A Practical Guide to Isolation Amplifier Selection

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Abstract **– Whether distributing a house standard, adding a distribution module in a larger circuit design, or just working with a measurement system on the bench, one must be aware of how a number of distribution amplifier parameters can make or break an entire system's performance. This paper looks at a high performance quartz oscillator, a hydrogen maser, and a rubidium fountain's performance both in the short-term and long-term to develop a model of the signals that one may want to measure or distribute. Two different classes of distribution amplifiers are then reviewed to see how they compare to the sources presented earlier. The front-to-back isolation and phase noise of a distribution amplifier are not the only important parameters that need to be considered. Other important terms such as the return loss, stability over temperature, port-to-port isolation, differential delay over temperature, construction techniques, and design practices must be taken into account. Most of these parameters can be rigorously related in an equation to deliver an expected level of performance from the system. Typical manufacturing and design practices that are necessary to ensure a reliable device are presented. The goal of the paper being to better equip the reader with the skills to evaluate distribution amplifiers to find the one that best fits the needs and expectations in both reliability and overall system performance.**

I. Introduction

Often a designer will come across some clock or reference signal that needs to be distributed or buffered into a system. This prompts a search for the proper amplifier to meet the desired system performance. There are so many different parameters that one could measure on an amplifier and data sheets are often hard to compare from one vendor to the next. This task and associated dilemma prompts a process of evaluating commercial products[*] or in-house designs to determine which amplifier is sufficient for the job at hand. The goals of this paper are to first baseline some of the performance requirements that one might have and then walk through many of the parameters that one might specify and consider.[1]

II. Typical Performance Review – Phase Noise

The phase noise (or phase modulation – PM) level of a source often dominates a system's performance close to the carrier. Therefore, it is necessary to understand the PM noise level of various sources and not further degrade the PM noise when amplifying and distributing a source. The data shown in Table I and subsequently illustrated in Fig. 1 shows the PM noise level for a commercially available hydrogen maser, cesium beam standard, high performance ovenized crystal oscillator (OCXO), and two different classes of distribution amplifiers. The phase noise plots are one representation of the short-term stability of each source which must be weighed with the long-term stability shown in Table II and illustrated in Fig. 2.

TABLE I
COMPARISON OF PM NOISE (PHASE NOISE) IN VARIOUS DEVICES AT 5 MHZ

Offset Frequency (Hz)	Hmaser $\mathcal{L}$(f) in dBc/Hz	Cesium $\mathcal{L}$(f) in dBc/Hz	OCXO $\mathcal{L}$(f) in dBc/Hz	Dist. Amp A $\mathcal{L}$(f) in dBc/Hz	Dist. Amp B $\mathcal{L}$(f) in dBc/Hz	Target $\mathcal{L}$(f) in dBc/Hz
1	-100	-106	-120	-135	-150	-150
10	-120	-136	-150	-145	-160	-160
100	-135	-151	-170	-155	-167	-167
1,000	-145	-156	-176	-163	-170	-173
10,000	-150	-160	-176	-163	-170	-175
100,000	-155	-160	-176	-163	-170	-175

III. Typical Performance Review – Frequency Stability

The hydrogen maser, cesium beam standard, and OCXO, whose PM noise is shown in Table I and Fig. 1, are shown in the time domain in Table II and Fig. 2. Additionally, the frequency stability of one of the United States Naval Observatory's (USNO) rubidium fountains and that of an auxiliary output generator (AOG) are shown. It is good to have some reference tables and graphs like this to compare with new devices and requirements that one might have in the future. Understanding what is currently commercially available allows one to make sanity check judgments on new requirements and claims. A careful comparison of the PM

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noise and Allan Deviation for the various devices shown in Table I, Table II, Fig. 1, and Fig. 2 will help the reader to understand some of the advantages and disadvantages of each device. For instance, the OCXO has some of the best close to the carrier PM noise and modest 1-second frequency stability,

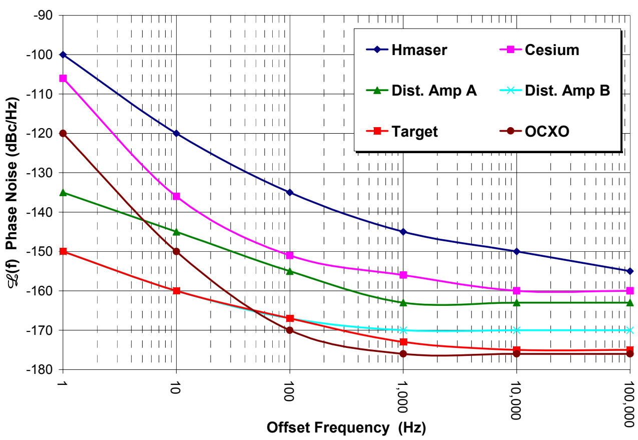

Fig. 1. Comparison of phase noise in various devices at 5 MHz

TABLE II
COMPARISON OF FREQUENCY STABILITY (ALLAN DEVIATION) IN VARIOUS DEVICES AT 5 MHZ ASSUMING A SYSTEM BANDWIDTH OF 1 MHZ

Averaging Time (s)	Hmaser $\sigma_y(\tau)$	Cesium $\sigma_y(\tau)$	OCXO $\sigma_y(\tau)$
1	2.0 E-13	5.0 E-12	1.0 E-11
10	5.0 E-14	3.5 E-12	2.0 E-12
100	1.3 E-14	8.5 E-13	1.0 E-12
1,000	3.2 E-15	2.7 E-13	5.0 E-12
10,000	3.0 E-15	8.5 E-14	5.0 E-11
100,000	3.0 E-15	2.7 E-14	5.0 E-10

Averaging Time (s)	Rb Fountain $\sigma_y(\tau)$	AOG Stability $\sigma_y(\tau)$	Target $\sigma_y(\tau)$
1	1.5 E-13	2.5 E-13	1.0 E-14
10	4.7 E-14	2.5 E-14	1.0 E-15
100	1.5 E-14	2.5 E-15	1.0 E-16
1,000	4.7 E-15	2.5 E-16	1.0 E-17
10,000	1.5 E-15	3.5 E-17	1.0 E-18
100,000	4.7 E-16	2.5 E-17	1.0 E-18

but does not have the best long-term stability. This is why one often uses an extremely low noise OCXO as a "clean-up" oscillator that is locked to an atomic standard to achieve the desired long-term frequency stability. Although phase noise and frequency stability typically are the most obvious make-or-break parameters, there are many more parameters and issues that need to be considered.

IV. AMPLIFIER COMPARISON – DISTRIBUTION AMPLIFIER A

Selecting the proper center (carrier) frequency, (υ_o), in one's RF string is very important and generally application specific. However, 5 MHz has been chosen for this paper as a matter of convenience and because it is one of the most frequently used

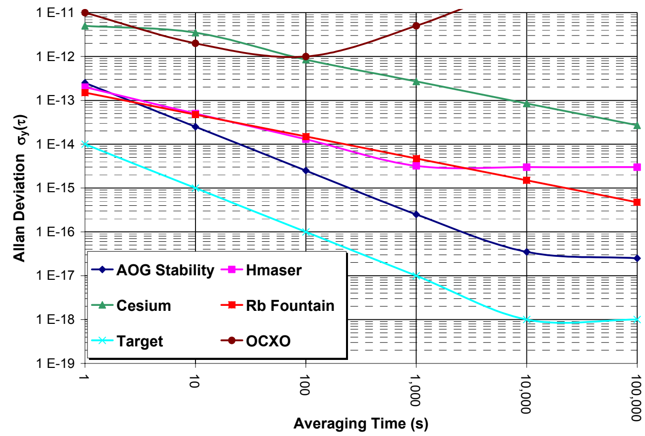

Fig. 2. Comparison of frequency stability in various devices at 5 MHz assuming a system bandwidth of 1 MHz

reference signals. Gain is another parameter that one may not have control over. A commercial distribution amplifier most likely is specified to have unity gain from the input to any given output. A stand-alone buffer amplifier may have some gain. One must verify that the PM noise measurements apply for the drive level intended in the final application. Amplifier noise figure specifications, which are derived from broadband small signal performance, have little correlation to PM noise performance under large signal conditions.[2] Although there may be no choice in center frequency and gain, the system bandwidth may be selectable. A quick survey of two different amplifiers in the next sections will help one to see the impact of phase stability, bandwidth, impedance matching and isolation.

Distribution Amplifier A is a mass-produced distribution amplifier that is sufficient for most applications, but may not be the best choice for the devices setout earlier in this paper.

Distribution Amplifier A:

- Center Frequency (υ_o) = 5 MHz
- Bandwidth (BW) = FH = 1 MHz
- Isolation = 100 dB
- Input Return Loss = 20 dB
- Output Return Loss = 20 dB
- Offset Frequency from the carrier = f
- $S_\phi(f) = \mathcal{L}(f) + 3$ dB

Assume:

- Source Return Loss = 10 dB
- Load Return Loss = 30 dB

STEP 1: EVALUATE THE PHASE NOISE IMPACT

The phase noise for this device was illustrated in Fig. 1. However, one must look at how this phase noise, along with system bandwidth, can impact the overall stability. The phase noise, which is given in the frequency domain, can be converted over to the time domain to view its equivalent impact.

Often data sheets report the single sideband phase noise of a single device, $\mathcal{L}(f)$. $S_\phi(f)$ is the phase noise of a single device at a given frequency offset, f, from the carrier taking into account the noise level of both sidebands. By multiplying by 2, or just adding 3 dB, one can convert from the single side band, single device, $\mathcal{L}(f)$ to the double side band, single device, $S_\phi(f)$. This in turn needs to be converted to the spectral density of fractional frequency fluctuations, $S_y(f)$, as a function of the fourier frequency, f,

$$S_y(f)=\frac{S_\phi(f)\cdot f^2}{\upsilon_o^2}. \tag{1}$$

Remember: f is the Fourier or offset frequency
υ_o is the carrier frequency (5 MHz).

The $\mathcal{L}(f)$ values for the first amplifier were taken through this process to generate $S_y(f)$. The results for Amplifier A are shown in Table III and illustrated in Fig. 3. There are two different slopes evident in Fig. 3. The place where the equivalent slope lines cross the 1 Hz axis is of particular interest. The slope of each segment is highlighted by the C4 and C5 lines where C4 and C5 correspond to the parameters in Equation 2.

TABLE III
SUMMARY OF $S_\phi(f)$ AND $S_y(f)$ VERSUS OFFSET FREQUENCY (f)

Offset Frequency (Hz)	Amplifier $\mathcal{L}(f)$ (dBc/Hz)	Amplifier $S_y(f)$
1	-135	2.5 E-27
10	-145	2.5 E-26
100	-155	2.5 E-25
1,000	-163	4.0 E-24
10,000	-163	4.0 E-22
100,000	-163	4.0 E-20

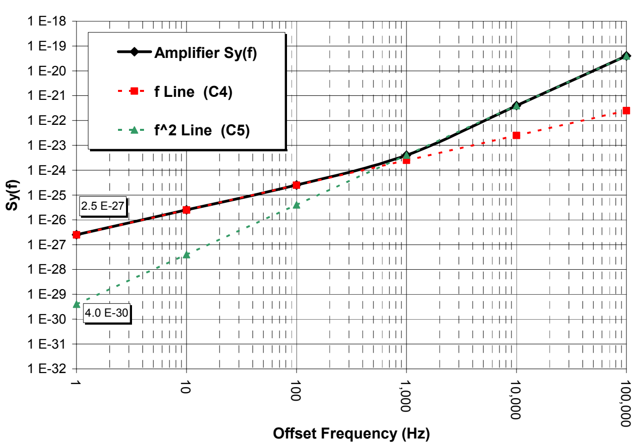

Fig. 3. Spectral density of fractional frequency fluctuations, $S_y(f)$, versus offset frequency, f, from the carrier.

$$S_y(f) \;=\; \frac{C_1}{f^2} \;+\; \frac{C_2}{f} \;+\; C_3 \;+\; C_4 f \;+\; C_5 f^2$$
$$S_y(f) = \begin{pmatrix}\text{Random}\\ \text{Walk}\end{pmatrix} + \begin{pmatrix}\text{Flicker}\\ \text{Freq.}\end{pmatrix} + \begin{pmatrix}\text{White}\\ \text{Freq.}\end{pmatrix} + \begin{pmatrix}\text{Flicker}\\ \text{Phase}\end{pmatrix} + \begin{pmatrix}\text{White}\\ \text{Phase}\end{pmatrix}. \tag{2}$$

Once the PM noise, $\mathcal{L}(f)$, has been broken down into the various coefficients that make up $S_y(f)$, one can compute the Allan deviation $\sigma_y(\tau)$ using Equation 3[3]

$$\sigma_y(\tau) = \frac{2}{(\pi\tau)^2}\int_0^\infty \frac{S_y(f)\sin^4(\pi f\tau)\,df}{f^2}. \tag{3}$$

This integration depends strongly on the high frequency dependence of the PM noise. For simplicity we assume that there is a system bandwidth f_h, beyond which the PM noise is negligible. This allows one to simply terminate the integration of Equation 3 at f_h. The integration is still moderately difficult due to the oscillating nature of the integrand. One of many approaches is to use a program called SigInt to determine the equivalent values of the Allan Deviation, $\sigma_y(\tau)$.[4]

The results in Table IV and Fig. 4 show that the program was executed for a bandwidth of 20 MHz, 1 MHz, and 10 kHz. As the system bandwidth is narrowed, the impact of the wide-band PM noise is lessened and the close in phase noise starts to dominate.

TABLE IV
SUMMARIZED DATA FOR AMPLIFIER A AND USNO'S Rb FOUNTAIN

Averaging Time (s)	$\sigma_y(\tau)$ from $\mathcal{L}(f)$ FH = 20 MHz	$\sigma_y(\tau)$ from $\mathcal{L}(f)$ FH = 1 MHz	$\sigma_y(\tau)$ from $\mathcal{L}(f)$ FH = 10 kHz	Rb Fountain (FH = 1 MHz)
0.001	2.5 E-09	5.5 E-10	6.2 E-11	
0.01	2.5 E-10	5.5 E-11	6.6 E-12	
0.1	2.5 E-11	5.5 E-12	6.9 E-13	
1	2.5 E-12	5.5 E-13	7.2 E-14	1.5 E-13
10	2.5 E-13	5.5 E-14	7.5 E-15	4.7 E-14
100	2.5 E-14	5.5 E-15	7.8 E-16	1.5 E-14
1,000	2.5 E-15	5.6 E-16	8.1 E-17	4.7 E-15
10,000	2.5 E-16	5.6 E-17	8.3 E-18	1.5 E-15
100,000	2.5 E-17	5.6 E-18	8.6 E-19	4.7 E-16
1,000,000	2.5 E-18	5.6 E-19	8.8 E-20	1.5 E-16

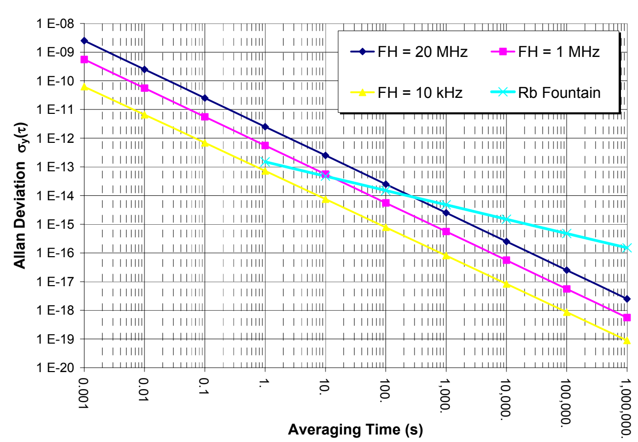

Fig. 4. Summarized data for Amplifier A and USNO's Rb Fountain

STEP 2: EVALUATE THE SYSTEM MATCH:

Any mismatch in a system will cause the signal to bounce back and forth between source and load causing interference resulting in a phase shift, inter-modulation products, and other interactions that can add noise to the system. These extra signals may also pull frequency sources or other tuned components and saturate amplifiers. A typical system might look something like Fig. 5. Each connector interface has the potential to add a mismatch. Each cable run or attenuation section can help to buffer the problems created by a mismatch by reducing the interference signal coming back through the system. Any component in the system can add a phase shift and/or mismatch if they are sensitive to temperature changes. The phase shift of the signal from ideal due to mismatch is given by Equation 4 as a function of source output mismatch, ρ_o, and load input mismatch, ρ_i, and the phase of the interfering terms ϕ.

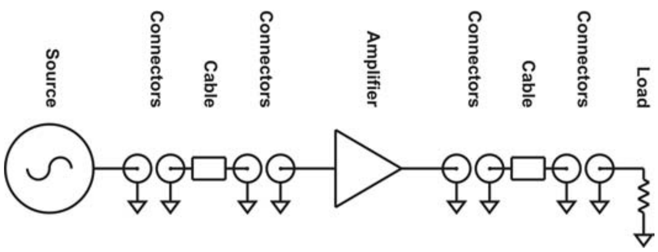

Fig. 7. Typical System Configuration

$$\text{Signal phase shift} = \left(\frac{\rho_i \rho_o \sin(\phi)}{\eta} \right) \text{ in radians} \quad (4)$$

η = round trip attenuation of the reflected signal
ϕ = angle of the twice reflected wave at the load.

In reality each component and interface may change its phase and match due to time and environmental changes. It is in fact how these things change and not actually the absolute values that matter the most. It is the change in phase with time and the environment that can result in serious limitations in the long term frequency stability of a system. Equation 5 illustrates an approximate understanding of how a system's stability may be impacted.

$$\sigma_y(\tau) = \left(\frac{1}{2\pi \upsilon_o \tau} \right) \left(\frac{\rho_i \rho_o \sin(\phi)}{\eta} \right)_{\text{Change}} . \quad (5)$$

Note that a considerable reduction in this effect can be obtained by making the cable length close to an odd multiple of one-half the signal wavelength (½λ) in the cable. This, however, is a narrow band solution and unless the system is to be used at only one frequency and the cable phase shift is carefully calibrated, it is best for system modeling to assume the worst case with $\sin\phi = 1$.

The system with the best performance would be one with a perfect match from the source to the input of the amplifier and a perfect match from the output of the amplifier to the final load. Any loss, like a 3 dB pad or cable losses, added to the input or output of the amplifier will attenuate the roundtrip reflected signal by twice the loss, i.e. 6 dB ($\eta = 2$). Thus any attenuation in the system increases the value of η, thereby improving the effectiveness of the segments input and output voltage standing wave ration (VSWR) at the cost of signal loss.

To evaluate Amplifier A in the Fig. 5 system one must first find each of the input and output return loss parameters and convert them to a linear expression for ρ_o. If the datasheet expresses the terms in logarithmic (dB) the return loss (RL) value must be converted back to linear terms using Equation 6.

$$\text{Return loss:} \quad \rho_o = \left| 10^{\frac{RL}{-20}} \right| . \quad (6)$$

If RL is given as 20 dB (remember if S_{11} is given as -20 dB then the loss is 20 dB or Return Loss (RL) is 20 dB), ρ_o is then 0.10 in linear terms. If VSWR is specified then one needs to convert to ρ_o using Equation 7.

$$\rho_o = \left[\frac{(\text{VSWR - 1})}{(\text{VSWR + 1})} \right] . \quad (7)$$

Using the values from the datasheet for Amplifier A:

Center Frequency	5 MHz	$\upsilon_o = 5.0$ E6
Amp. A Input Return Loss	20 dB	$\rho_i = 0.1$
Amp. A Output Return Loss	20 dB	$\rho_o = 0.1$
Source Return Loss	10 dB	$\rho_s = 0.32$
Load Return Loss	30 dB	$\rho_L = 0.032$
Assume no Insertion Loss	0 dB	$\eta = 1$
Assume Worse Case	$\phi = \pi/2$	$\sin\phi = 1$

The input and output return loss of the amplifier as well as that of the source and load as illustrated in Fig. 5 must be considered when evaluating Equation 5. The phase shift of the ρ_o parameters is expressed in Equation 8.

$$\text{Phase Shift} = \rho_s \rho_i + \rho_o \rho_L = \quad (8)$$
$$= (0.032) + (0.0032) = 0.0352 \text{ rad.}$$

A phase shift through the system of 0.0352 radians does not seem like very much, however a small change in the overall phase shift can cause a big jump in the frequency instability. Assume that the system illustrated in Fig. 5 were to experience a change in phase shift of only 0.1%, over a 1,000 second period, due to some environmental change, such as an air-conditioner turning on. Taking the results from Equation 8 and inserting them in Equation 5 and evaluating the results for a change of only 0.1% over 1000 seconds produces the example shown in Equation 9.

$$\sigma_y(\tau) = \left(\frac{1}{2\pi (5 \times 10^6) 10^3} \right) \left(\frac{(0.0352)(1)}{(1)} \right) (0.001) = 1.2 \times 10^{-15} . \quad (9)$$

The change of only 0.1% created a $1.2{\times}10^{-15}$ shift at 1,000 seconds, which is close to the performance of a hydrogen maser at 1,000 seconds and a factor of 120 higher than the target goal shown in Table II.

STEP 3: DETERMINE ISOLATION

Finite front-to-back and channel-to-channel isolation is similar to the impedance mismatch in that it leads to a phase shift of the signal that can change with the environment. This can cause frequency pulling in sources, intermod products, and other trash in a system. Good front-to-back isolation prevents a change in the output load on one channel from changing the phase of the input signal, which is then transmitted to all the other channels on the distribution amplifier, or in some cases, can pull the frequency of the source. Such changes in load most commonly occur when one disconnects the load on a channel to change the measurement configuration. One also needs to have good channel-to-channel isolation because a signal on a parallel channel that is close in frequency to the good signal can cause a phase shift that varies with time.

The worst case isolation of 100 dB for Amplifier A roughly produces the phase shift impact shown in Equation 10.

$$\text{Phase shift } \theta \approx \frac{1}{\sqrt{isolation}} = 10^{-5} \text{ rad.} \qquad (10)$$

This is equivalent to a worst case frequency shift shown in Equation 11.

$$\sigma_y(\tau) = \frac{\theta}{2\pi\nu_o\tau} = \frac{10^{-5}}{2\pi\left(5\times10^{6}\right)\tau} = \frac{3.2\times10^{-13}}{\tau}. \qquad (11)$$

This scenario provides a worst case impact that is on the order of 32 times noisier than the target goals listed in Table II.

STEP 4: PERFORMANCE ROLL-UP

The impact of the change in phase shift across the system due to the Return Loss as well as the worst case isolation of the system can be related as shown in Equation 12. Together these parameters can impact the total system performance. Small changes in the environment over time and other effects such as ageing and internal heating can contribute significant changes in the system stability.

$$\sigma_y(\tau) = \left(\frac{1}{2\pi\upsilon_o\tau}\right)\left[\left(\frac{\rho_i\rho_o\sin\phi}{\eta}\right)_{\text{change}} + \frac{1}{\sqrt{\text{iso}}}\right]. \qquad (12)$$

V. AMPLIFIER COMPARISON – DISTRIBUTION AMPLIFIER B

Following the same sequence as was done for Amplifier A, one can determine the $\sigma_y(\tau)$ from the $\mathscr{L}(f)$ as summarized in Table VI and Fig 9 for Amplifier B.

TABLE VI
SUMMARIZED DATA FOR AMPLIFIER B AND USNO'S RB FOUNTAIN

Averaging Time (s)	$\sigma_y(\tau)$ from $\mathscr{L}(f)$ FH = 20 MHz	$\sigma_y(\tau)$ from $\mathscr{L}(f)$ FH = 1 MHz	$\sigma_y(\tau)$ from $\mathscr{L}(f)$ FH = 10 kHz	Rb Fountain (FH = 1 MHz)
0.001	1.1 E-09	2.5 E-10	2.6 E-11	
0.01	1.1 E-10	2.5 E-11	2.6 E-12	
0.1	1.1 E-11	2.5 E-12	2.6 E-13	
1	1.1 E-12	2.5 E-13	2.6 E-14	1.5 E-13
10	1.1 E-13	2.5 E-14	2.6 E-15	4.7 E-14
100	1.1 E-14	2.5 E-15	2.7 E-16	1.5 E-14
1,000	1.1 E-15	2.5 E-16	2.7 E-17	4.7 E-15
10,000	1.1 E-16	2.5 E-17	2.7 E-18	1.5 E-15
100,000	1.1 E-17	2.5 E-18	2.7 E-19	4.7 E-16
1,000,000	1.1 E-18	2.5 E-19	2.8 E-20	1.5 E-16

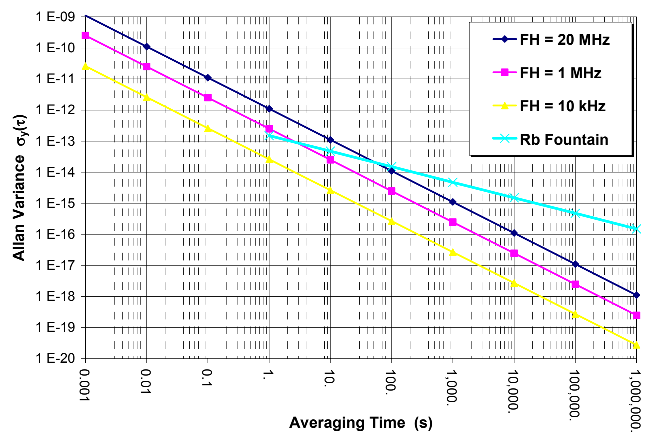

Fig. 9. Summarized data for Amplifier B and USNO's Rb Fountain

Using the following specification for Amplifier B one can determine the impact of the increased isolation and improved impedance match.

Distribution Amplifier B:

- Center Frequency (υ_o) = 5 MHz
- Bandwidth (BW) = FH = 1 MHz
- Isolation = 120 dB
- Input RL = 35 dB
- Output RL = 35 dB

Assume:

- Source Return Loss = 10 dB
- Load Return Loss = 30 dB

Using these parameters along with Equation 8 and a 0.1% change in phase shift over 1000s yields a worst case limit on $\sigma_y(\tau)$ shown in Equation 13.

$$\sigma_y(\tau) = \left(\frac{1}{2\pi\left(5\times10^{6}\right)\left(10^{3}\right)}\right)\left(\frac{(0.0064)(1)}{(1)}\right)(0.001) = 2\times10^{-16}. \qquad (13)$$

The worst case isolation of 120 dB for Amplifier A roughly produces a limit on $\sigma_y(\tau)$ in Equation 14.

$$\sigma_y(\tau) = \frac{\theta}{2\pi\nu_o\tau} = \frac{10^{-6}}{2\pi\left(5\times10^{6}\right)\tau} = \frac{3.2\times10^{-14}}{\tau}. \qquad (14)$$

This scenario provides a worst case impact that is of order of 10 times better than Amplifier A and much closer to the target goals of Table II.

VI. Temperature and Delay

It is important to carefully review the target operating environment in which a given system will reside. Sometimes it is possible to establish an optimal ambient temperature region and a survival range. One often finds that there is a larger temperature range over which equipment will survive and produce reasonable results even though the optimal performance occurs over a smaller, but more typical environment. Manufacturers will specify the phase change or impact of changing the temperature over a large range, but that doesn't correctly capture the best performance over a narrow temperature region at a particular absolute operating point. It is not uncommon to get substantially better performance around a particular set point, but find a steep change at a different temperature.

The designer of electronic hardware needs to carefully evaluate the operating temperature of the components including the power supply. Typically hardware operating at higher temperatures is more susceptible to thermal run-away and accelerated aging. The long term reliability of hardware running hot is often not acceptable.

VII. Electrical Mechanical Packaging

Although the RF performance of an amplifier and its impact on overall system performance is crucial, one must not forget the electrical mechanical packaging. Units that have been designed well are rugged enough for their application environment, easy to service, and generally modular. For rack mount or bench top units, it is nice to have more than one way to provide power. Some of the distribution amplifiers have AC and / or DC power slices that plug in and latch in place without using any tools. Since power supplies are typically the most likely portion of a system that will age and go bad, one needs to have some way of replacing or repairing the power supply. Systems that allow one to choose between having any combination of a pair of AC or DC supplies allows one to have some redundancy built into the system. Solutions that require a lot of disassembly, tools, or removal of extra panels are not nearly as easy to work with and sometimes cannot be serviced while the overall unit is mounted in place.

The input, output, and supply connectors are also important. Standard IEC connectors for the AC inputs allows one to change the cord to accommodate different wall outlets. Good threaded connectors for the input and outputs provide much more reliable and phase stable connections. Analysis shown in this paper illustrate how good impedance matches and stable connections are crucial for maintaining good signal stability. Connectors such as SMA, TNC, or Type N are much better choices than something like BNC.

VIII. Construction and Quality Control

A brand new amplifier may work initially and look nice, but will it last? The key to good reliability lies in the construction of the equipment from the ground up. A vendor must make sure they are procuring good parts, maintaining a clean inventory system, are protecting against ESD problems, and appropriately training their staff. Surface mount capacitors in particular are very sensitive to thermal gradient stresses that can occur during soldering. With all of the changes in the cleaning solutions, solder, and techniques, it is important that the vendor pay close attention to the details. Too often vendors try to inspect quality into a product right before it goes out the door. This is not the cost effective or useful approach.

IX. Conclusion

This paper looked carefully at several different types of sources and two different distribution amplifiers to review how the phase noise and Allan deviation compared. A technique to compare phase noise to Allan deviation was demonstrated. The impact of isolation and return loss was also compared between the two amplifiers. Finally power requirements and electromechanical packaging requirements as well as assembly practices were discussed. These issues roll up to a review process that one must perform when looking at distribution amplifiers to determine if they fit the desired target application.

X. References

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