Measurements of Allan Variance and short term phase noise of millimeter Local Oscillators

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Abstract

Phase stability over rather wide time scales is one of the most crucial requirements for the receivers of a millimeter interferometer like ALMA. The short term part of its spectrum is mainly related to the possibility of multiplying a signal source up to the millimeter region. The long-term part deals with a successful integration of the radioastronomical signal, after the down conversion operated by the many local oscillators (LO), spread over the array.

The SSB phase noise and the Allan Variance are the physical quantities usually measured, with different techniques, to represent the two spectral regions of phase stability, with a crossover around one second.

Here we propose a new data acquisition system, essentially dedicated to the measurement of the Allan Variance, which is built around two programs, written in the LabView environment. The RF configuration is the same of the one used for phase noise measurements, so it turns out to be very convenient to characterize the wide range of LO frequencies, expected in ALMA, both at long and short term.

The main program, called Time Stability Analyzer (TSA), runs in real time accumulating data and computing Allan Variances from 1s up to 100 000 seconds in 2,5,10 sequence on each decade. Results are displayed on log-log plots for both cumulative statistics (since the beginning of the measuring session) and restricted to single batches of data. All information is recorded on disk and, optionally, hard copied on paper at each batch end.

A simultaneous acquisition of a temperature sensor allows looking for a correlation with the environment (as commonly happens).

A second program, called TSAcal, makes a very accurate calibration of the transfer function of the mixer, used as a phase detector. Its working parameters (Kv and Offset) are retrieved by a non-linear fit on line, even in a very short time, because the frequency of the calibration tone can be as high as 100Hz.

All previous features make the new developed TSA software, together with the RF configuration we propose here, an easy-to-use tool during the design phase of the many LO planned for ALMA, and a convenient aid for their maintenance.

Introduction

Millimeter interferometers require an extremely high level of phase stability from the receiver electronics, in order to preserve the coherence between the radioastronomical signals collected at the individual antennas.

For the ALMA project, the specification of a maximum phase difference of 1/30 cycle at 1 THz [1] at short term, should also be combined with a mid term value, estimated to be much less than a radiant over half an hour [2].

If we convert phases into time intervals, it turns out that the stability requirement can be expressed as a fraction of picosecond per second and a slope proportional to the inverse of the integration time of the observation (τ^{-1}).

It is well known that the most critical functional block from this point of view is the generation of the local oscillator (LO) signal, that it is used to convert the sky signal frequency to the so called “video band” where it can be digitized and then analyzed.

Good design of the LO implies to minimize the phase jitter added by the real performance of mainly mixers and multipliers, needed to generate the millimeter signal which usually starts from an atomic frequency reference. This in turn requires a measuring setup that can estimate the phase stability accurately over a very wide range of working frequency and over all the time scale relevant for radioastronomy.

The short term part of this spectrum is related to the inevitable “build up” of the phase noise when a signal is multiplied in frequency, while the long term is associated to the possibility of integrating the signal obtained from the cross correlation of individual antennas.

The two spectral regions are usually analyzed separately, in the so-called frequency and time domain, respectively. $\Im(\nu)$ and the Allan Variance are the physical quantities which are the most used in the two respectively main application fields of Telecommunication and Timekeeping.

Interferometry and space research like Doppler tracking of interplanetary spacecraft, need to get the lowest possible frequency instabilities altogether, both at short and long time scales. Being involved in both application fields I have decided to arrange a more versatile configuration setup that can handle both type of measurements.

The RF part is essentially the same and equal to the one used for phase noise. While data analysis in this last case is straightforward (Fourier spectrum), I had to write a dedicated LabView code for the estimation of the Allan Variance.

The Allan Variance measurement configuration

In a conventional configuration, a universal counter acquires, in Time Interval mode, successive periods of the beat note (Tb) obtained by mixing the Device Under Test (DUT) with some reference source (with an equal or of higher stability performance).

Usually this requires to modify one of the DUT, if they are equal, or arrange a special mixing scheme to get that beat note, in such a way to be around 1s (inevitably fractional) and with square wave shape (in order to reduce the counter trigger uncertainty).

Then the Allan Variance algorithm accumulates temporal phases as zero crossings @ Tb intervals and its multiples, plotting the results in a Log/Log scale.

In the alternative scheme, I am proposing here (see Fig.1), no beat note is required, apart from the initial calibration. This last is made only once before the measurement and the beat frequency can span up to 100Hz, starting from any lower value. Moreover, because the tone is not required during the measurement, its generation does not imply any special care. Simply unlocking one of the multiplier or switching it to its internal reference can be acceptable.

The millimeter mixer acts as a phase detector. If driven properly, its transfer function can be accurately described as a pure sinusoidal function. This operation can be easily verified looking at the level of the higher harmonics content when a beat note is made to appear between the two devices under test (DUT). By the way, this is also very close to the calibration part of the short-term phase noise measurement.

In case the millimeter mixer is not suitable to be DC coupled at the output and then used as a phase detector, an intermediate conversion scheme (in common to both arms) can be implemented. Then a standard phase detector would work at a lower frequency. The stability of the transfer oscillator would not be critical, because it is seen in common mode by the two arms.

From the same beat note it is possible to extract the operating parameters Kv (mV/rad) and Offset (mV), that determine its transfer function (from phase to voltage):

$$V(t) = Kv \sin(\varphi(t)) + Of$$

In the retrieving process of the input phase value, the use of the arcsine function allows an accurate reconstruction over a much wider range ($\Delta\varphi$ range up to 120°) as follows:

$$\varphi(t) = \arcsin[(V(t) - Of)/ Kv]$$

Using the arcsine function also relax the “phase quadrature” requirement normally claimed in conventional phase noise measurements. Here any value reasonably close to 90 degrees (mixer output voltage $\cong$ Of) is acceptable.

This condition can be usually achieved by unlocking and locking again one of the two DUT, if they are synthesizer or PLL multipliers, or, in the worst case, by trimming the cable length of one arm.

Finally an implementation of the Allan Variance algorithm accumulates these temporal phases under the control of a LabView program called TSA (Time Stability Analyzer).

The phase values are retrieved, according to the previous equation, from the DC voltages acquired by an A/D card (used as a digital voltmeter under computer control). Phase data are numerically filtered on line to emulate a 1Hz noise bandwidth, as required for an accurate estimation of the Allan Variance.

This solution avoids the use of any extra hardware to implement the filter and any contamination from drifts in the actual components used.

With the down conversion scheme, one can also benefit from a proportionally larger working range (phase) of the system: sources with higher noise can be measured and the initial quadrature setting is even more relaxed.

Main features of the TSA program can be inferred from its display panel, as reported in Fig. 2.

Features of the TSA program

Many of the powerful capabilities of the LabView code are implemented in the TSA program.

First of all the A/D card is fully configured, under the “measurement and automation” routine, for two independent input analog channels: one for the differential millimeter phase and the second for a temperature sensor.

It is well known in fact that temperature gradients are the primary responsible for mid and long-term phase instabilities. These show up as bumps on the Allan Variance plot. Displaying both quantities on the same strip chart allow an easier identification of possible correlation with the environment (sampled by the sensor).

Secondly, buffered data acquisition makes possible to have a precise timing on data sampling (exact 1 second spacing), while, in real time, the same data are processed and the results displayed on screen.

One phase and one temperature values are obtained every second.
The first time series is filtered on line to limit the “noise” bandwidth to 1Hz. Filtering is implemented as a 10th order IIR filter with Butterworth response which handle the 1000 samples acquired each second. Actually a simpler filter would have been adequate, but this is a standard routine for LabView.

In order to guarantee that, in spite of the initial value, the filter has a stable output, the first three phase data are discarded from the measurement.

The temperature point is simply obtained as an average over all the samples.

Computation of a valid data point of the Allan Variance requires a triplet of phase measurements, acquired at times 0, τ and 2τ seconds. TSA implements an algorithm that continuously selects phase triplets at τ = 1,2,5 in each decade from 1s to 10^5s in order to build a log/log plot for τ ranging from 1s up to 1 day.

Two graphs are displayed: the first refers to the last batch of data, while the second accounts statistics since the beginning of the measurement session.
Data accumulation on successive, independent, batches has been chosen for trying to identify anomalous spikes, very often related to some specific, maybe external, cause.

Statistically evaluated error bars are represented below and above each Allan Variance data point as open circles of different colors.

In the cumulative plot, it is also displayed the “accumulated time error” equal to $\sigma_y(\tau) *\tau$ (the product of the Allan Variance times the integration time), also as a visual aid to more easily estimate a pure white noise slope (τ^{-1}).

Main control panel of the TSA program, at program start, allows entering the input parameters, needed for computing the Allan Variance, an easy viewing display and data archiving:

- comparison (mixing) Frequency, according to the RF configuration
- Session name for the session, for later retrieval of data recorder on disk
- Reference type: Prefect or Equal
- Duration of data batches: length in seconds of each batch plot
- Range of Y scale in the temporal phase plot (input value is constrained within the equivalent of +/- 60 degrees at the selected mixing frequency). The central value is automatically selected at program start around the first valid phase sample.
- Selection of an automatic Print an save at each batch end

At any following second, these panel displays are updated:

- the chart record of both phase and temperature; in real time, a scrolling bar let you see previous data and zooming into it, both in time and Yrange
- the plot and table of the Allan Variances computed over the last batch
- the statistics of phase and temperature (max, min), over batch and session

At the end of each data batch:

- the cumulative plot and table of the Allan Variances, are updated
- the phase triplets, at all τ values shorter than half the batch duration, are reset in order to be started again in the following batch
- all relevant results are save on disk and, if this option was selected, all front panel plots and tables hard copied on printer.

Features of the Calibration program (TSA cal)

This is the part of the data acquisition that has been dramatically improved with respect to a previous version of this measuring system [1].

First of all the input beat note, needed to measure the Kv and Offset parameters of the phase mixer, can now be as high as 100Hz. The calibration can then be extremely rapid (a few seconds), but much more than that, it does not require any more any special care in order to generate a very small frequency offset between the two DUT.

Secondly, it has been implemented a non-linear Fit in order to retrieve the mixer parameters, simply starting from a very rough estimation given by the user. This guarantees an optimum fit over the acquired data (rejection of input noise) and allows also a very accurate calibration of Allan Variances computed over extremely long integration times.

Finally the end result averages are transferred through a file to main TSA program to avoid any human error in this process (or later ambiguous interpretation of the calibration constants).

Each individual batch data set can be recovered by opening the file relative file recorded on disk, with a dedicated program called “Read TSAfile”.

It can also be mentioned that there is not an accuracy problem in the voltage units used by the card, because the same A/D is used both during calibration and main data acquisition.

Present system performance

With a 16 bit resolution D/A card (type PCI-MIO-16XE-50 by NI) we have measured, over many sessions, a system noise floor (card terminated into 50 Ohms) of

2.1 E-13 @ 1s with an almost perfect τ^{-1} slope

One of the longest sessions lasted over two days, so the previous slope has been significantly verified up to 50 000s. In all tests, the comparison frequency was 1 MHz.

Because the Allan Variance scales linearly with the comparison frequency, this card can successfully measure $\sigma_y(\tau)$ of any microwave synthesizer and of any future, top performance, atomic frequency standard, if fmix is reasonably high.

It can be worthwhile to mention that this system can also be used to characterize, top performance, atomic frequency standards (independent sources as DUT). Switching among three phase stable cables, differing by around 120° in equivalent electrical lengths, inserted in the RF path of one of the two DUT, the computer can track unambiguously the input phase indefinitely [1].

ALMA can find TSA as an easy tool for phase stability measurements.

The phase stability measuring system proposed here could be very convenient within the ALMA project for at least three reasons.

The very high frequency of the LO relax any specification on the D/A resolution, so even a lower performance card can be used (reconfiguration of TSA for others NI cards is straightforward with LabView).

While the linearity problem can require a careful choice of the signal levels driving the mixer at very low mixing frequencies (typically below 100MHz), again for ALMA I do not see any problem in this respect.

The rather short long-term phase stability requirements of half an hour, for the ALMA interferometer [2], do not justify the design of a dedicated RF setup.

Because TSA utilizes the same configuration of conventional measures of (short term) phase noise, it can be considered a convenient solution, over all the wide range of mixing frequencies planned for the project.

The intrinsically more accurate calibration technique, used by TSA for modeling the transfer function of the mixer, can be also transferred to the phase noise measurements (by the way, LabView itself offers some Fourier analysis capability through any A/D card).

Finally the limited working range as phase detector of the mixer used here should be not a problem in measuring LO chains, that are expected not to loose lock at any time.

Features of TSA as a measuring tool of the Allan Variance

- Same RF layout as for Phase Noise, at any mixing frequency
- Easy implementation and low cost: only an A/D card on a PC running LabView
- Initial Calibration is accurate, fast (beat up to 100Hz) and noise robust (non-linear fit on line)
- Accuracy of phase retrieval can be predicted in advance with a dedicated program (TSA-LIN) when low (<100MHz) mixing frequencies are used. Because ALMA working frequencies are so high, this will be never a problem
- Real time displays of Allan plots, current phase and temperature
- Data is filtered on line to limit the noise bandwidth to 1Hz, as required
- Cumulative, individual batches & general statistics
- Automatic printing and saving on disk
- Easy modification of the source code; access to the very powerful set of the LabView tools (like for example a full remote control).
- TSA can be used in real time to identify phase sensitive parts or components or their dependence with temperature, then as a design aid of the ALMA LOs.

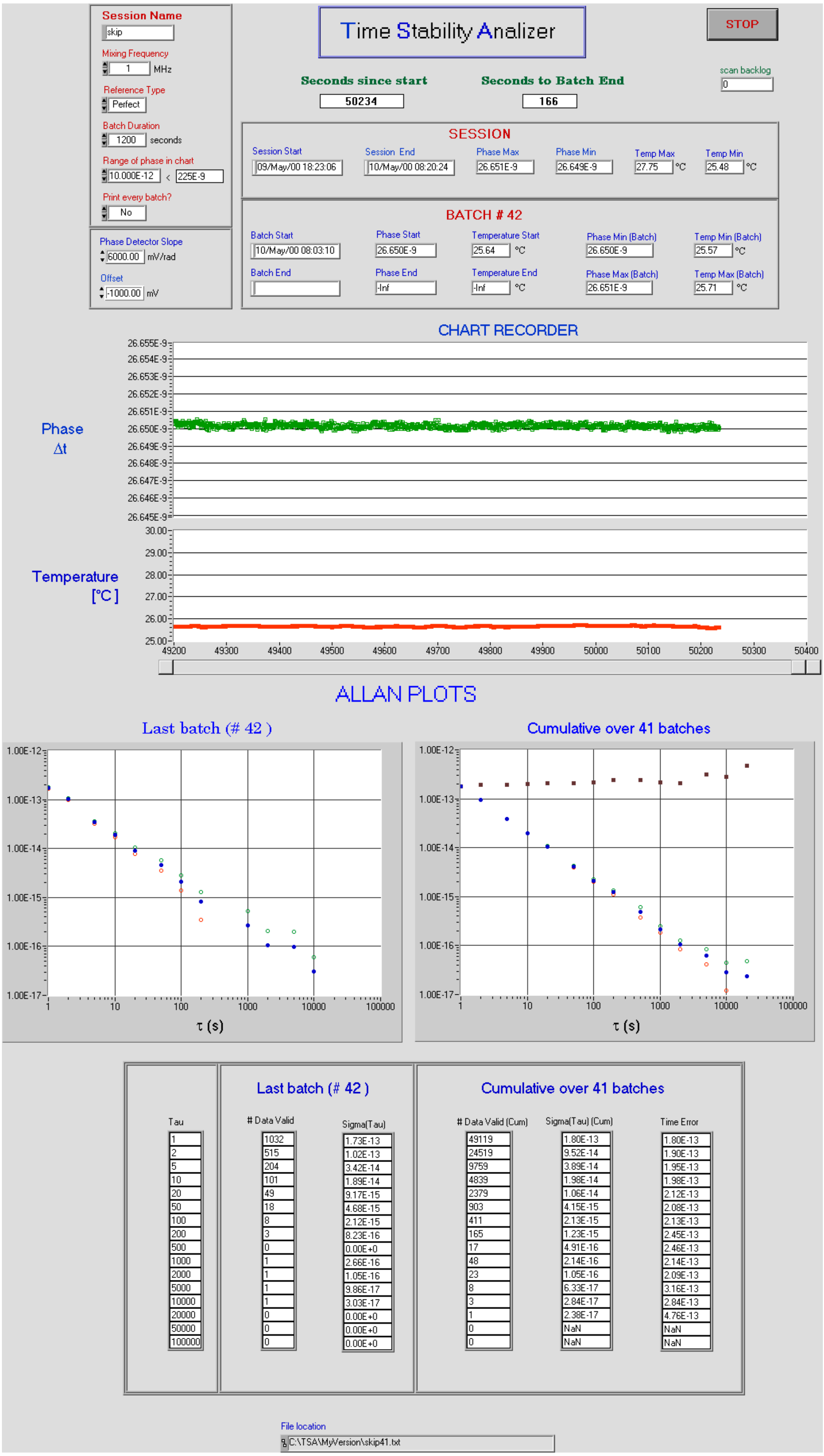
References

[1] R. Ambrosini, M. Caporaloni, “A simple and versatile phase comparison method can accurately measure long term instability”, IEEE-Transactions on Instrumentation and Measurements, IM-37, 127 (1988).

[2] J. Payne, private communication, 29 March 2000

Acknowledgment

I thanks Gianni Comoretto for revising this memo and the useful discussions.



Tau	# Data Valid	Sigma(Tau)	# Data Valid (Cum)	Sigma(Tau) (Cum)	Time Error
1	1032	1.73E-13	49119	1.80E-13	1.80E-13
2	515	1.02E-13	24519	9.52E-14	1.90E-13
5	204	3.42E-14	9759	3.89E-14	1.95E-13
10	101	1.89E-14	4839	1.98E-14	1.98E-13
20	49	9.17E-15	2379	1.06E-14	2.12E-13
50	18	4.68E-15	903	4.15E-15	2.08E-13
100	8	2.12E-15	411	2.13E-15	2.13E-13
200	3	8.23E-16	165	1.23E-15	2.45E-13
500	0	0.00E+0	17	4.91E-16	2.46E-13
1000	1	2.66E-16	48	2.14E-16	2.14E-13
2000	1	1.05E-16	23	1.05E-16	2.09E-13
5000	1	9.86E-17	8	6.33E-17	3.16E-13
10000	1	3.03E-17	3	2.84E-17	2.84E-13
20000	0	0.00E+0	1	2.38E-17	4.76E-13
50000	0	0.00E+0	0	NaN	NaN
100000	0	0.00E+0	0	NaN	NaN

Fig. 2

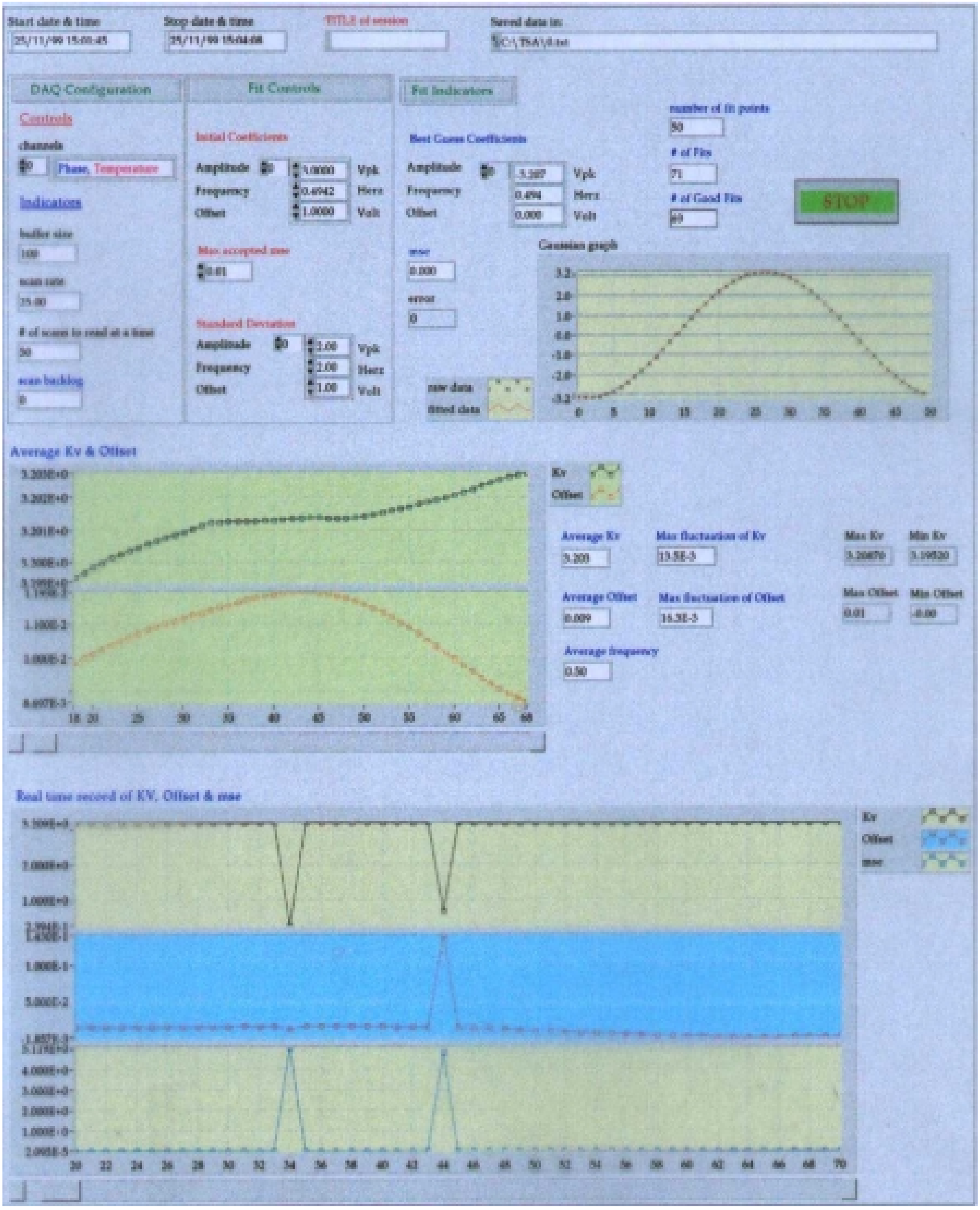
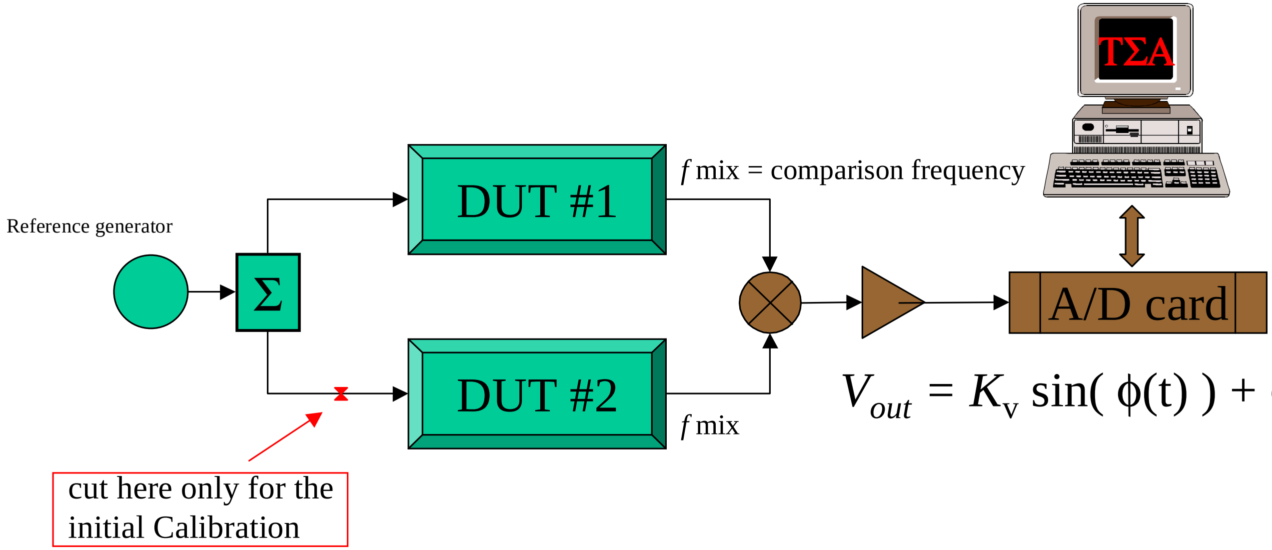

Start date & time
Stop date & time
TITLE of session
Saved data in:
DAQ Configuration
Fit Controls
Fit Indicators
Controls
channels
Indicators
buffer size
scan rate
# of scans to read at a time
scan backlog
Initial Coefficients
Amplitude
Frequency
Offset
Max accepted mse
Standard Deviation
number of fit points
# of Fits
# of Good Fits
STOP
Gaussian graph
raw data
fitted data
Average Kv & Offset
Kv
Offset
Average Kv
Max fluctuation of Kv
Max Kv
Min Kv
Average Offset
Max fluctuation of Offset
Max Offset
Min Offset
Average frequency
Real time record of KV, Offset & mse
mse

Fig. 3

Time Stability Analyzer



$$V_{out} = K_v \sin(\phi(t)) + Of$$

R. Ambrosini, May 2000

Fig. 1