TOTAL} = \sqrt{jitter_{REF}^2 + jitter_{DEV}^2}$$

The jitter of various T&S users is listed in Table 1.

Table 1: Jitter of Various T&S Users

user	*total jitter [fsec$_{RMS}$]*	*reference jitter*
RF plants, S-band	<100	71
RF plants, X-band	<70	50
Photo-injector laser	<100	71
Seed laser	<15	10
Used laser	<15	10
Bunch arrival monitor	<15	10
Electro Optical Sampling	<15	10

The most demanding timing users to synchronize are to be the seed laser and user laser as well as some high resolution longitudinal diagnostics.

FEMTOSECOND PHASE REFERENCE

The requirements of the Phase Reference system are:

- jitter <10fsec$_{RMS}$
- drift <10fsec$_{RMS}$
- frequency 100sMHz to ≈GHz

State of the art proposed solutions are based on the optical clock concept, i.e. using stabilized FO links to distribute the phase reference signal. Two state of the art systems have been proposed and demonstrated so far:

- the *Pulsed Optical Phase Reference* system developed at RLE/MIT (Cambridge, MA) [4] and DESY (Hamburg, D) [5]
- the *Continuous Wave* (CW) *Optical Phase Reference* system developed at LBNL (Berkeley, CA) [6]

For such fsec phase reference systems the key issue is distributing the phase reference over the whole facility without spoiling the Reference Oscillator fsec jitter. Today available optical oscillators (usually soliton fibre lasers [7]) typically exhibit a lower jitter, in the offset frequency bandwidth of interest (f>1kHz) than micro-wave oscillators. Furthermore, these optical oscillators are ideally matched to the optical stabilized links. Electro-optical longitudinal diagnostics have been already implemented, making full use of the optical reference [8].

Pulsed Optical Phase Reference System

In these systems, the phase information is encoded into the repetition rate of a soliton fibre laser (aka Master Laser Oscillator, MLO) which is phase locked to a micro-wave reference oscillator to improve its jitter, particularly at low offset frequencies, and drift. The train of optical pulses is sent over single mode optical fibre, the repetition rate being typically few hundreds of Megahertz. The propagation over the FO link is stabilized by means of an active loop which adopts a cross-correlator as phase detector [9]. This system is ideally suited for the synchronization of remote laser oscillators. Direct seeding of remote optical amplifiers is under investigation which is also of great interest for 4GLS, as it could lead to the *single oscillator* facility. Ultra low phase noise extraction of a harmonic RF electrical signal at the remote stations has been implemented as well [10] using the *Sagnac Loop*. The field tests of the Bunch Arrival Monitor [8] demonstrated a resolution of <10fsec$_{RMS}$.

CW Optical Phase Reference System

In CW Phase Reference systems, the optical link is stabilized using the o*ptical mixing* concept [11], applied to the optical carrier and to its 110MHz frequency shifted replica (f_{CAR}=190THz @1560nm), as shown in Fig. 3. As heterodyning preserves phase relationships, we have:

- 1 degree at optical = 1 degree RF
- 1 degree at 110 MHz = 0.014fsec at optical

A factor 10^5 improvement in the phase noise detection sensitivity over RF-based systems is achieved.

The RF is then sent over such stabilized link by amplitude modulating the optical carrier signal.

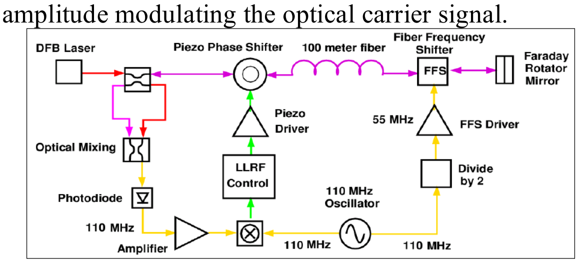

Figure 3: Schematic of the original CW link stabilization.

These CW systems have been optimized by the LBNL team. Thanks to the deep integration of the link stabilization firmware into the Low Level RF (LLRF) [12], available at each remote LLRF timing user, the piezo phase shifter of Fig. 3 has been removed: the phase changes are sensed and then applied as phase delay at the remote end.

PHASE REFERENCE SYSTEM RESULTS

Thanks to the extensive R&D efforts and demonstration activities which have been successfully carried out at several laboratories since 2005: RLE/MIT, DESY and Sincrotrone Trieste (ST) for the pulsed system; LBNL for the CW one. Both systems demonstrated sub-10fsec$_{RMS}$ jitter and drift, both in the laboratory frame (MIT, ST and LBNL) as well as when deployed to real machine environments (DESY, LCLS by LBNL).

Pulsed Phase Reference System Results

An extensive documentation on the achieved results can be found in the literature. The results achieved at ST [13] in the framework of the collaboration between RLE/MIT and ST on the pulsed optical timing system for FERMI@Elettra facility, are presented hereinafter.

One key performance indicator of a phase reference system is the so called *out-of-loop* measurement (for jitter and drift) whose set-up, for the pulsed phase reference system, is shown in Fig. 4.

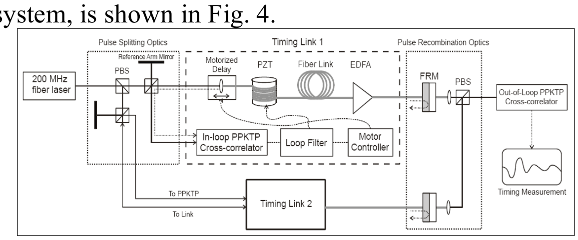

Figure 4: Two stabilized link set-up for the out-of-loop jitter and drift measurement.

The phase reference outputs of two separate stabilized links are recombined for the out-of-loop measurement with a third balanced cross-correlator.

The transfer function (S-curve, shown in Fig. 5) of the balanced cross-correlator shows the measurement sensitivity of the X-correlator. It is performed by modulating the piezo to provide a time-varying delay.

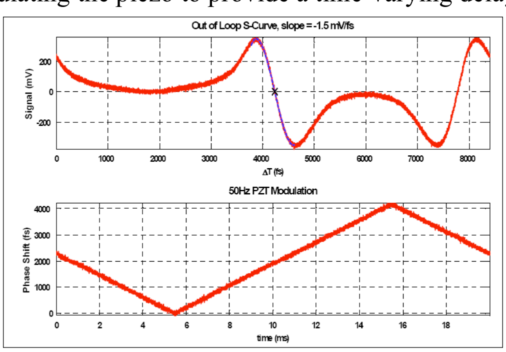

Figure 5: Top trace: S-curve for the cross-correlator calibration. Bottom trace: piezo driving voltage.

The measurement of the out-of-loop correlator signal carried out over 2.5hours (Fig. 6) showed a <20fsec$_{RMS}$ total drift and jitter between end point of link 1 and link 2.

CW Phase Reference System Results

The CW Phase Reference system has under gone extensive testing at LBNL and, then, field tested at the LCLS, at SLAC, for a demonstration session [14].

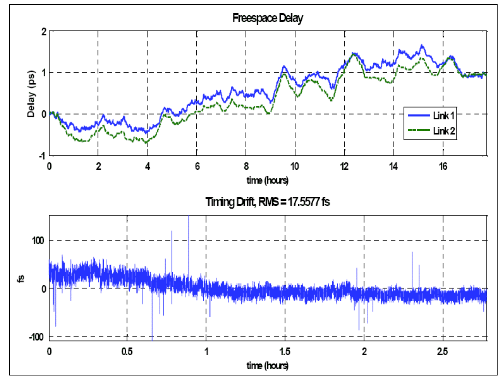

Figure 6: Upper plot: drift of the two fiber links which the system compensates for over 18 hours. Lower plot: out-of-loop drift as measured by X-correlator between both links.

At LBNL, a comparison of RF phase transmission through 2m fibre (reference link) and 200m, or 2km, respectively has been carried out (see Fig. 7). Fibres were in loose coils in laboratory, with ±2^{o}C air temperature stability. The periodic error in 2km data is due to air conditioning; 15fsec$_{RMS}$ have been observed for first 48 hours.

At the LCLS (SLAC) the CW Phase Reference system has been tested by synching both RF plants and two laser oscillators. The mode locked lasers have been synchronized by sending over the stabilized link signals at three different frequencies: 2850, 476 and 68MHz. The total observed jitter (24 hours) was <100fsec$_{RMS}$. The CW system has been in continuous operation over one week.

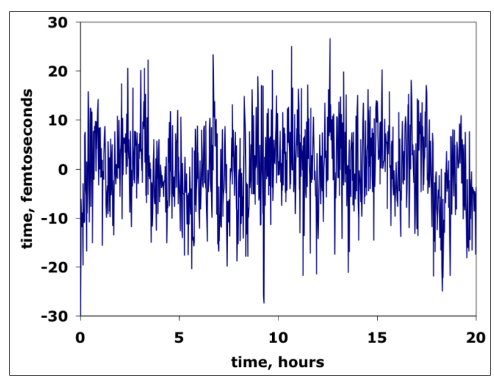

Figure 7: Results of the RF transmission jitter during the laboratory tests at LBNL for a 200m long stabilized link: a total drift of 8.4fsec$_{RMS}$ over 20h has been measured.

FSEC LONGITUDINAL DIAGNOSTICS

The largest set-up of the pulsed phase reference system has been installed at DESY, on FLASH. RF plants, lasers and diagnostics are all synchronized using the pulses generated in the Master Laser Oscillator running at 216MHz. One successful implementation that relies on the pulsed optical reference to achieve sub 10fsec resolution is the Bunch Arrival Monitor developed and tested at DESY [8].

Results of the Bunch Arrival Monitor (BAM)

The system has been described and presented in detail at previous conferences. Here, some recent correlation measurements are reported to demonstrate the achieved performances. Two BAMs have been installed at two different locations along the accelerator, the distance BAM 1 to BAM 2, being 60m. The correlation between the data of the two BAMs has been plotted in Fig. 8. The single bunch resolution of the entire measurement chain (laser, links, BAMs) resulted to be 8.4fsec$_{RMS}$.

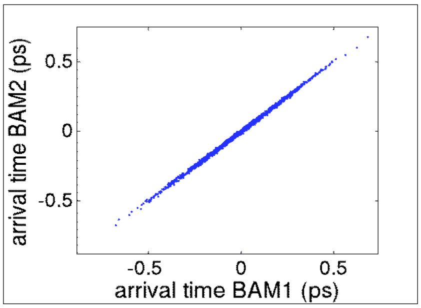

Figure 8: Correlation of the data from two BAMs. The un-correlated jitter over 4300 shots is 8.4fsec$_{RMS}$.

DAY ZERO CW OPTICAL TIMING

In the framework of the collaboration between ST, *Instrumentation Technologies* [15] and prof. M. Vidmar of the *Department of Electrical Engineering* of the Ljubljana University (SLO), the development of a prototype has started to test the RF signal transmission over a stabilized FO Link [16]. The idea is to stabilize the propagation over the fibre by exploiting the temperature dependence of a DFB laser wavelength. The prototype is currently undergoing the first tests for the transmission of a 3GHz signal. The total (oscillator plus link) jitter has been measured to be as low as 22fsec$_{RMS}$. A 2 link test bed will be tested soon at ST.

OPTICAL CABLE ISSUES

High quality [17] fibres systems [18] have been developed to simplify the installation. Bundles of fibres are blown in thin pipes for more than 1km. The Polarization Mode Dispersion (PMD) has been measured on an 8 fibre bundle (L=500m) by the *Laboratorio di Fotonica*, (DEI) at the Padua University. The results [19] are very good as four fibres, out of eight, exhibit a PMD smaller than 20fs; PMD affects the drift rather than the jitter.

BEYOND ACCELERATORS

ALMA [19], the Atacama Large Millimeter/ sub millimeter Array, will be a single research instrument composed of up to 80 high-precision antennas, located in the Chilean Andes. One of the major challenges for ALMA is to distribute the reference signal to the antennas (up to 16km apart) with sufficient precision to keep the local oscillators synchronized to an accuracy of much better than 1rad of phase. The limit on phase noise in the timing is 38fsec on short time scales [20]. An advanced optical system has been developed where the optical path in each fibre is monitored; changes due to thermal expansion are compensated by means of a fibre stretcher. This scheme has been extensively tested and then deployed to the accelerator Community.

ACKNOWLEDGEMENT

The Author thanks all the Colleagues from all cited Laboratories (see refs.) who developed most of the work here presented making the optical clock a real breakthrough for the whole Accelerator Community.

REFERENCES

[1] S. Hunziker, "Layout of the PSI 250MeV Injector Synchronization System and Latest Results", II T&S w-shop, ICTP-Trieste, March, 9th 2009.
[2] E. Allaria et al. "FERMI@Elettra: a seeded FEL facility for EUV and soft x-rays" FEL 2006, Berlin.
[3] FERMI@Elettra Conceptual Design Report 2007.
[4] Research Lab. of Electronics, Optics and Quantum Electronics Group; http://www.rle.mit.edu/oqe.
[5] A.Winter et al "Layout of the Optical Synchronization system for FLASH", EPAC '06, Edinburgh, Scotland.
[6] J. M. Byrd et al., "Timing distribution in accelerators via stabilized optical fiber links" LINAC 2006 Knoxville, USA.
[7] A. Winter et al. , "High-precision Laser Master Oscillators for Optical Timing Distribution Systems in Future Light Sources", EPAC '06, Edinburgh.
[8] F. Loehl, "Optical Synchronization of a Free Electron Laser with femtosecond precision", Ph.D. Thesis at Hamburg University, 2009.
[9] J. Kim et al. "Drift-free femtosecond timing synchronization of remote optical and microwave sources", Nature Photonics 2, 733 - 736 (2008).
[10] J. Kim et al. "Femtosecond synchronization and stabilization techniques", FEL '06 Berlin.
[11] R. Wilcox, "Recent Results of RF synchronization at LBNL" II T&S w-shop, ICTP - Trieste, March 2009.
[12] J. M. Byrd, "Plans for precision RF controls for FERMI@elettra" PAC 07 Albunquerque, NM, USA.
[13] J. Cox and F. Rossi , "Dual Fiber Timing Link Test Bed @ ELETTRA", ST Technical Note, 2008.
[14] R.Wilcox (LBNL) private communication
[15] http://www.i-tech.si.
[16] Patent pending, Slovenian Pat. Office P-200900127
[17] ITU-T G.652: Characteristics of a single-mode optical fibre cable.
[18] Sirocco Blown fibre system, http://www.prysmian.it.
[19] A. Galtarossa,"Relazione Tecnica alle misure di dispersione di Polarizzazione", Tech. Note, Photonics Group at Univ. Padua, http://peg.dei.unipd.it.
[19] http://www.alma.nrao.edu.
[20] B. Shillue, "Millimeter wave RF Power measurements of a Commercial Photomixer", ALMA Memo # 313 - June 26, 2000.- National Radio Astronomy Observatory, Tucson AZ.