LO System and Signal Transport

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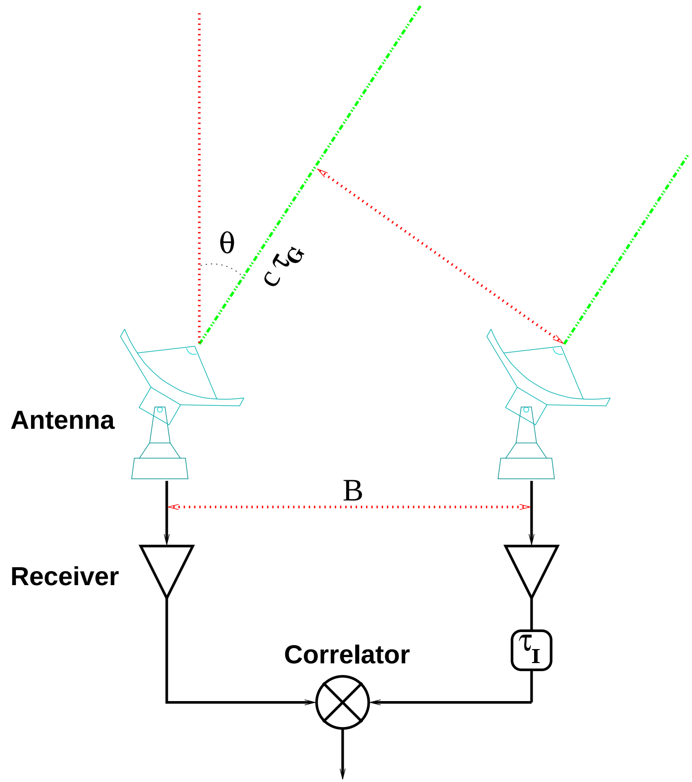
A simple interferometer

2 antennas, a multiplier, an integrator
$\tau_{\mathrm{G}} = 2\pi\mathbf{b}.\mathbf{s}/c$ is the geometrical delay, compensated in the hardware
- The output of the correlator is the real part of the visibility:

$$r(t) = A\cos\varphi(t)$$

- A complex correlator (using a quadrature network) measures the imaginary part too



A heterodyne interferometer

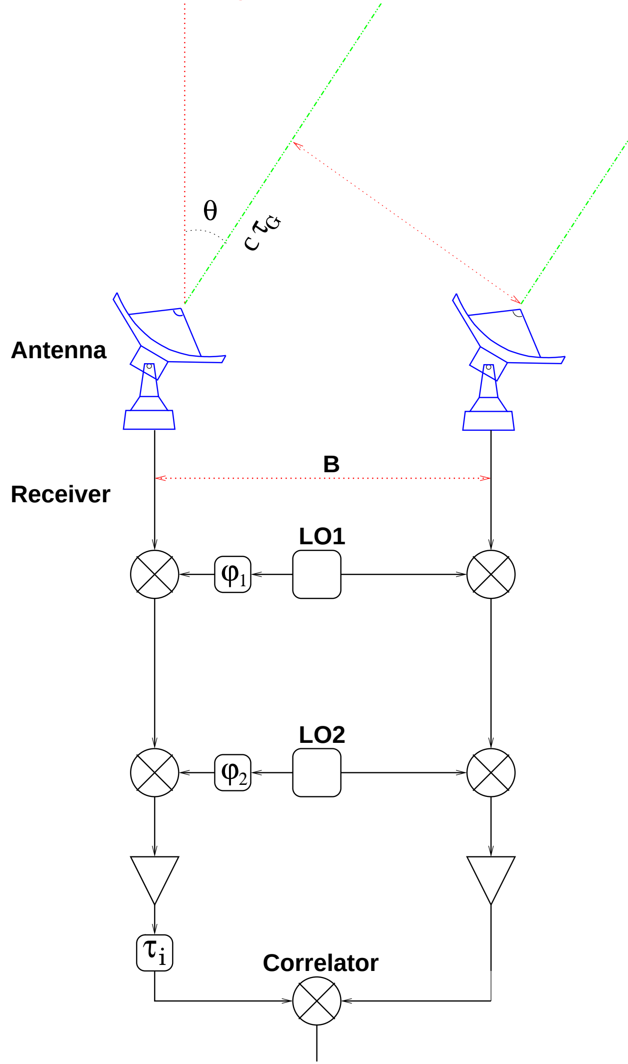
- Now with 2 frequency conversions (4 at PdB)
- A frequency conversion affects the signal phase:

-input: $V(t) = E\cos(\omega t + \varphi)$
-LO: $V_1(t) = E_1\cos(\omega_1 t + \varphi_1)$
-output: $\propto [V(t) + V_1(t)]^2$

we select $\Delta\omega$ centered on $\omega_{\rm IF}$

$$V_{\rm IF}(t) \propto E_{\rm U}\cos(\omega_{\rm IF} t + \varphi_{\rm U} - \varphi_1) + E_{\rm L}\cos(\omega_{\rm IF} t - \varphi_{\rm L} + \varphi_1)$$

	USB	LSB
frequency:	$\omega_{\rm IF} = \omega_{\rm U} - \omega_1$	$\omega_{\rm IF} = -\omega_{\rm L} + \omega_1$
phase:	$\varphi_{\rm IF} = \varphi_{\rm U} - \varphi_1$	$\varphi_{\rm IF} = -\varphi_{\rm L} + \varphi_1$



Signal phase (1)

	USB	LSB
HF Frequency HF Phase	ω_U $\varphi_U + \omega_U \tau_G$	ω_L $\varphi_L + \omega_L \tau_G$
LO1 Frequency LO1 Phase	ω_1 φ_1	ω_1 φ_1
IF1 Frequency IF1 Phase	$\omega_{IF1} = \omega_U - \omega_1$ $\varphi_U + \omega_U \tau_G - \varphi_1$	$\omega_{IF1} = \omega_1 - \omega_L$ $-\varphi_L - \omega_L \tau_G + \varphi_1$
LO2 Frequency LO2 Phase	ω_2 φ_2	ω_2 φ_2
IF2 Frequency IF2 Phase after τ_I	$\omega_{IF2} = \omega_U - \omega_1 - \omega_2$ $\varphi_U + \omega_U \tau_G - \varphi_1 - \varphi_2$ $\varphi_U + \omega_U \tau_G - \varphi_1 - \varphi_2 + \omega_{IF2} \tau_I$	$\omega_{IF2} = \omega_1 - \omega_L - \omega_2$ $-\varphi_L - \omega_L \tau_G + \varphi_1 - \varphi_2$ $-\varphi_L - \omega_L \tau_G + \varphi_1 - \varphi_2 + \omega_{IF2} \tau_I$
Final IF2 Phase	$\varphi_U + \omega_{IF2} \Delta\tau$ $-(\varphi_1 + \omega_1 \tau_G)$ $-(\varphi_2 + \omega_2 \tau_G)$	$-\varphi_L + \omega_{IF2} \Delta\tau$ $+(\varphi_1 + \omega_1 \tau_G)$ $-(\varphi_2 + \omega_2 \tau_G)$

Signal phase (1, easier)

	USB	LSB
IF2 Frequency	$\omega_{\mathrm{IF2}} = \omega_{\mathrm{U}} - \omega_1 - \omega_2$	$\omega_{\mathrm{IF2}} = \omega_1 - \omega_{\mathrm{L}} - \omega_2$
Final IF2 Phase	$\varphi_{\mathrm{U}} + \omega_{\mathrm{IF2}}\Delta\tau$ $-(\varphi_1 + \omega_1\tau_{\mathrm{G}})$ $-(\varphi_2 + \omega_2\tau_{\mathrm{G}})$	$-\varphi_{\mathrm{L}} + \omega_{\mathrm{IF2}}\Delta\tau$ $+(\varphi_1 + \omega_1\tau_{\mathrm{G}})$ $-(\varphi_2 + \omega_2\tau_{\mathrm{G}})$

Signal phase (2)

To stop the fringes in both sidebands we need the following conditions:

$$\Delta\tau = \tau_{\mathrm{I}} + \tau_{\mathrm{G}} = 0$$

$$\varphi_1 + \omega_1 \tau_{\mathrm{G}} = 0$$

$$\varphi_2 + \omega_2 \tau_{\mathrm{G}} = 0$$

- *Delay tracking* in the second IF imposes a *phase tracking* on the first and second oscillators.
- $\Delta\tau$ appears as a phase term proportional to frequency in the IF2 band ω_{IF2}.
- φ_1 must be commanded to vary at a rate

$$\dot{\varphi}_1 = -\omega_1 \dot{\tau}_{\mathrm{G}} \sim 2\pi \frac{b}{\lambda_1} \frac{2\pi}{86400}$$

~ 70 turns per second for $\lambda_1 = 1$mm and $b = 1000$m.

Finite bandwidth

Assume only upper side band:

$$V_r = A\cos\left(\varphi + \omega_{\mathrm{IF2}}\Delta\tau\right)$$

while the sine correlator would give:

$$V_i = A\sin\left(\varphi + \omega_{\mathrm{IF2}}\Delta\tau\right)$$

$$V = V_r + iV_i = Ae^{i(\varphi+\omega_{\mathrm{IF2}}\Delta\tau)}$$

Assume we use a correlator with a finite bandwidth $\Delta\nu$:

$$V = \int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} Ae^{i(\varphi+\omega_{\mathrm{IF2}}\Delta\tau)} B(\omega_{\mathrm{IF2}})d\omega_{\mathrm{IF2}}$$

where $B(\omega_{\mathrm{IF}})$ is a complex passband function

$$V = Ae^{i\varphi}\int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} e^{i\omega_{\mathrm{IF2}}\Delta\tau} B(\omega_{\mathrm{IF2}})d\omega_{\mathrm{IF2}}$$

Finite bandwidth (cont'd)

$$V = Ae^{i\varphi} \int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} e^{i\omega_{\mathrm{IF2}}\Delta\tau} B(\omega_{\mathrm{IF2}}) d\omega_{\mathrm{IF2}}$$

- The source visibility, when the delay error varies, is multiplied by the Fourier transform of the complex passband.
- $\Delta\tau$ must be kept much smaller than $1/\Delta\nu$
- To limit the loss to 1%, the minimum delay step must be $\sim 0.25/\Delta\nu$ (0.5 ns for a 500 MHz bandwidth).

Double side band system

- The signals from the upper and lower side bands have similar attenuation in the RF part and similar conversion loss in the mixers
- They will have similar amplitudes in the correlator output.

$$
\begin{aligned}
V &= A_{\mathrm{U}} e^{i[\varphi_{\mathrm{U}} + \omega_{\mathrm{IF2}}\Delta\tau - (\varphi_1 + \omega_1 \tau_{\mathrm{G}}) - (\varphi_2 + \omega_2 \tau_{\mathrm{G}})]} \\
&\quad + A_{\mathrm{L}} e^{i[-\varphi_{\mathrm{L}} + \omega_{\mathrm{IF2}}\Delta\tau + (\varphi_1 + \omega_1 \tau_{\mathrm{G}}) - (\varphi_2 + \omega_2 \tau_{\mathrm{G}})]} \\
&= A \cos(\varphi - \varphi_1 - \omega_1 \tau_{\mathrm{G}}) e^{i(\omega_{\mathrm{IF2}}\Delta\tau - \varphi_2 - \omega_2 \tau_{\mathrm{G}})}
\end{aligned}
$$

- If the delays are tracked and the LO phases rotated, the exponential term is 1 and only the real part of the visibility is measured.
- Some trick is thus needed to separate the signal from the image side band.

Side band separation

- Mixer rejection is difficult for low IF frequencies; image rejection varies with frequency.
- This is desirable however since one may avoid to add up the noise contributions of both side bands.
- Additional methods can cancel the signal in the unwanted side band by a larger factor. They are based on the fact that the LO1 phase φ_1 appears with a different sign on the USB and LSB signals.
- The main advantage is improved calibration.

Fringe rate method

- Drop the phase rotation on the second LO and let the fringes drift at their natural fringe rates.
- Rates opposed in sign for the USB and LSB, and they might be separated electronically.
- However the natural fringe rate sometimes goes to zero, and at in these cases the method would fail.
- Offset the LO1 and LO2 phase rates $\dot{\varphi}_1$ and $\dot{\varphi}_2$ by the same amount ω_{OFF}.
- If the offsets have the same sign, they will compensate for the USB and offset the fringe rate by $2\omega_{\mathrm{OFF}}$ in the LSB.
- If ω_{OFF} is large enough, the LSB signal is canceled.
- Note that offsetting $\dot{\varphi}_1$ by a fixed amount is equivalent to offsetting the LO1 frequency.
- Unwanted side band rejected but the associated noise is not rejected
- Will be used for ALMA in conjunction with side-band separating mixers.

Phase switching method

- A variable phase offset ψ_1 is added to the LO1 phase command:

$$\varphi_1 = -\omega_1 \tau_G + \psi_1$$

- ψ_1 will be subtracted to the phase of the USB signal, and added to that of the LSB signal.
- If ψ_1 is switched between 0 and $\pi/2$, the relative phase of the USB and LSB will be switched between 0 and π,
- The signals may be separated by synchronous demodulation:

ψ_1	Signal
0	$V_1 = A_U e^{i\varphi_U} + A_L e^{-i\varphi_L}$
$\pi/2$	$V_2 = A_U e^{i(\varphi_U - \pi/2)} + A_L e^{i(-\varphi_L + \pi/2)}$

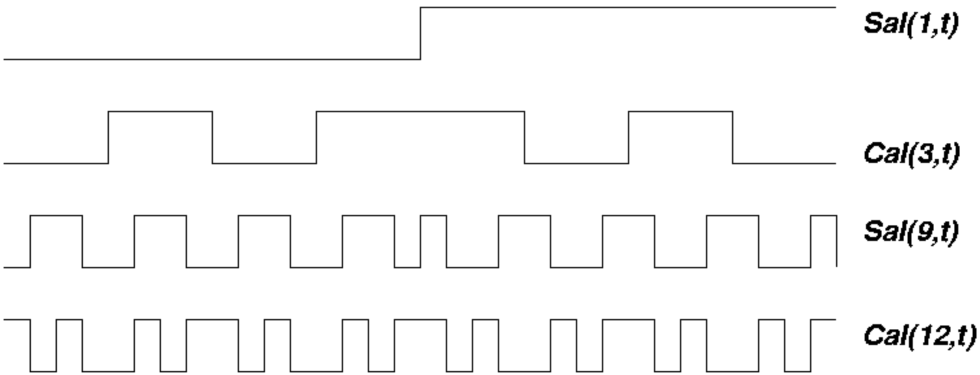
- One may compute the visibilities in each side band:

$$A_U e^{i\varphi_U} = (V_1 + iV_2)/2 \qquad A_L e^{-i\varphi_L} = (V_1 - iV_2)/2$$

- We have assumed here that we have a complex correlator (sine + cosine), or equivalently a spectral correlator measuring positive and negative delays (see Correlator lecture, this afternoon).

π phase switch

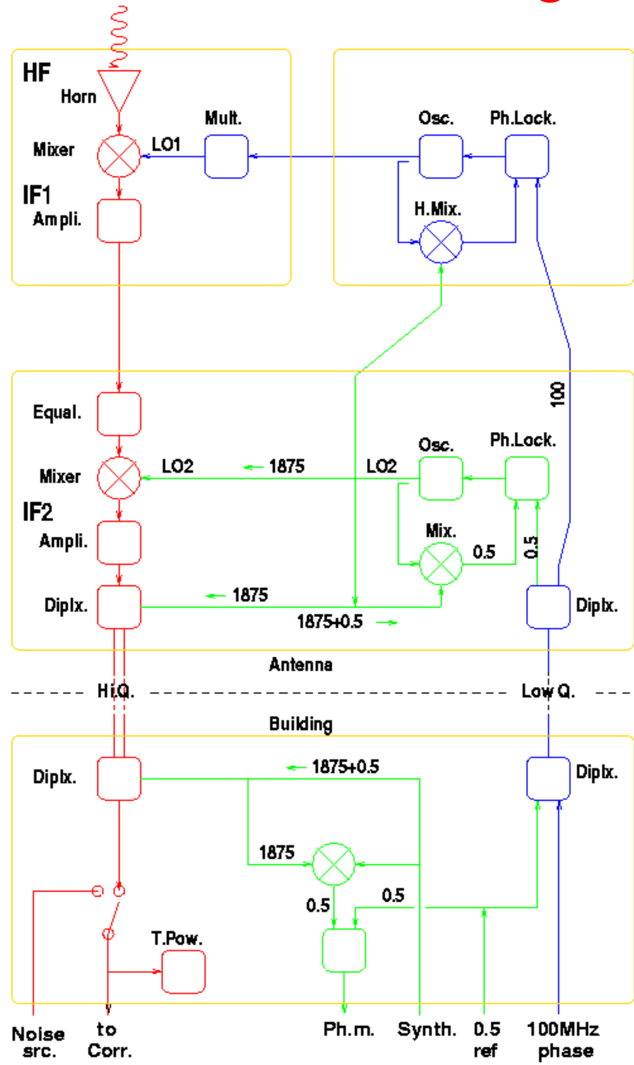
- One may also switch the phase by π, in which case the sign of all the correlated voltages is reversed.
- This has the advantage of suppressing any offsets in the system.
- In a N antenna system one needs to switch the relative phases of all antenna pairs. This could be done by applying the above square-wave switching on antenna 2, then on antenna 3 at twice the switching frequency, and so on.
- In practice the switching waveforms are orthogonal Walsh functions. This has the advantage of reducing cross-talks.



Four examples of Walsh functions

Signal Path

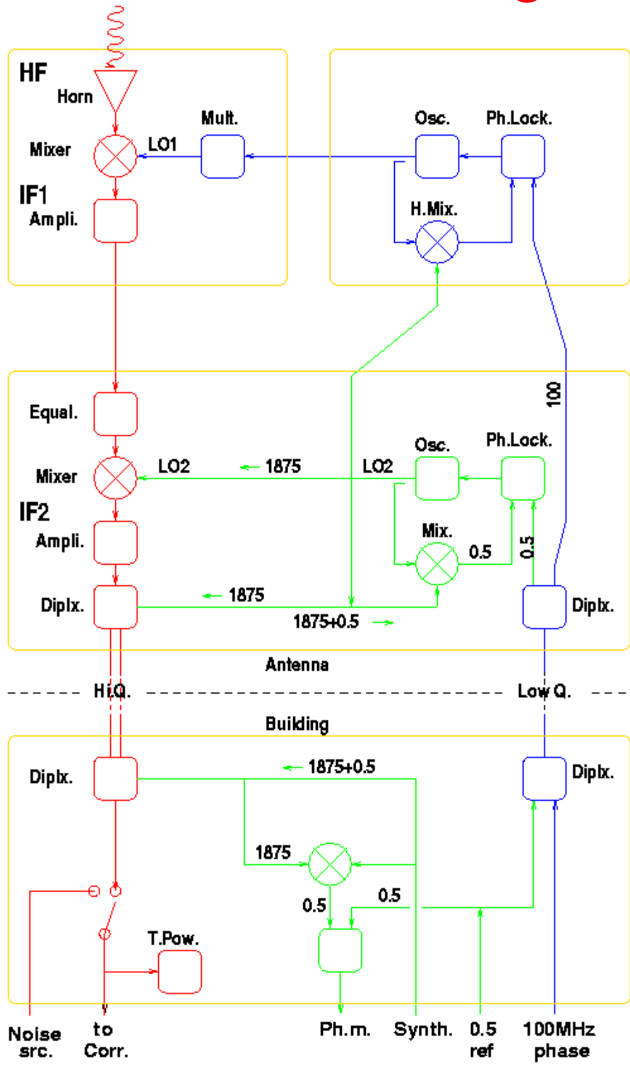
- First IF output (1075-1775 MHz) down-converted to the $100 - 800$ MHz band and transported to the central building in a high-quality cable.
- Before down-conversion, the band shape is modified by a low-pass filter to compensate for the frequency dependent attenuation in the cable.
- The $100 - 800$ MHz band in the central building is directed to the correlator analog IF processor inputs and to total power detectors which are used for the atmospheric calibration and for the radiometric phase correction.



First LO generation

- First LO is a Gunn oscillator (a tripler is used for the 1.3mm receiver).
- The Gunn is phase-locked with a harmonic of a signal, used also as the second LO
- The reference signal at $\epsilon_1 = 100$ MHz is used to carry the phase commands to be applied to the first LO: a continuously varying phase to compensate for earth motion, and phase switching

$$\nu_{\mathrm{LO1}} = (N_{\mathrm{H}} \nu_{\mathrm{LO2}} \pm \epsilon_1) N_{\mathrm{M}}$$



Second LO generation

- The second LO, at $\nu_{\mathrm{LO2}} = 1875 \pm 25$ MHz, is phase locked ϵ_2=0.5 MHz below the frequency sent by the synthesizer in the central building

$$\nu_{\mathrm{LO2}} = \nu_{\mathrm{SYN}} - \epsilon_2$$

- The ϵ_2 reference is sent to all antennas from the central building in a low quality cable, together with the ϵ_1 reference for the first LO. The ν_{SYN} is sent to the antennas via the same high-Q cable that transports the IF2 signal.
- No phase rotation is applied on the second local oscillator.
- The relation between the RF signal frequencies (in the local rest frame) in the USB and LSB and the signal frequency in the second IF band is thus (for high lock):

$$\nu_{\mathrm{USB}} = \nu_{\mathrm{LO1}} + (\nu_{\mathrm{LO2}} - \nu_{\mathrm{IF2}}) = (N_{\mathrm{M}} N_{\mathrm{H}} + 1)\nu_{\mathrm{LO2}} + N_{\mathrm{M}}\epsilon_1 - \nu_{\mathrm{IF2}}$$
$$\nu_{\mathrm{LSB}} = \nu_{\mathrm{LO1}} - (\nu_{\mathrm{LO2}} - \nu_{\mathrm{IF2}}) = (N_{\mathrm{M}} N_{\mathrm{H}} - 1)\nu_{\mathrm{LO2}} + N_{\mathrm{M}}\epsilon_1 + \nu_{\mathrm{IF2}}$$

Further signal processing

- In each correlator a variable section of the IF2 band is down-converted to baseband by means of two frequency changes, with a fixed third LO and a tunable fourth LO.
- phase rotations needed to compensate delay change are applied on LO4
- No phase rotation is applied on the second and third local oscillators.
- The phase rotations applied on the LO4 's are:

$$\varphi_4 = (\omega_2 + \omega_3 - \omega_4)\tau_{\mathrm{G}}$$

- They are different in the different correlator units since the ω_4 frequencies are different.

Phase stability requirements

- Short term phase errors in the local oscillators (jitter) will cause a decorrelation of the signal and reduce the visibility amplitude by a factor

$$\eta_{12} = e^{-({\sigma_1}^2+{\sigma_2}^2)/2} = \eta_1 \eta_2$$

where σ_1 is the rms phase fluctuation of the LO in one of the antennas (σ_2 in the other). $\eta_1 = e^{-{\sigma_1}^2/2}$ is the decorrelation factor for one antenna; typical requirements on σ_1 are:

η_1	0.99	0.98	0.95	0.90
σ_1 (degrees)	8.1	11.5	18.3	26.4

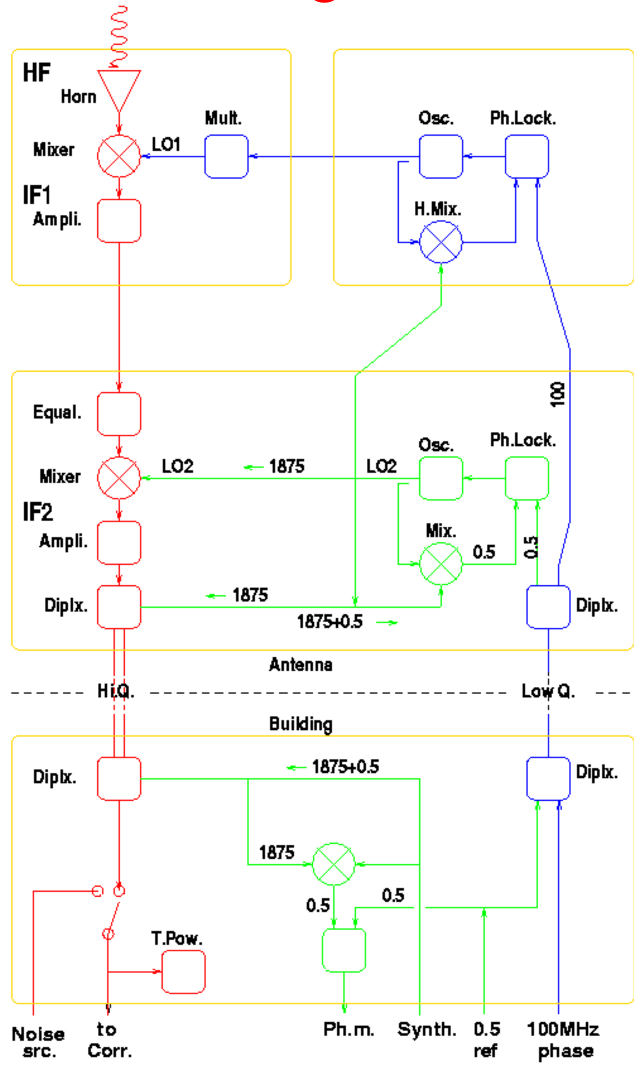
- The phase stability required on the LO2 is $\sigma_1/(N_{\mathrm{M}} N_{\mathrm{H}}) \sim 0.15^\circ$ for a 0.95 efficiency at 1.3mm
- Very stable oscillators are needed.

Cable electrical length control: why ?

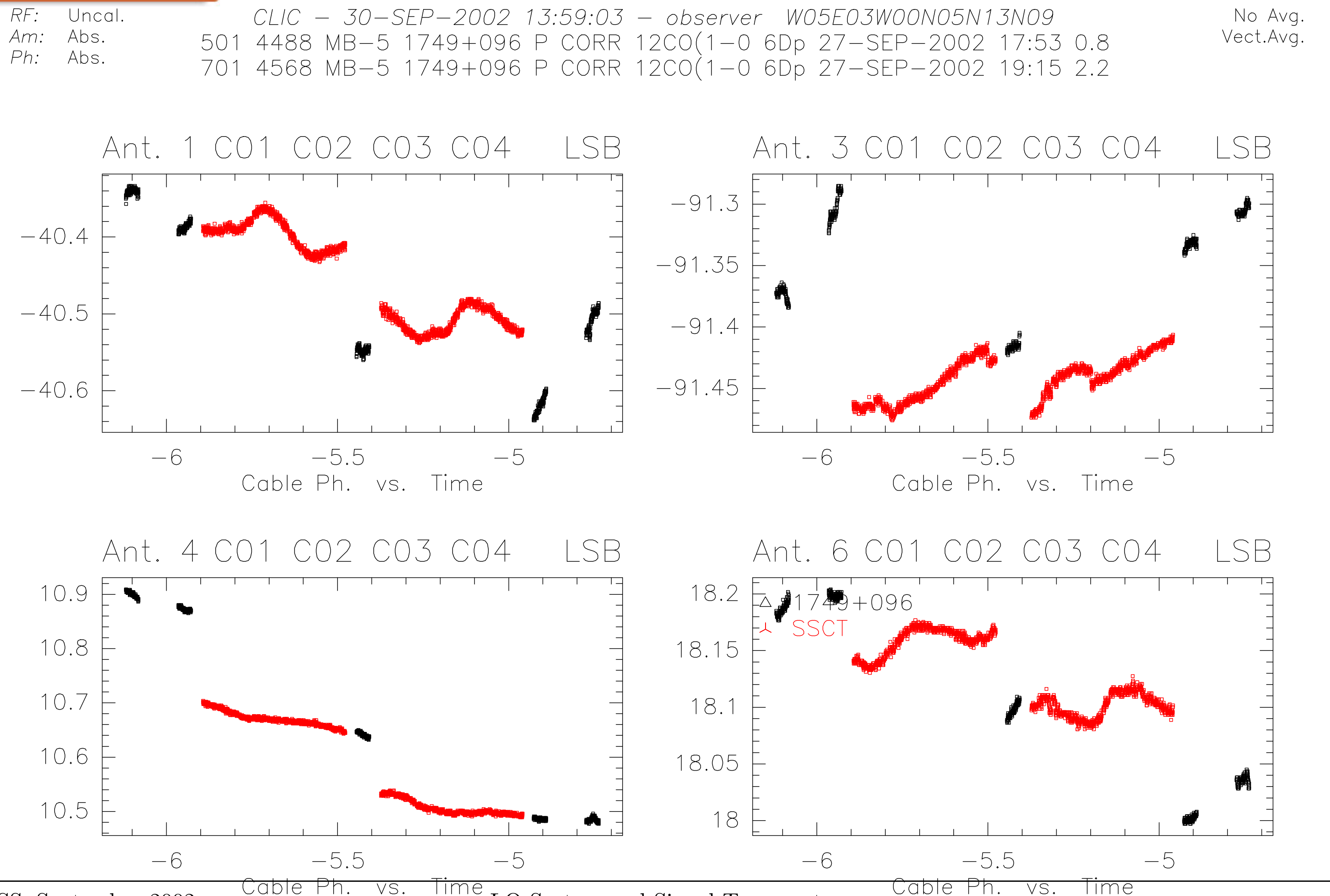
- A variation ΔL in the electrical length of the High-Q cable will affect the signal phase by $360\Delta L/\lambda_{\rm IF2}$ degrees
- For a length of 500m and a temperature coefficient of 10^{-5} : $\Delta L = 5$ mm or 17ps, a phase shift of 4 degrees at the high end of the passband: this is a very small effect.
- The same ΔL induces a phase shift of $360 \times 0.017 \times 1.875 = 11.5$ degrees at the LO2 frequency.
- This signal is multiplied by $(N_{\rm H}+1)N_{\rm M} \sim \nu_{\rm USB}/\nu_{\rm LO2} \sim 120$ for the 1.3mm receiver: shift of about 4 turns.
- The cables are buried in the ground for most of their length; however they also run up the antennas and suffer from varying torsion when the sources are tracked, and in particular when the antenna is moved from the source to a phase calibrator.

Cable electrical length control: How?

- The LO2 is sent back to the central building in the High Q. cable, and there it is mixed with the $\nu_{\mathrm{LO2}} + \epsilon_2$ signal from the synthesizer.
- The phase-meter measures every second the phase difference between the beat signal at 0.5 MHz and a reference 0.5 MHz signal.
- The measured phase difference is twice the phase offset affecting the LO2, it is used by the computer to correct the LO1 phase φ_1 after multiplication by $\nu_{\mathrm{LO1}}/\nu_{\mathrm{LO2}}$.



Sample cable length monitoring



Next generation instruments

Next generation instruments (e.g. ALMA) will operate at higher frequencies, and need higher bandwidths, and better angular resolution. The major changes expected are:
- Use of optical fibers rather than cables. Actually this is already the case in some interferometers.
e.g. use of optical fibers foreseen at Plateau de Bure for the signal chain.
- Digitize earlier in the signal chain: transporting digital signals requires more bandwidth but is more accurate.
- Generate LO signals using beating infrared lasers rather than by multiplying lower frequency signals.