

Coherent Reference Generator Phase Stability

V. N. Korwar

Communications Systems Research Section

The extent of phase noise introduced by the coherent reference generator (CRG) unit in the DSN's Frequency and Timing Subsystem (FTS) has not so far been measured or analyzed. This report calculates approximate phase stability estimates for the CRG. The method used involves estimating the phase noise introduced by CRG components based upon measurements made in the past on similar components in other parts of the FTS and obtaining the CRG phase noise from the component phase noises.

Three estimates of phase stability are calculated – the fractional frequency change for a 5°C step in temperature, the phase noise spectral density and the Allan standard deviation. It is found from these estimates that the CRG phase stability is better than that of the H-maser physics unit + receiver, which has been measured in the past. Thus, the first step in improving FTS phase stability would be to make improvements in the H-maser physics unit + receiver. These results are corroborated by indirect clock stability estimates calculated from Doppler data by R. W. Hellings.

I. Introduction

The DSN's Frequency and Timing Subsystem (FTS) may be divided into three separate subsystems – the primary frequency unit called the physics unit (such as H-maser or Cs standard), the receiver, and the coherent reference generator (CRG). The first two of these together, i.e., the physics unit + receiver, will be referred to as the H-maser system or the Cs system as appropriate. All three subsystems taken together will be referred to as the H or the Cs clock. The receiver that goes with the H-maser system is different from the one that goes with the Cs system. However, the same CRG is used in the DSN, no matter whether the H-maser or the Cs system is used.

So far, measurements of phase noise have been made on the Cs system and on the H-maser system, but none on the CRG (or on the receiver portion alone for either the H-maser or the Cs system). In order to improve the frequency stability of the FTS, it is necessary to identify the prime sources of phase/frequency instability in the FTS. To do this, the first step is to estimate the phase errors of the three subsystems separately, so that improvement can first be made in the poorest of the three subsystems.

This report describes an attempt to estimate the phase instability introduced by the CRG alone and identifies areas needing further work. While the CRG phase noise estimates

given here are very approximate, they do provide a starting point for better estimates.

II. CRG Description

The CRG consists of the circuitry needed to synthesize and distribute signals of frequencies 0.1, 1, 5, 10, 10.1, 45, 50, 55 MHz. The CRG inputs are signals of frequencies 0.1, 5 and 10 MHz, derived from the primary frequency unit + receiver. A block diagram of the CRG is given in Fig. 1 (Fig. 2.1 of Ref. 1).

III. Phase Noise Measures

Three measures of phase noise have been calculated here (wherever possible). They are:

- (1) $\Delta f/f$, the fractional frequency variation for a 5°C temperature step. The box in which the CRG is located is assumed to have a response time of $T = 2000$ s. Phase drifts ($\Delta\phi$) with temperature are often measured or specified. From these, $\Delta f/f$ can be calculated as

$$\frac{\Delta f}{f} = \frac{2}{3} \times \frac{\Delta\phi}{T} \times \frac{1}{2\pi f_0}, \quad (1)$$

where $\Delta\phi$ is in radians, f_0 is the nominal frequency, and $T = 2000$ s.

- (2) S_ϕ (10 Hz), the one-sided spectral density of phase noise $S_\phi(f)$ evaluated at $f = 10$ Hz. In all cases considered here, the noise is assumed to be flicker of phase; i.e.,

$$S_\phi(f) = \frac{\text{constant}}{f}, \quad (2)$$

so that specifying S_ϕ (10 Hz) is sufficient to specify the whole $S_\phi(f)$ curve. This assumption is justified by measurement for multipliers (Ref. 2) and distribution amplifiers (Ref. 3).

- (3) σ_y (1 s), the Allan standard deviation $\sigma_y(\tau)$ evaluated for $\tau = 1$ s. This is calculated from $S_\phi(f)$, by using the expression given in Ref. 4 and corrected in Ref. 5. After expressing the constant in $S_\phi(f)$ in terms of S_ϕ (10 Hz), this gives

$$\sigma_y(\tau) = \frac{2.42}{f_0 \tau} (S_\phi(10 \text{ Hz}))^{1/2} (1 + 0.13 \ln \tau)^{1/2} \quad (3)$$

where f_0 is the nominal frequency, and τ is the observation interval for calculating Allan standard deviation.

Since temperature-induced phase drifts are not independent, the overall $\Delta f/f$ introduced in a cascade of identical components is just the sum of the individual $\Delta f/f$ values. If the components are of different types, the $\Delta f/f$'s may actually tend to cancel each other; however, they are assumed to be additive in making the estimates here. The S_ϕ (10 Hz) values are also summed, since they represent noise powers that are uncorrelated. The σ_y (1 s) values are proportional to $(S_\phi(10 \text{ Hz}))^{1/2}$, so that the overall σ_y (1 s) is obtained as the root-sum-square (rss) value of the individual σ_y (1 s) values.

IV. Sources of Phase Noise

There are several components in the coherent reference generator (CRG), each potentially a noise source. Unless otherwise stated, "noise" will mean "phase noise" throughout. There are no frequency or phase control loops involving voltage controlled oscillators (VCOs) in the CRG, so that one of the largest of the usual sources of noise is not present in the CRG, as it is in the receiver. However, there are various components, each of which introduces small amounts of noise. In roughly descending order of phase noise introduced, they are: tuned amplifiers and crystal filters, distribution amplifiers, power splitters, mixers and multipliers.

VCOs are noisy because they convert voltage noise, from whatever source present at their inputs, into phase noise. The other components do not have such an I/O property and hence are less noisy.

Tuned amplifiers and crystal filters mainly introduce phase drifts with temperature changes. This is because their transfer functions (both amplitude and phase) are narrowband around a center frequency that changes with temperature as the (L, C) component values defining this center frequency change with temperature. This is especially true with crystal filters.

Distribution amplifiers (DA) usually introduce noise because of the driver amplifiers preceding and/or following the power divider/splitter present in the DA. All driver amplifiers now used in the coherent reference generator (CRG) are Class A amplifiers operating in the linear region of their characteristics, which are much less noisy than Class C amplifiers.

Power splitting is usually accomplished by transformers with the proper turns ratios – these usually introduce negligible phase noise.

V. Direct Method for Estimating Phase Noise

The amounts of phase noise introduced by various components in the CRG are difficult to estimate correctly, because

phase noise measurements on most of these components have not been made, nor is any analysis available. Inquiries with the manufacturers of several of the components (crystals, crystal filters, multipliers) also did not produce any results, except in the case of one multiplier.

The calculations of CRG phase noise described here are obtained by including noise estimates for only those of the components that have some sort of estimate/measurement available, and assuming that all others are zero, so that an estimate of lower bound on the CRG phase noise can be obtained. Even these lower bounds should not be taken as rigid, because the phase noise for many of the components has not been measured for the specific models used in the CRG, but extrapolated from measurements on *similar* components in other subsystems (such as in the maser receiver).

A. The Components

1. **Tuned amplifiers and crystal filters.** Unfortunately, there are no data available on these components, not even with the manufacturers. These are important sources of phase drift with temperature, but if the temperature is controlled, the phase noise they introduce may be small. However, the coherent reference generator (CRG) is not typically operated in a temperature-controlled environment.

Tuned amplifiers/crystal filters are used only in generating the 10.1-MHz, 45-MHz and 55-MHz outputs, but not the other outputs. Thus the phase noise for these outputs will be higher than the numerical estimates given here, which don't take the tuned amplifiers and crystal filters into account.

2. **Distribution amplifiers.** Phase noise estimates for the CRG distribution amplifiers (DAs) are calculated from phase drift and S_ϕ (10-Hz) measurements made for DAs used in the H-maser receiver. The DAs in the H-maser receiver consist of an n -way (usually 12-way) power splitter, where each of the n output ports is followed by a driver amplifier (labeled AR2 through AR($n + 1$)). The distribution amplifiers in the CRG, on the other hand (see Fig. 2), consist of an input driver amplifier (AR1) followed by the power splitter and driver amplifiers structure used in the receiver DAs.

The input driver amplifier AR1 is different in design from the output driver amplifiers typified by AR2. It is assumed here that the measured distribution amplifier noise in the receiver (Refs. 3, 6) comes entirely from the output driver amplifiers such as AR2; this neglects the power splitter noise, which is reasonable as stated in Section 4. It is then assumed that AR1 has the same noise as AR2. This may not be accurate, since AR1 is an OP AMP (operational amplifier) with many stages of amplification, while AR2 is a hybrid amplifier

with one or two stages; so AR1 is probably a little worse than AR2. On the other hand, AR1 has feedback that would reduce the noise to some extent, so that on the whole, AR1 may be assumed to be about as noisy as AR2.

Then the coherent reference generator (CRG) distribution amplifier noise is estimated as the noise introduced by two driver amplifiers like AR2 cascaded together, according to the rules for cascading given in Section III.

3. **Frequency multipliers.** There are two (frequency) multipliers used in the CRG. The first is a $\times 2$ multiplier, which is a harmonic generator, followed by a tuned amplifier. However, as can be seen in Fig. 1, this $\times 2$ multiplier is used only as a backup in generating a 10-MHz signal from a 5-MHz input. What is primarily used is an independent 10-MHz input. For this reason the effects of this multiplier and tuned amplifier (on which no data are available) are not important.

The second multiplier used is a $\times 10$ multiplier from Zeta Laboratories. This is a chain-type multiplier; i.e., it uses a chain of harmonic generators, filters and mixers to get the desired multiplication. The $\Delta f/f$ for a 5°C step in temperature for this multiplier was estimated from Eq. (1) by using $\Delta\phi$ data supplied by Zeta Laboratories. The S_ϕ (10 Hz) and the σ_y (1 s) for the multiplier were estimated based on measured S_ϕ (10 Hz) data (Refs. 2, 7) for a JPL-built multiplier which had a somewhat similar design (i.e., it was a chain-type multiplier, as opposed to a step-recovery diode or phase-locked loop type). The JPL multiplier was a $\times 14$ multiplier, and appropriately scaled-down values were used to estimate the noise on the $\times 10$ multiplier used here.

B. Phase Noises for Coherent Reference Generator (CRG) Outputs

Using the phase noise data for individual components described in Section V-A, the phase noises for the various CRG outputs can be estimated as follows:

1. **The 0.1, 1, 5, 10 MHz outputs.** For these outputs, the only significant contributions to phase noise are from an input driver (D_i) and a distribution amplifier (DA) – there are no mixers or multipliers or filters used in generating these outputs. As an example, consider the 0.1-MHz output. In the block diagram (Fig. 1), the input driver D_i is labeled 9455393-1. The distribution amplifier (DA) is A4A2 or A4A3. Detailed block diagrams of A4A2 and A4A3 show a DA like the one in Fig. 2. Thus the phase noise for this group of CRG outputs is given in Table 1. For uniformity, all data given are referenced to a 100-MHz output; i.e., the phase noise spectral density is what would be present if the outputs were multiplied in frequency, by a perfect multiplier, to 100 MHz.

2. Other outputs. All the other CRG outputs have a minimum phase noise given by Table 1, because they all include a DA and an input driver. However, the 10.1-, 45- and 55-MHz outputs will have a larger noise because they all include crystal filters — this is because the 10.1-MHz signal is obtained by mixing the 10- and 0.1-MHz inputs, while the 45- and 55-MHz signals are obtained by mixing 50-MHz and 5-MHz inputs, and the mixed outputs are filtered by a crystal in the 10.1-MHz case and a crystal filter in the 45-MHz and 55-MHz cases. No estimates are available for the extent of noise introduced by the filtering.

The 45-, 50- and 55-MHz signals will have, in addition to the noise in Table 1, a component due to the $\times 10$ multiplier used in generating the 50-MHz signal from a 5-MHz input. The phase estimates for this multiplier are given in Table 2. Thus, we get Table 3 for the 10.1-, 45-, 50-, and 55-MHz CRG outputs.

VI. Indirect Estimates of Coherent Reference Generator (CRG) Noise

A. Very Long Baseline Interferometer (VLBI) Experiments

Some groups performing VLBI experiments have noticed that on days when the Cs clock is used by the DSN, the phase data taken in the VLBI measurements are worse than when the H-maser clock is used. This would indicate that, since the same CRG is used in both cases, (with only the Cs physics unit + receiver being replaced by the H-maser physics unit + receiver), then the CRG stability is at least about as good as the worst of the two — the Cs system and the H-maser system. These results from the VLBI experiments are not very quantitative or very reliable, since the purpose of the experiments was *not* to estimate the noise on the primary standard and, in fact, the experimenters were not always aware of what frequency standard was in use on a particular day. Controlled VLBI experiments, with the same (celestial) source being observed on two successive days, with the Cs clock used on one day and the H-maser clock on the other day, could perhaps be useful. Such experiments would help in getting an indirect estimate of CRG stability.

B. Doppler Tracking Calculations

R. W. Hellings (Ref. 8) made calculations with Doppler tracking data from Voyager (1979) and Viking (1977) that enable estimation of the primary standard phase noise. In 1977, the Cs clock was used, while in 1979, the H-maser clock was used. Hellings was able to infer the phase on the clock by the following method:

In two-way tracking of spacecraft, the ground clock (frequency standard) controls the transmitter frequency ν as well as providing the reference for measuring the Doppler shift $\Delta\nu$ on the return signal. In normal DSN operation, the received signal is tracked in a phase-locked loop, the clock being used to beat the received frequency down to the Doppler tone. If there is a fluctuation $\delta\nu = q(t)$ in the frequency produced by the clock, then since the fluctuation is also present on the return signal a round-trip light time (RTL) later, the Doppler record has a noise term given by

$$\nu(t) = -q(t) + q \left\{ t - \left(\frac{2r_0}{c} \right) \right\}$$

where r_0 is the distance between the transmitter and the spacecraft.

It can be seen that autocorrelating the Doppler tone (after subtracting the predicted Doppler) will give rise to a negative peak in the autocorrelation function (acf) at $t = 2r_0/c$ having half the magnitude of the peak occurring at $t = 0$.

Other noises like white phase system noise will not produce this second peak, because this noise is present only on the return signal. Other noises like plasma and tropospheric noise have a spectrum that is quite different from the flicker of phase or frequency that is characteristic of clock noise, and hence the autocorrelation function is quite different. Details of spectra are given in Ref. 11. Thus, the clock noise can be identified and measured.

In obtaining both the 1977 and the 1979 data, the DSN 64-m-diameter antennas and S-band transmission frequencies were used. The S-band frequency for the 64-m subnetwork is derived from the 50-MHz CRG output by a multiplication by 48 in a Dana synthesizer. There have been no major changes in the multiplier or the coherent reference generator (CRG) between 1977 and 1979. Thus the difference between the clock noise results of Hellings in 1977 and 1979 shows the difference between the 50-MHz output obtained from the Cs standard + CRG system and the H-maser + CRG system. From the 1977 data, the clock phase noise as measured by its standard deviation was determined to be 10^{-13} ; from the 1979 data, the clock phase noise was determined to be below the instrument sensitivity, i.e., $< 3 \times 10^{-14}$. This order-of-magnitude difference is about the same as the ratio of phase stability of the H-maser + receiver to the phase stability of the Cs standard + receiver, as determined by previous measurements. This supports the idea that the CRG phase stability is at least about as good as the stability of the Cs standard + receiver.

VII. Conclusions

The CRG phase noise has been estimated based on data about components similar to the CRG components. The phase noise calculations given here, taken together with the measured data (Refs. 9, 10) for the H-maser + receiver, of

$$\left. \frac{\Delta f}{f} \right|_{5^\circ \text{C step}} = 5 \times 10^{-13}, S_\phi (10 \text{ Hz}) = -98 \text{ dB},$$

$$\sigma_y(1 \text{ s}) = 3 \times 10^{-13}$$

show that the coherent reference generator (CRG) phase stability, at least for the 0.1-, 1-, 5-, 10-, 50-MHz outputs, is better than that of the H-maser + receiver system.

The phase noise on the other CRG outputs (10.1, 45, 55 MHz) is expected to be higher, but by an unknown amount, because of crystal filter instabilities that are unknown.

The calculated results for the 50-MHz output corroborate the results that have been obtained indirectly by Hellings from Doppler data.

However, all the estimates here are tentative, because they are based on measurements not made directly on CRG components. The inferences of CRG noise from Hellings' calculations may also be incorrect, because the data were taken in 1977 for the Cs-based clock and in 1979 for the H-maser based clock, and many FTS components may have been changed during the period between the two measurements, although this does not appear to be the case.

VIII. Suggested Areas of Investigation

A. Direct Measurements

No measurements have been made either on the CRG as a whole or on most of its components. The best way to find the CRG stability would be to make direct measurements on it. The equipment needed to make this kind of measurement is not yet available but is soon expected to be.

Alternately, the phase noises of individual CRG components can be measured, as has been done for some of the H-maser receiver components. In particular, the crystals and crystal filters used in the CRG should be measured for phase stability, since no estimates for these are available, and they are expected to be important noise sources in the CRG. The overall CRG stability can be calculated once the individual component stabilities are correctly known.

B. Indirect Measurements

It would be worthwhile to set up a VLBI experiment specifically for the purpose of measuring the relative stability of the Cs and H-based clocks. This would be useful if a direct estimate of CRG noise cannot be made.

This kind of experiment would require using the two standards separately for observing the same celestial source. The two sets of measurements would have to be made within a short period of each other, so as to minimize errors due to different paths to the source. Intermediate phase data, not normally preserved in VLBI experiments, may need to be kept in order to compare clock stabilities.

The direct method of CRG stability estimation would be preferable because there are too many variables, especially atmospheric effects on phase, that cannot be correctly accounted for in VLBI experiments.

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Table 1. Phase noise estimates for 0.1-, 1-, 5-, 10-MHz outputs of CRG, referenced to a 100-MHz output

	$\Delta f/f$ for 5°C step	$S_\phi(10 \text{ Hz})$	$\sigma_y(1 \text{ s})$
1) Input driver (D_i)	3.7×10^{-14}	-111 dB	1×10^{-13}
2) Distribution amplifier (DA)	7.4×10^{-14}	-108 dB	1.4×10^{-13}
Total	1.11×10^{-13}	-106 dB	1.7×10^{-13}

Table 2. $\times 10$ (zeta) multiplier phase noise estimates, referenced to a 100-MHz output

$\Delta f/f$ for 5°C step	$S_\phi(10 \text{ Hz})$	$\sigma_y(1 \text{ s})$
1.04×10^{-14}	-133 dB	5.4×10^{-15}

Table 3. Phase noise estimates for 10.1-, 45-, 50-, 55-MHz CRG outputs, referenced to a 100-MHz output

	$\Delta f/f$ for 5°C step	$S_\phi(10 \text{ Hz})$	$\sigma_y(1 \text{ s})$	Remarks
50 MHz	1.2×10^{-13}	-106 dB	1.7×10^{-13}	From Tables 1 and 2
10.1 MHz	$>1.1 \times 10^{-13}$	$>-106 \text{ dB}$	$>1.7 \times 10^{-13}$	From Table 1 and allowing for filters
45, 55 MHz	$>1.2 \times 10^{-13}$	$>-106 \text{ dB}$	$>1.7 \times 10^{-13}$	From Tables 1 and 2 and allowing for filters

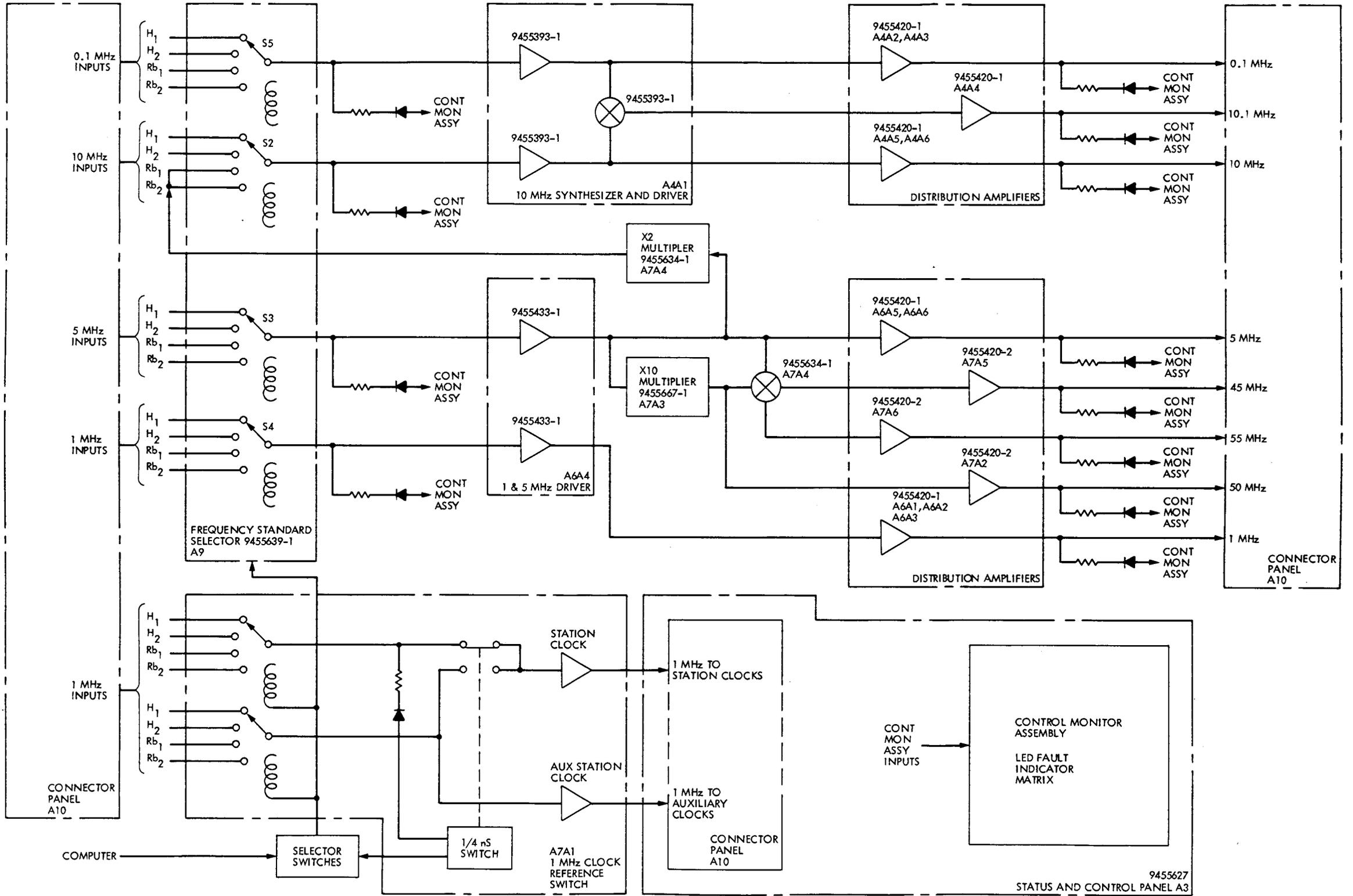


Fig. 1. Coherent reference generator, detailed block diagram

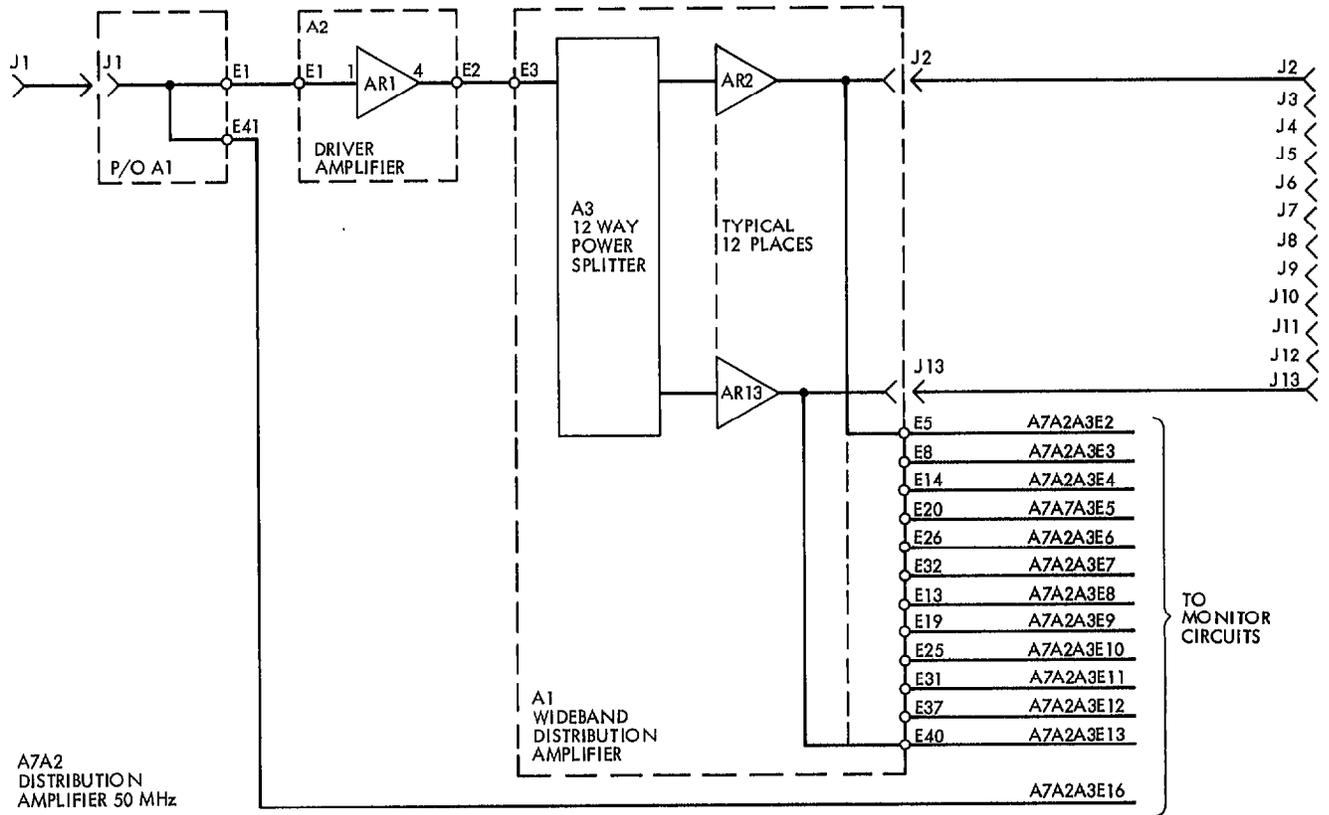


Fig. 2. Typical coherent reference generator distribution amplifier