A MULTI-CHANNEL STABILITY ANALYZER FOR FREQUENCY STANDARDS IN THE DEEP SPACE NETWORK

C. A. Greenhall, A. Kirk, and R. L. Tjoelker
Jet Propulsion Laboratory
California Institute of Technology[1]

Abstract

We present a final report on the development of a multi-channel Frequency Standards Stability Analyzer (FSSA) for characterizing and monitoring several frequency sources at each of the three Deep Space Network (DSN) sites and at JPL's Frequency Standards Test Laboratory (FSTL). The system can simultaneously measure the relative stability of six independent 100 MHz frequency sources and one source at an arbitrary frequency (typically X or Ka band) when down-converted with a low-noise synthesizer. The measured noise floor is approximately 2×10^{-15} at 1 second and 1×10^{-18} at 4000 seconds, currently sufficient to measure all operational DSN frequency standards and distribution links. Four instruments are operating well in the DSN and the FSTL.

INTRODUCTION

The NASA Deep Space Network (DSN) relies on highly stable and well calibrated frequency and timing references for precision deep space navigation and radio science. In support of this effort, JPL develops and operates state-of-the-art frequency standards including hydrogen masers, mercury Linear Ion Trap Standards (LITS), Cryogenic Sapphire Oscillators (CSO), and cold-atom atomic fountain standards. These sources, which provide high stability over a wide range of averaging intervals, are used in the operational DSN Frequency and Timing Subsystem (FTS) and the JPL Frequency Standards Test Laboratory (FSTL). As the stabilities of frequency standards and distribution links improve, so must the performance of the instruments used for characterizing and validating them. In addition, measurement systems are in constant demand and use at the JPL FSTL, which supports all of the DSN frequency standards.

The DSN is a particularly demanding application for high-performance frequency reference and distribution. The network consists of three major sites located near Goldstone, California, USA; Madrid, Spain; and Canberra, Australia. Each site supports several antennas, with the Goldstone site currently supporting 11. A central frequency standard provides coherent frequency references to all users and antennas at the site, including the master clock and timing system. Several backup frequency standards are available. Antennas are distributed up to 30 km from the central standard and clock, and it is important to distribute signals free from interference or degradation.

---

[1] This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Successful DSN FTS operation requires that frequency stability be characterized and validated from each frequency standard and at the reference end-user. Signals can be degraded anywhere along the signal path; consequently, there is need for a measurement system that can be used for troubleshooting both the frequency standards and the associated signal transport hardware, such as the stabilized fiber-optic distribution capability developed for the Cassini Radio Science Mission. Such a measurement system should be able to monitor the performance of the DSN frequency standards, validate their requirements, support *in-situ* tuning and calibration, and detect a degraded frequency standard or distribution link. In the past, the stations were equipped with a variety of custom-developed, one-of-a-kind, single-channel systems that were inadequate for these tasks. In addition, their noise floor was too high for characterizing the CSO or other upcoming frequency standard technologies.

The development of a multi-channel Frequency Standards Stability Analyzer (FSSA) originated in 1999 within a NASA program to improve DSN performance monitoring[2]. The FSSA design goals included a low noise floor, multi-channel capability, and an interface that can easily be operated by DSN users and operations personnel. An initial progress report of the FSSA development was presented at PTTI in 2001 **[1]**. Here, we update and summarize the final developed system and its capability.

PRINCIPLES OF OPERATION

Phase comparators based on the dual-mixer principle have been in use for about thirty years **[2-8]**. In this method, two or more frequency sources, running at the same frequency f_0, are down-converted to beat notes at frequency f_b by mixing them with a common transfer oscillator running at frequency $f_0 - f_b$. If $x_b(t)$ is the time offset between two of these low-frequency beat notes at time t, then the measured time offset between the two sources is $(f_b / f_0) x_b(t)$. Most dual-mixer analyzers keep track of $x_b(t)$ by using a time-interval counter to measure the delay between corresponding zero-crossing times of the two beat notes. These instruments are called dual-mixer time-difference (DMTD) analyzers. The transfer oscillator introduces short-term measurement noise that depends locally on the phase offset of the two beat notes **[9]**. To reduce this noise, some analyzers use a phase shifter to keep the beat notes approximately in phase, while others use an interpolation technique while keeping track of whole-cycle slips.

The FSSA, which generates several beat notes by mixing the sources under test against a common transfer oscillator, does not keep the beat notes in phase. It uses a combination of interpolation and averaging to capture averaged phase residuals of each beat note independently **[1]**. The beat frequency f_b is at least 100 Hz. The zero-crossing times t_n of all the beat notes are latched by a continuously running event timer. The phase of each beat note, relative to the nominal "perfect" phase $f_b t_n$ cycles, is interpolated and averaged over each interval of a time grid $\tau_s, 2\tau_s, 3\tau_s, \ldots$ that is the same for all channels, where $f_b \tau_s >> 1$. As a default, $\tau_s = 0.5$ s for a nominal bandwidth of 1 Hz. The average phase residuals for each source are stored; these express the deviations of the source relative to the transfer oscillator. In postprocessing, the stored phases of one source can be subtracted from those of another source, the noise of the transfer oscillator being suppressed by the subtraction. Moreover, a disturbance in one source can usually be isolated by a pairwise comparison of that source and two others.

[2] **Frequency and Timing Subsystem Monitor and Control, Preliminary Definition and Cost Review**, 23 June 1999 (JPL internal document).

HARDWARE DESCRIPTION

The FSSA is packaged into a single standard electronic rack, along with an Environment Monitor Assembly and some optional auxiliary equipment. The unit is located in the Frequency Standards Room of each Signal Processing Center of the DSN. The temperature variation in these rooms is less than 0.5 degrees C during any 24-hour period, but can exceed 1 degree seasonally or when personnel are working around the equipment.

The function of the FSSA is to monitor phase, frequency, and Allan deviation of up to seven precision signal sources, such as hydrogen masers, cesium standards, distribution equipment, local-oscillator chains, and down-converters. Although it has eight inputs (channels 0 to 7), two channels are used for the reference input and self-testing of the noise floor. Except possibly for channel 7, all of the inputs are at 100 MHz.

The precision Radio Frequency (RF) Hardware Assemblies continuously feed signals to an eight-channel Counter Assembly, the event timer of the system. Its output, a serial stream of timetags and identifiers, is routed into Com Port 1 of a commercial computer with a Windows XP Professional operating system. The block diagram (Figure 1) shows how the signals to be monitored are processed before the final data stream enters the computer. Note that this is a continuous process for all channels that have a signal input within the specified limits. The computer does not control any hardware.

There are seven signal inputs from outside sources. One of these is designated as the reference, generally chosen to be the most reliable source on site. It is the only signal that must be present for the system to operate. The signal from this input provides the reference for the Counter Assembly and is also used to generate the 10 MHz and 5 MHz outputs. One of the 10 MHz outputs drives the offset generator (OG), a synthesizer whose output frequency is set to 100 MHz minus the desired beat frequency, which must be at least 96 Hz because of the rollover of the Counter Assembly. The OG output drives each of the two Mixer - Zero Crosser Assemblies, ZC “A” and ZC “B”, which are identical except for channel 7. Each zero crosser generates two trains of TTL pulses of width 20 μS. The positive-going pulses drive the corresponding channel of the Counter Assembly, and the complementary negative-going pulses are available for the auxiliary counter. The output marked “B” is a high-impedance test port for viewing the sinusoidal beat signal, which is normally 0.6 Vpp.

Channel 7 requires an input signal at J21 that has already been down-converted to a low-frequency beat, which can be realized by the separate built-in mixer from any two signals that one wishes to compare. This is very useful in the DSN, where specific signals at S, X, and Ka band are commonly used for deep space communications, tracking, and navigation. Its amplitude should be about 0.6 Vpp. An extra OG signal is available at J12 if another 100MHz signal is to be measured.

In general, all RF ports are +10 dBm into 50 ohm. The Counter Assembly, however, requires a high-power 100 MHz reference signal, which is realized in the Reference Distribution Assembly and delivered out of J4 at +18 dBm.

An auxiliary counter measures the beat frequency out of the negative-going zero-crosser port of any desired channel in order to record real-time frequency data on a chart recorder. It is used for tuning, calibrating, and troubleshooting frequency standards. The computer is a commercial Windows box with 512 MB SDRAM and an 80 GB hard drive. The LCD display and keyboard with trackball are one integrated unit, which is normally turned off and in its stowed position.

The Power Supply is a custom-made vendor supplied item that furnishes +8 V and ±20 V from low-noise highly regulated standard modules to each of the three RF subassemblies. Each RF module has internal regulators to realize low noise and stable +5 V and ±15 V as required. This method also provides extra isolation between modules to prevent crosstalk. All other items have their own DC power supplies fed from the AC line. Isolation between outputs on all the distribution modules exceeds 100 dB. This is especially critical for the 100 MHz OG distribution modules. All interconnect RF cables are double shielded and use threaded Type N, TNC, or SMA connectors. AC cooling fans are used, one for each RF subassembly, to prevent excessive temperature rise. They are a long-life, ball-bearing type and are easily replaced in the field.

The offset generator is a commercial, off-the-shelf synthesizer that replaces the in-house OG used in the prototype FSSA **[1]**. It has good short-term stability. Like all synthesizers, it is temperature sensitive, but the dual-mixer comparison of two channels completely cancels that out.

Four assemblies are custom JPL designed and built. These are the Frequency Divider, Distribution Amplifier, Zero Crosser modules, and Counter Assembly[3]. The Counter Assembly, which is based on an FPGA and a microcontroller, replaces the commercial event-timer computer card used in the prototype **[1]**. It latches the readings of a continuously-running 100 MHz counter at the zero-crossing times of all channels that have a valid signal present. The output is fed continuously into the computer's serial port with no flow control.

SOFTWARE DESCRIPTION

The FSSA is operated by two Visual Basic applications, the front end and the postprocessor. The postprocessor uses a National Instruments Measurement Studio plug-in package for generating plots. The Remote Desktop Connection feature of Windows XP Professional allows the computer to be operated from JPL. The examples shown in Figs. 2–4 were collected from the FSSA at Madrid.

The front end reads the counter, maintains synchronization of the data stream, carries out the preprocessing, and stores averaged phase residuals to disk. Figure 2 (top) shows the main front-end window. The "phase/cycles" column shows the real-time phase residual of each single-mixer channel (source minus OG). The front end can detect missing timetags and substitute interpolated values to maintain phase integrity across gaps. A "short-term glitch" alarm is triggered when the current frequency residual of a channel is significantly greater than an RMS average of recent residuals; the user can adjust the threshold and time constant for each channel.

The postprocessor retrieves the stored phase residuals from disk and prepares plots of phase residuals, frequency residuals, and Allan deviation. Figure 2 (bottom) shows the main postprocessor window. To run the postprocessor, the user chooses a time span and one or two channel numbers. Choosing one channel gives single-mixer results for that channel minus the OG; choosing two channels gives dual-mixer results for the difference of the two channels with the OG noise suppressed. The current dual-mixer noise floor can be evaluated by comparing two channels that are fed by the same source, which may also be the system 100 MHz reference. As the phase residuals are read from disk, they are automatically subsampled by powers of 2 to give an array of reasonable size for plotting. Figure 3 (top) shows plots of phase and frequency residuals of the difference of two hydrogen masers. The user can choose whether or not to bring the phase endpoints to zero by subtracting the mean frequency. The user

[3] S. W. Cole, 2003, **Technical Description, Continuous Timer Card** (Measurement Technology Center; JPL internal document)

can also subtract an estimated linear frequency drift and plot the moving average of frequency residuals over an averaging time greater than the automatic subsampling period. Figure 3 (bottom) shows the corresponding Allan deviation. This general-purpose test software does not try to evaluate the uncertainty of the estimates; in lieu of error bars, the number of samples of frequency difference (if less than 100) is lettered alongside each point. A text file of subsampled phases is available if the user wishes to make further analyses.

PERFORMANCE

The estimated noise floor of a dual-mixer measurement has been calculated to depend on the phase noise of the OG near multiples of the beat frequency from the carrier, the phase offset of the two beat notes, the averaging period τ_s of the phase residuals, and the resolution of the event timer (10 ns) **[10]**. In practice, the noise floor depends on the beat frequency; after a sequence of trials, we chose a default beat frequency of 123 Hz. Figure 4 shows a noise floor example for $\tau_s = 0.5$ s. The same hydrogen maser drives the OG and the inputs of channels 0 and 1. The peak-to-peak phase variation over one day is 36 fs. The Allan deviation at 1 second is 2.3×10^{-15}. In other situations, the noise floor has been observed to be as high as 2×10^{-14} at 1 second, as when the beats are not in phase or a less stable commercial cesium beam standard drives the OG. This performance is still sufficient for all current applications except characterizing the CSO at 100 MHz. But it must be noted that a comprehensive set of noise-floor tests has not been carried out with the current hardware.

In some recent noise-floor tests, the phase residuals were observed to oscillate with a 1-second period. These small oscillations were mitigated by changing the beat frequency from 123 Hz to 122 Hz. This problem has not yet been further diagnosed.

The FSSA is designed to collect data and manage the disk storage continuously for months at a time. Because of the lack of a real-time operating system, occasional computer events interrupt the handling of the data entering the serial interface. The front-end program detects the disruption, issues alarms, and recovers automatically, but the integrity of the data is broken. These disruptions may occur every few weeks, depending on the site.

CONCLUSIONS

A new Frequency Standards Stability Analyzer (FSSA) capability is now operating in the JPL FSTL and the NASA Deep Space Network Frequency and Timing Subsystem. It compares six independent 100 MHz test signals with state-of-the-art noise floor, and includes a channel for measurement of any frequency source that can be down-converted to approximately 100 Hz (typically X and Ka band sources in the DSN). The Allan deviation noise floor is measured to be approximately 2×0^{-15} at 1 second and 1×10^{-18} at 4000 seconds, currently sufficient to measure all operational DSN frequency references and distribution links.

The analyzer has a simple, intuitive operator interface and can be accessed remotely from JPL. Currently, four complete systems are operating well, with one installed at each of the three DSN signal processing centers and one in the JPL FSTL. The FSSA in the DSN is used to validate and monitor the performance of the hydrogen masers, the backup cesium standards, the frequency distribution links, the LITS, and the CSO when required. The FSSA in the FSTL is currently used to measure FSTL hydrogen masers, the new compensated multi-pole LITS reference standard **[11]**, and the JPL cesium atomic fountain.

REFERENCES

[1] C. A. Greenhall, A. Kirk, and G. L. Stevens, 2002, *"A multichannel dual-mixer stability analyzer: progress report,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C), pp. 377-383.

[2] D. W. Allan, 1976, "*Report of NBS Dual Mixer Time Difference System (DMTD) Built for Time-Domain Measurements Associated with Phase 1 of GPS*," **Report NBSIR 75-827** (National Bureau of Standards, Boulder, Colorado).

[3] D. A. Howe, D. W. Allan, and J. A. Barnes, 1981, *"Properties of signal sources and measurement methods,"* in Proceedings of the 35th Annual Frequency Control Symposium, 27-29 May 1961, Philadelphia, Pennsylvania, USA (Electronic Industries Association, Washington, D.C.), pp. 1–47

[4] S. Stein, G. Glaze, J. Levine, J. Gray, D. Hilliard, D. Howe, and A. Erb, 1983, *"Automated high-accuracy phase measurement system,"* **IEEE Transactions on Instrumentation and Measurement, IM-32**, 227–231

[5] S. R. Stein, 1985, *"Frequency and time—their measurement and characterization,"* in E. A. Gerber and A. Ballato, eds., **Precision Frequency Control, Vol. 2** (Academic Press, New York), pp. 191–232, 399–416.

[6] G. Brida, 2002, *"High resolution frequency stability measurement system,"* **Review of Scientific Instruments, 73**, 2171–2174

[7] L. Šojdr, J. Čermák, and R. Barillet, 2004, *"Optimization of dual-mixer time-difference multiplier,"* in Proceedings of the 18th European Frequency and Time Forum (EFTF), 5-7 April 2004, Guildford, UK, CD-Session 6B/130.pdf.

[8] F. Nakagawa, M. Imae, Y. Hanado, and A. Masanori, 2005, *"Development of multichannel dual-mixer time difference system to generate UTC (NICT),"* **IEEE Transactions on Instrumentation and Measurement, 54**, 829–852.

[9] S.-M. Low, 1986, *"Influence of noise of common oscillator in dual-mixer time-difference measurement system,"* **IEEE Transactions on Instrumentation and Measurement, IM-35**, 648–651.

[10] C. A. Greenhall, 2000, *"Common-source phase error of a dual-mixer stability analyzer,"* **TMO Progress Report, 42-143** (Jet Propulsion Laboratory, Pasadena, California), *http://tmo.jpl.nasa.gov/progress_report/42-143/143K.pdf.*

[11] E. A. Burt, D. G. Enzer, R. T. Wang, W. A. Diener, and R. L. Tjoelker, 2006, *"Sub-10^{-16} Frequency Stability for Continuously Running Clocks: JPL's Multipole LITS Frequency Standards,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 271-292.

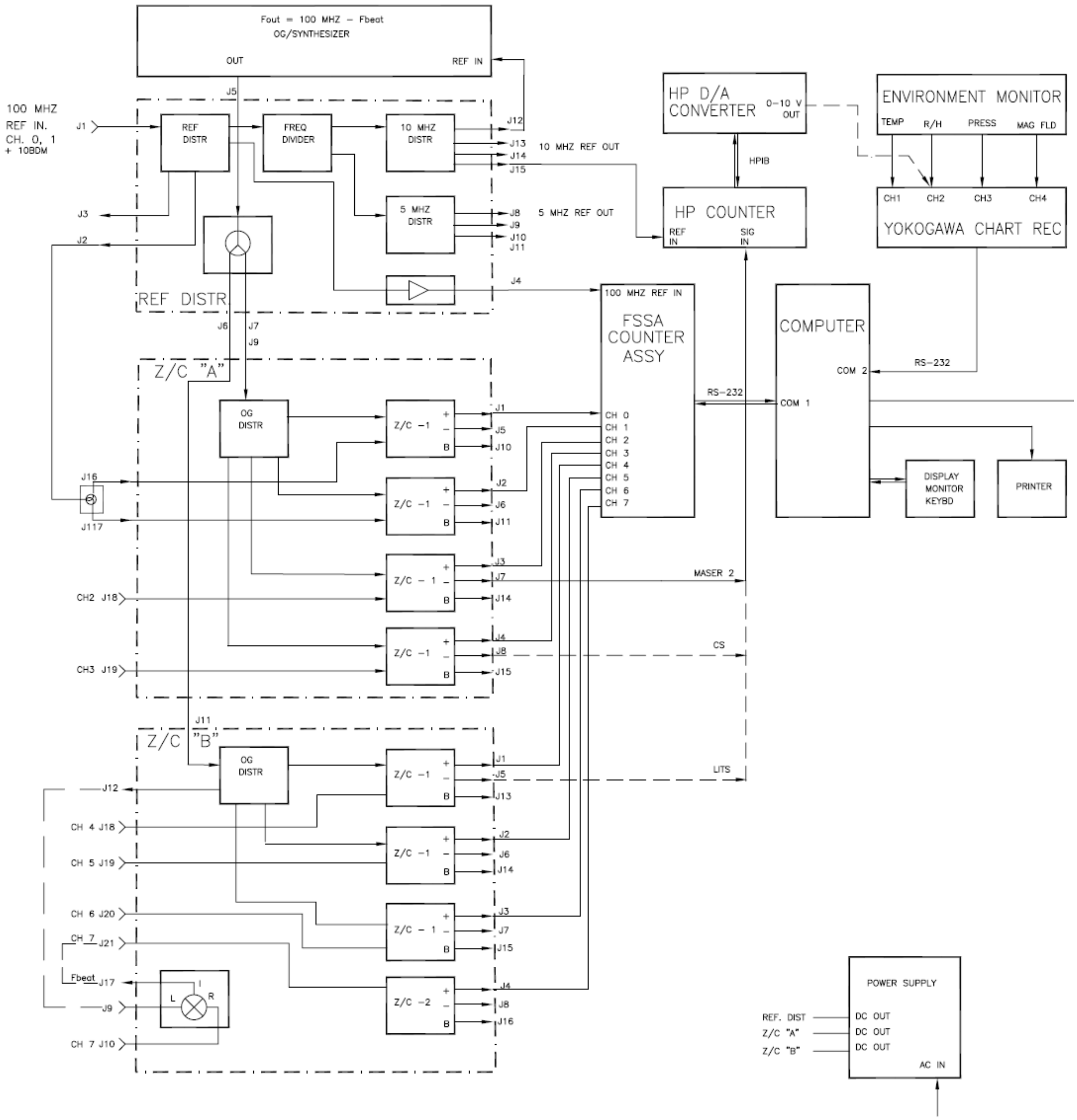

Figure 1. Block diagram of the FSSA.

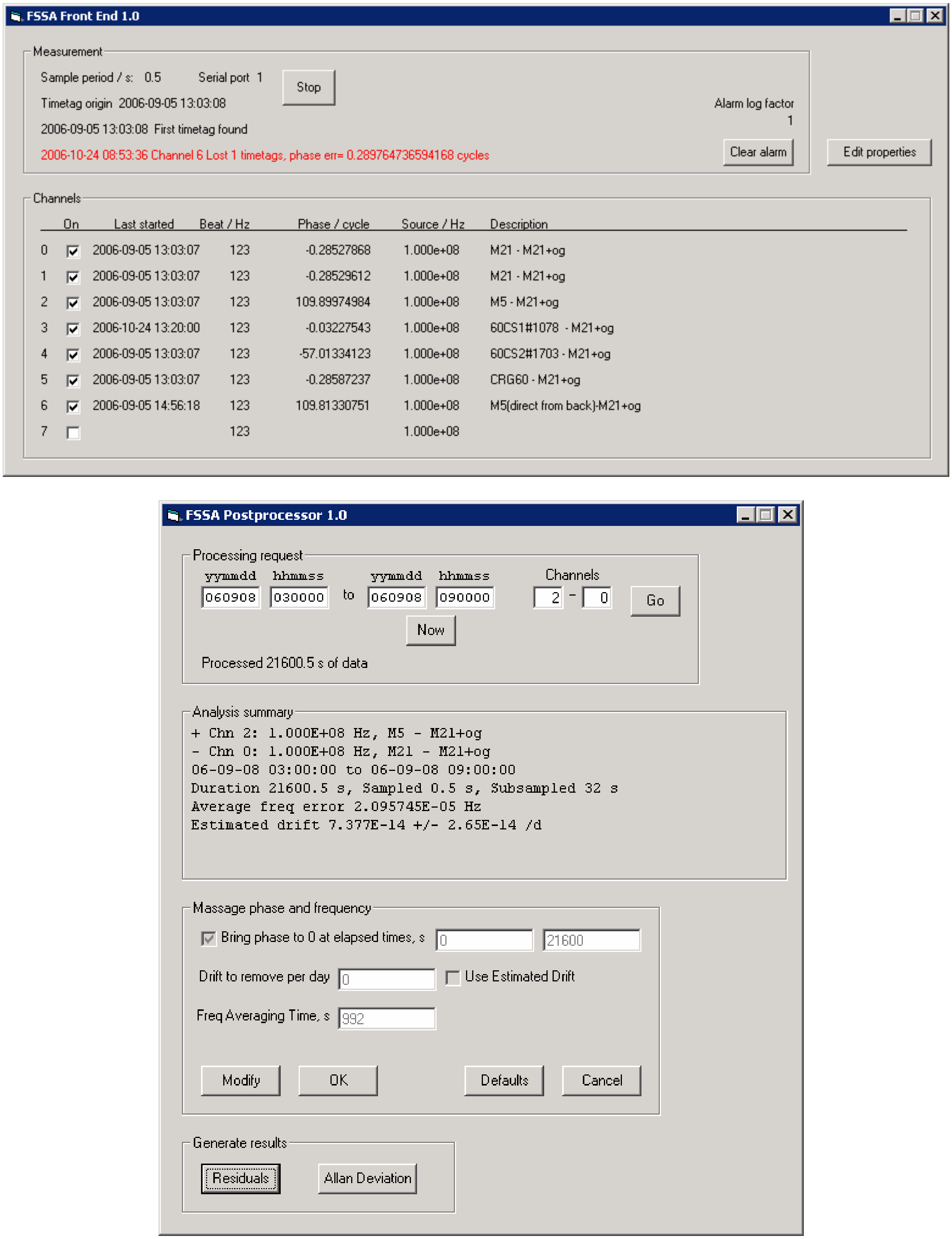

Figure 2. FSSA front-end and postprocessor user interfaces.

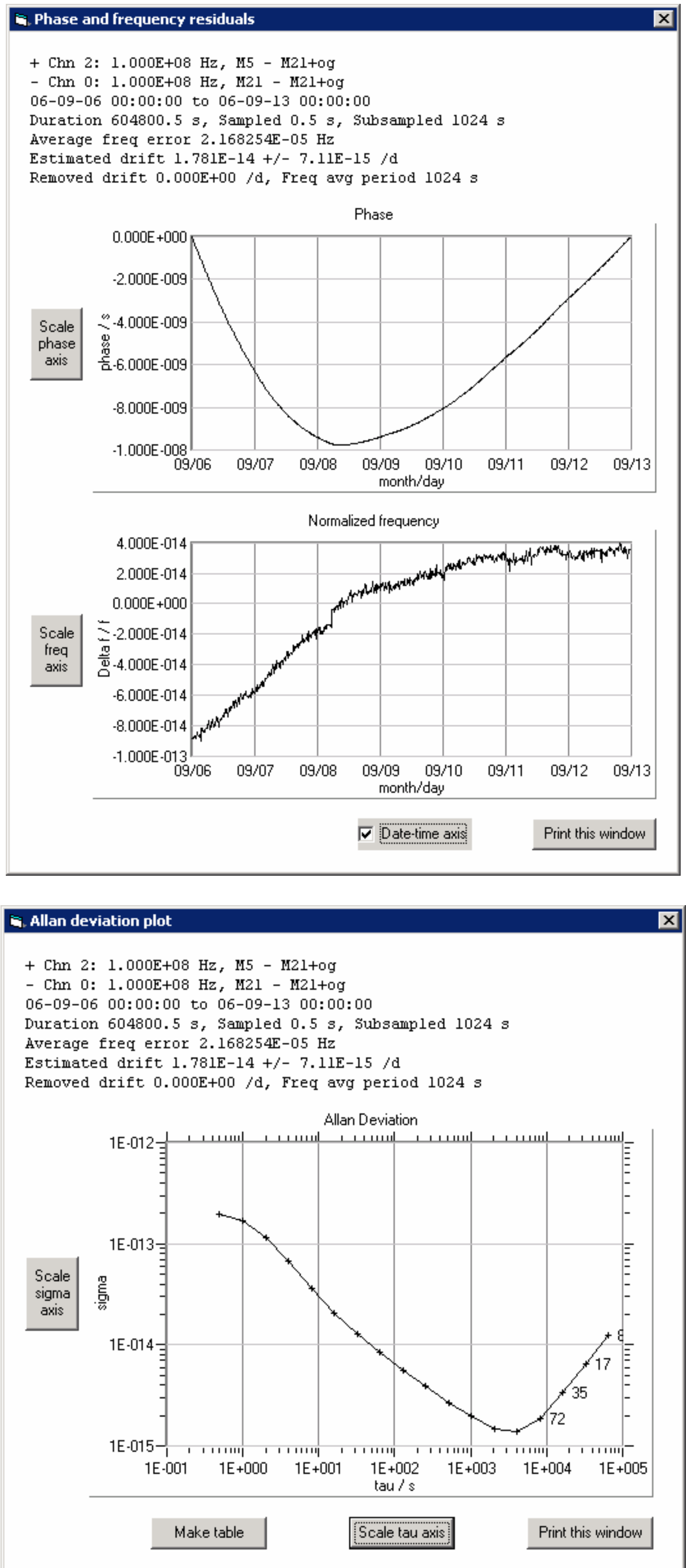

Figure 3. Comparing two hydrogen masers for a week.

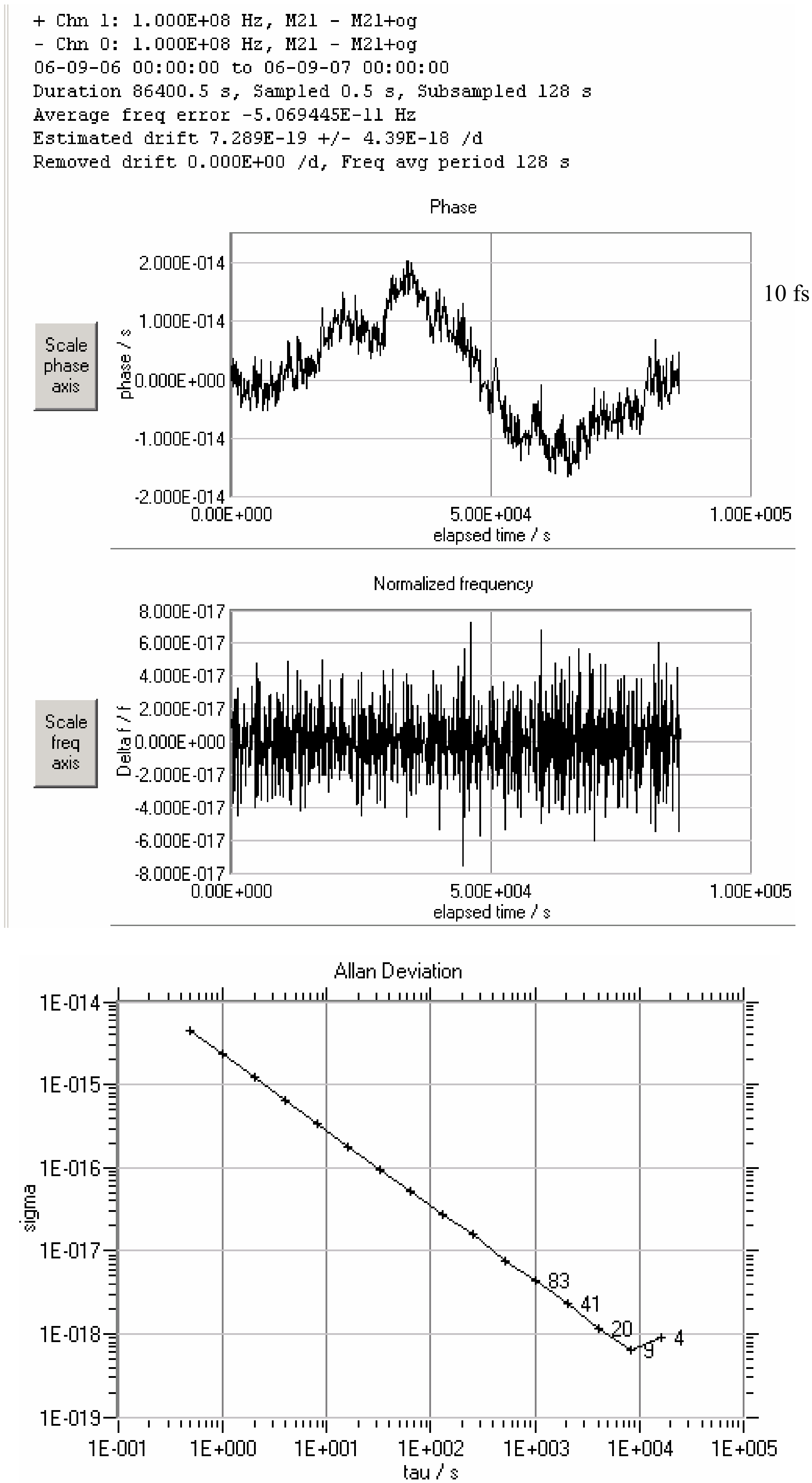

Figure 4. An example of noise floor. The same H-maser drives the OG, channel 0, and channel 1.