Frequency Standards Stability Analyzer for the Deep Space Network

C. A. Greenhall,[1] A. Kirk,[1] and R. L. Tjoelker[1]

A multi-channel Frequency Standards Stability Analyzer (FSSA) has been developed and installed in each of the three Deep Space Network (DSN) sites and at JPL's Frequency Standards Test Laboratory. The FSSA can simultaneously measure and monitor the relative stability of six independent 100-MHz frequency sources and one source at an arbitrary frequency when downconverted with a low-noise synthesizer. Pairwise comparisons of any two sources connected to the system can be made at any time with no hardware reconfiguration. The measured Allan-deviation 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.*

I. 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) [1,2], cryogenic sapphire oscillators (CSOs) [3], and a cold-atom atomic fountain standard [4]. 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. Each of the three major DSN sites supports several antennas, with the Goldstone site currently supporting eleven. 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.

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

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[1] Tracking Systems and Applications Section.

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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 [5,6]. 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 systems that were inadequate for these tasks. Besides admitting at most three test inputs, they were cumbersome, inflexible, unreliable, and expensive in different combinations.

The development of the 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 be operated easily by DSN users and operations personnel. A progress report on a prototype FSSA was presented at the 2001 Precise Time and Time Interval (PTTI) Meeting [7]. The present report updates and summarizes the final developed system and its capability; a previous version was given at the 2006 PTTI Meeting [17], and a New Technology Report is on file.[3]

II. 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.

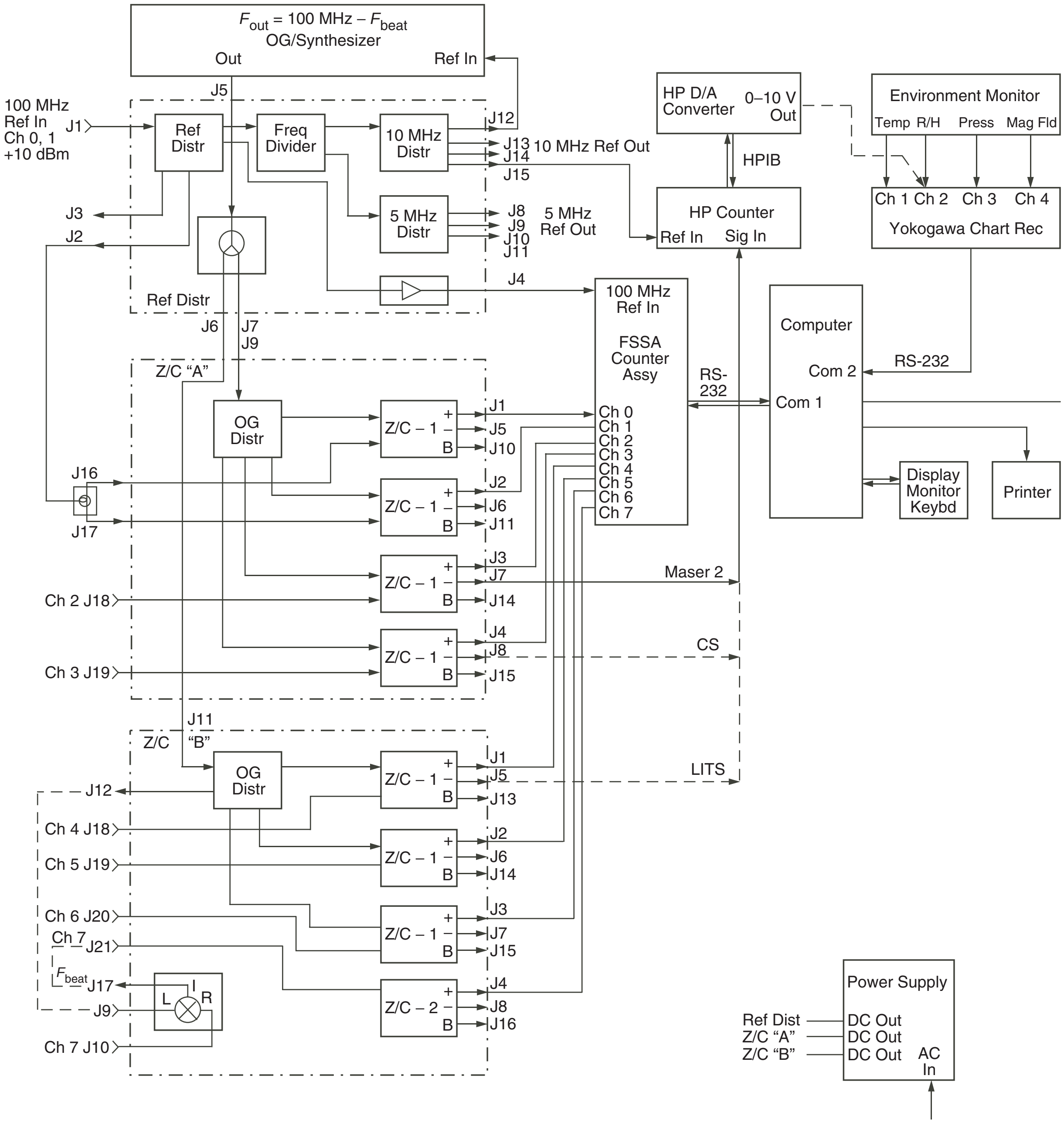
The function of the FSSA is to monitor phase, frequency, and Allan deviation of up to seven precision signal sources such as hydrogen masers, cesium standards, distribution equipment, local-oscillator chains, and downconverters. Any two sources can be compared at any time with no hardware changes. A disturbance in one source usually can be isolated by a three-way comparison of that source and two others. Although the FSSA 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 downconverted signals to an eight-channel counter assembly, which captures their zero-crossing times. Its output, a serial stream of time tags and identifiers, is routed into serial port 1 of a commercial computer with a Windows XP Professional operating system. The block diagram (Fig. 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, nominally 100 Hz. The OG output drives each of the two mixer–zero crosser (ZC) assemblies, ZC "A" and ZC "B," which are identical except for channel 7. Each zero crosser generates two trains of transistor–transistor logic (TTL) pulses of width 20 μs. The positive-going pulses drive the corresponding channel of the

[2] *Frequency and Timing Subsystem Monitor and Control, Preliminary Definition and Cost Review* (internal document), Jet Propulsion Laboratory, Pasadena, California, June 23, 1999.

[3] *A Multiple-Channel Dual-Mixer Stability Analyzer*, NTR 40468 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 27, 2003.



Legend

- Assy = Assembly
- B = Sinusoidal Beat
- Ch = Channel
- Com = Serial Port
- CS = Cesium Standard
- D/A = Digital-to-analog
- Distr = Distribution
- Fld = Field
- Freq = Frequency
- HP = Hewlett-Packard
- HPIB = HP Interface Bus
- I = Intermediate
- Keybd = Keyboard
- L = Left
- Mag = Magnetic
- R = Right
- Rec = Recorder
- Ref = Reference
- R/H = Relative Humidity
- RS-232 = Recommended Standard 232
- Sig = Signal
- Temp = Temperature
- Z/C = Zero-crosser

Fig. 1. Block diagram of the FSSA.

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 downconverted 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 2.3 GHz, 8.4 GHz, and 32 GHz are commonly used for deep-space communications, tracking, and navigation. The signal's amplitude should be about 0.6 Vpp. An extra OG signal is available at J12 if another 100-MHz signal is to be measured.

In general, all RF ports are +10 dBm into 50 ohms. 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 commercial time-interval 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 system with 512-MB memory and an 80-GB hard drive. The liquid crystal 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 direct current (DC) power supplies fed from the alternating current (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, threaded Neill–Concelman (TNC), or subminiature version A (SMA) connectors. AC cooling fans are used, one for each RF subassembly, to prevent excessive temperature increase. 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 prototype in-house OG, which consisted of a single-sideband mixer followed by a cleanup loop [7]. It has good short-term stability. Like all synthesizers, it is temperature sensitive, but slow variations in its frequency are suppressed when the phase data from two channels are compared, because the synthesizer is common to both channels. The next section has further discussion of common-source noise suppression.

Four assemblies are custom JPL designed and built. These are the frequency divider, distribution amplifier, zero-crosser modules, and counter assembly.[4] The counter assembly, which is based on a field-programmable gate array (FPGA) and a microcontroller, is an event timer with a resolution of 10 ns, half that of the commercial computer interface card used in the prototype [7]. It latches the readings of a continuously running 100-MHz 20-bit counter at the zero crossings of all channels that have a valid signal present. Because the counter rolls over every 10.486 ms, the beat frequency must be at least 96 Hz. The output of the counter assembly is fed continuously into the computer's serial port with no flow control.

III. Principles of Operation

Phase comparators based on the dual-mixer principle have been in use for about 30 years [8–14]. In this method, two or more frequency sources at the same frequency f_0 are downconverted to beat notes at frequency f_b by mixing them with a common offset generator running at frequency $f_0 - f_b$. Downconversion

[4] S. W. Cole, *Technical Description, Continuous Timer Card* (internal document), Measurement Technology Center, Jet Propulsion Laboratory, Pasadena, California, 2003.

magnifies the time offset of the two signals, allowing it to be measured by ordinary counters; thus, if $x_b(t)$ is the measured time offset between two of these low-frequency beat notes at time t, then the actual 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 varying delay between corresponding zero-crossing times of the two beat notes. These instruments are called dual-mixer time-difference (DMTD) analyzers. The offset generator introduces short-term measurement noise that depends locally on the phase offset of the two beat notes [15]. 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 does not keep the beat notes in phase; nor does the front end of the instrument measure their relative offsets. Instead, the front end uses a combination of interpolation and averaging to capture averaged phase residuals of each beat note independently on a common timescale [7]. The beat frequency f_b is at least 100 Hz. The zero-crossing times of all the beat notes are latched by a continuously running event timer. If t_n is the nth zero-crossing time of a beat note, then the phase residual in cycles of the beat note at time t_n, relative to a nominal "perfect" phase $f_b t_n$, is given by the formula

$$\xi(t_n) = n - f_b t_n$$

The essential term on the right is n, which is the total phase at time t_n; the other term is a constant frequency offset that makes the values numerically smaller and thereby more manageable. As shown in Fig. 2, the phase residuals are interpolated and averaged over each interval of a time grid that is common to all channels. The grid has spacing τ_s, chosen so that $f_b \tau_s \gg 1$. As a default, $\tau_s = 0.5$ s to give a nominal bandwidth of 1 Hz. The averaged phase residuals for each channel are stored; these express the deviations of that source relative to the offset generator. Only in post-processing are the stored phases of one channel subtracted from those of another channel to give a dual-mixer comparison of the two sources, in which the noise of the common offset generator is suppressed.

Before starting the development, we checked the feasibility of the design by estimating two components of the noise floor of a dual-mixer comparison. First, the differencing of two channels suppresses the noise of the common offset generator except in a set of narrow frequency bands centered at multiples of f_s from the carrier [16]. The root-mean-square (RMS) phase noise of the measurement depends on the noise spectrum of the offset generator, the lowpass filter response of the mixers, the phase offset of the two beat notes, and the parameters f_0, f_b, and τ_s. An upper bound of 3.4×10^{-15} was calculated for 1-second Allan deviation from this effect, averaged over a cycle of phase offsets [7,16]. This value applies to the prototype offset generator, however, and has not been calculated for the commercial synthesizer that is now being used.

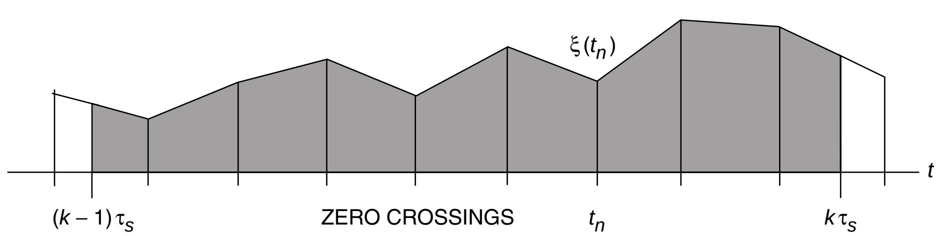


Fig. 2. A beat-note zero crossing at t_n gives rise to a phase residual $\xi(t_n)$. Between the zero crossings, the phase is interpolated linearly. The average phase between $(k-1)\tau_S$ and $k\tau_S$ is the shaded area divided by τ_S.

Second, the contribution of timer quantization to the noise floor can be estimated. Let q be the resolution of the event timer, and assume that the zero-crossing measurements have uncorrelated quantization errors with standard deviation $q/\sqrt{12}$. The Allan deviation of this effect [7] is

$$\sigma_y(\tau) = \frac{q}{f_0 \tau} \sqrt{\frac{f_b}{2\tau_s}}$$

which equals $10^{-15}/\tau$ for $q = 10$ ns, $f_0 = 100$ MHz, $f_b = 100$ Hz, $\tau_s = 0.5$ s.

IV. Software Description

The FSSA is operated by two Visual Basic applications, called 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. 3 through 5 were collected from the FSSA at the Madrid station.

The front end reads the counter, maintains synchronization of the data stream, carries out the preprocessing, and stores averaged phase residuals to a disk database, which is maintained autonomously over many months. Figure 3(a) shows the main front-end window. The "Phase/cycle" column shows the real-time averaged phase residual of each single-mixer channel (source minus OG). The front end can detect missing time tags 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 the database and prepares plots of phase residuals, frequency residuals, and Allan deviation. Figure 3(b) 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 source minus the OG; choosing two channels gives dual-mixer results for the difference of the two sources 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 sub-sampled by powers of 2 to give an array of reasonable size for plotting. Figure 4(a) 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 also can subtract an estimated linear frequency drift and plot the moving average of frequency residuals over an averaging time greater than the automatic sub-sampling period. Figure 4(b) shows a plot of 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 sub-sampled phases is available if the user wishes to make further analyses.

This project was carried out without the benefit of real-time system and application software. The postprocessor does not interfere with the front end, but remote desktop log-ins and other, unknown, events have been observed to interrupt the handling of data from the serial interface. The front end detects the disruption, issues alarms, and recovers automatically, but the results show large phase jumps. These disruptions can occur every few weeks, depending on the site.

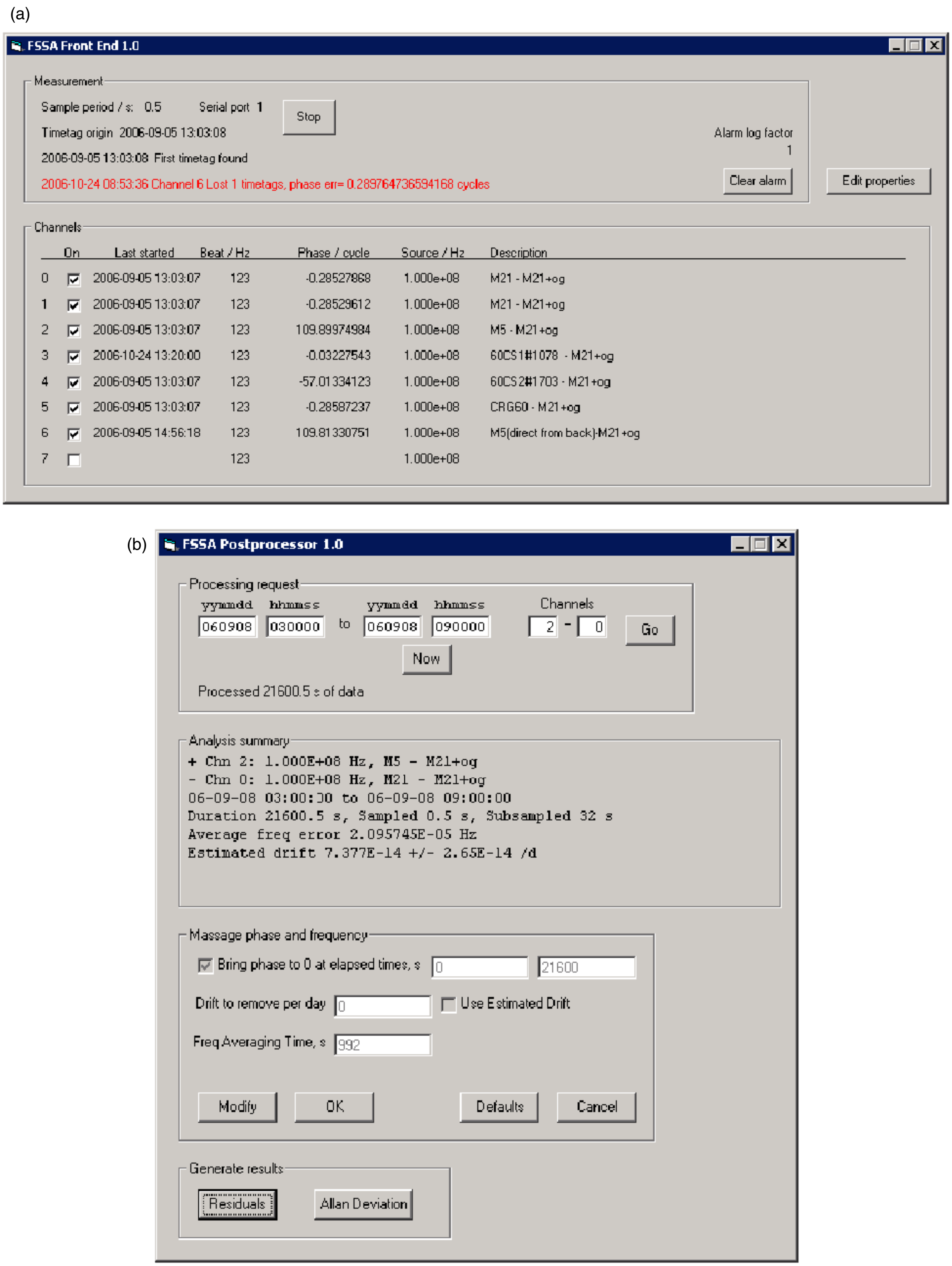


Fig. 3. FSSA user interfaces: (a) front end and (b) postprocessor.

(a) (b)

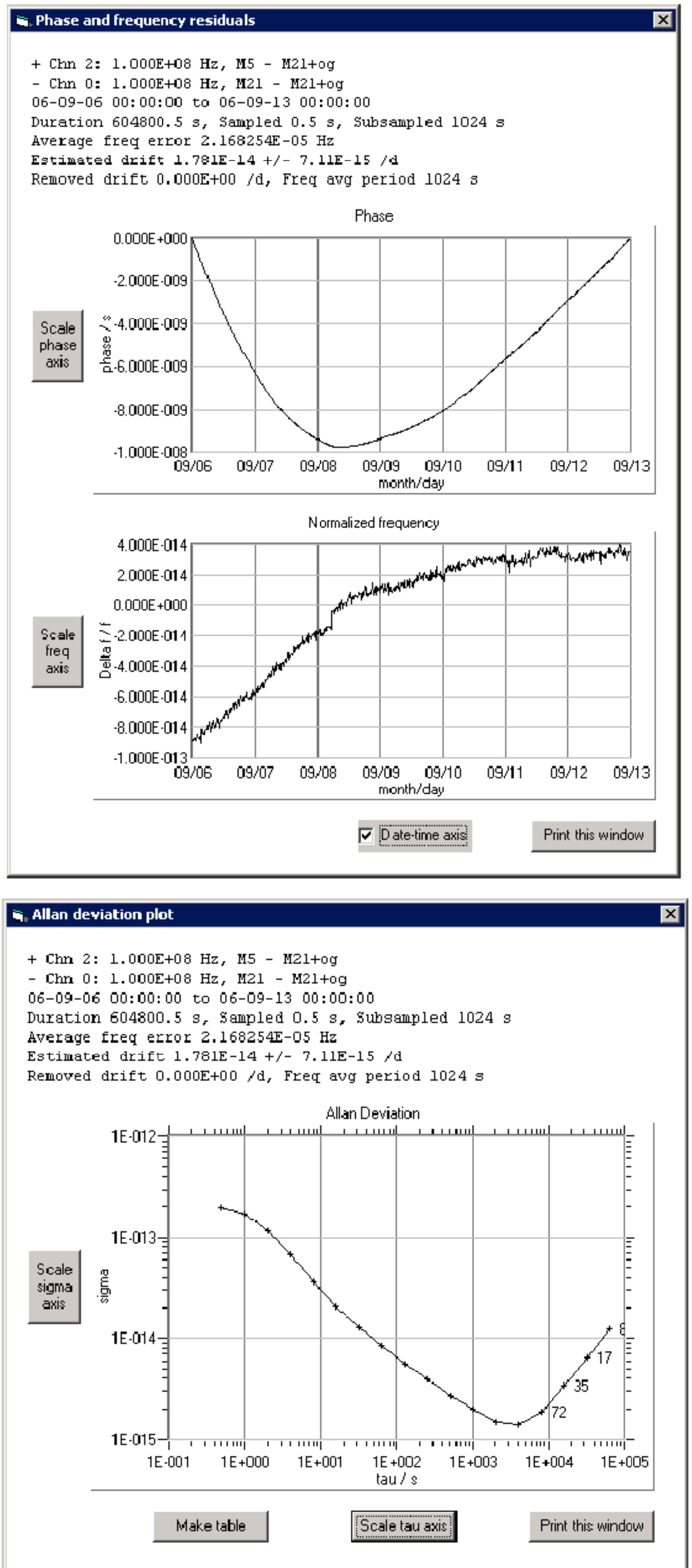


Fig. 4. Comparison of two hydrogen masers for a week: (a) phase and frequency residuals and (b) Allan deviation.

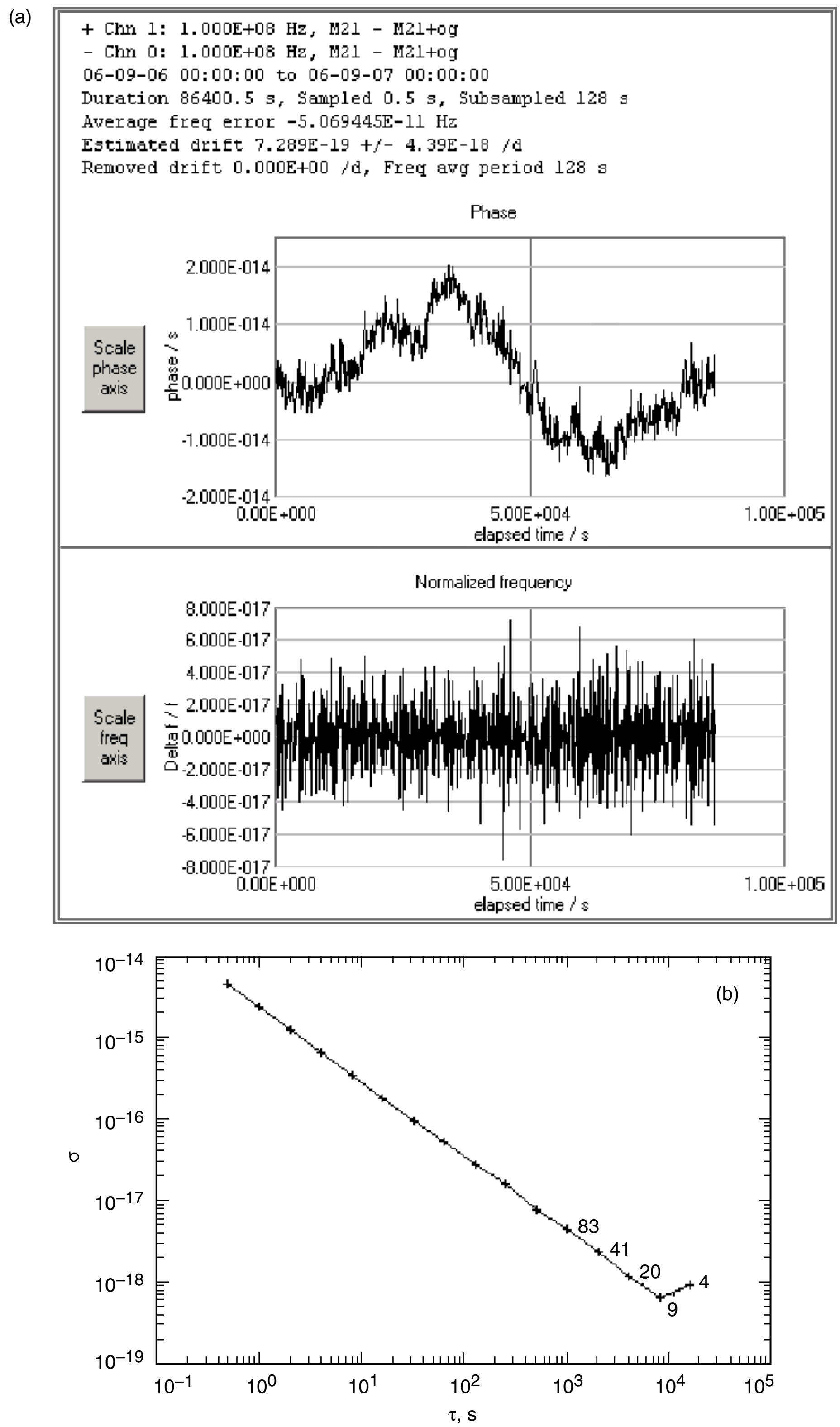


Fig. 5. An example of noise floor: (a) phase and frequency residuals and (b) Allan deviation. The same H-maser drives the offset generator, channel 0, and channel 1.

V. Noise-Floor Observations

The noise floor of the FSSA is still adequate when a commercial synthesizer is used as the OG in place of the prototype single-sideband (SSB) mixer and cleanup loop [7]. We observed that the noise floor could be optimized further by adjusting the beat frequency f_b. We guess that the dependence of the noise floor on f_b might be caused by local variations in the phase noise spectrum of the synthesizer. After a set of trials, we chose a default value of 123 Hz. Figure 5 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. For this example the Allan deviation at 1 second is 2.3×10^{-15}. In some 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 standard drives the OG. This performance is still good enough for all current applications except for characterizing the CSO at 100 MHz. A comprehensive set of noise floor tests under all conditions has not been carried out with the current hardware.

VI. Conclusions

The Frequency Standards Stability Analyzer provides a new and needed capability for the DSN Frequency and Timing Subsystem. Each instrument can monitor the performance of six frequency standards and measure the stability of RF and microwave distribution links. By using a low-noise synthesizer to downconvert RF signals, any DSN reference frequency can be characterized down to the noise floor of the instrument. The Allan deviation noise floor is measured to be approximately 2×10^{-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.

At this time, four complete instruments are operating well, with one installed at each of the three DSN Signal Processing Centers and one in the JPL FSTL. Each 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 hydrogen masers, the new compensated multi-pole LITS reference standard [2], and the JPL cesium atomic fountain [4].

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