Observatory 10 MHz Reference Distribution Amplifier

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1. Introduction

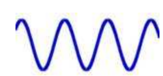
A reference signal is used in an observatory or on a test bench to *syntonize* receivers and test equipment to a higher-accuracy frequency source so that their measurement accuracy is improved. The reference usually is traceable to a national frequency service such as that provided by the National Institute of Standards and Technology, NIST, in the United States. Note that I use the term *syntonize* (for frequency or tone) whereas much more common, but technically incorrect, usage is *synchronize* (for time or clock). This point is really not important if we understand that the concepts discussed here apply to frequency and not time.

Glossary of Abbreviations:

GNSS:	Global Navigation Satellite System
GPS:	Global Positioning System
NIST:	National Institute of Standards and Technology
OCXO:	Oven-Controlled Crystal Oscillator
PCB:	Printed Circuit Board
SMD:	Surface-Mount Device
TCXO:	Temperature-Compensated Crystal Oscillator
TTL:	Transistor-Transistor Logic
USD:	United States Dollar

In many systems the reference signal is derived from the Global Positioning System (GPS) or more generically from a global navigation satellite system (GNSS) in conjunction with a disciplined oscillator. The signal also may be derived directly from a rubidium or cesium beam *atomic frequency standard*. Standalone temperature-compensated crystal oscillators (TCXO) and oven-controlled crystal oscillators (OCXO) sometimes are used where long-term frequency accuracy requirements are not too demanding. Although the TCXO and OCXO do not provide good long-term accuracy due to aging and other drift, they do provide far superior short-term stability. It is for this reason they always are embedded in very high-accuracy frequency and time systems including GNSS and atomic frequency sources.

2. Applications Overview



A 10 MHz sinewave probably is the most common reference frequency in use. Other common frequencies are 1, 2 and 5 MHz. In industrial applications, particularly the telecommunications industry, many other frequencies and signals are used, but they typically are ultimately derived from a 10 MHz source. Most analog receivers used by amateur radio astronomers must be modified to connect their internal oscillators to an external reference source but many modern software defined radio (SDR) receivers have built-in or optional provisions for that purpose (figure 1). A few examples of SDR receivers that have these provisions are the SDRPlay RSP2 and RSP2 Pro, AirSpy and the RFSpace NetSDR and SDR-IP. Other popular SDR receivers such as the RTL-SDR types must be modified to accept an external reference source. The Callisto instrument used in the e-Callisto solar radio spectrometer network may be connected to an external 1 MHz TTL level reference source.

Test equipment typically connected to a reference source includes frequency counters, spectrum analyzers, AF and RF signal generators, function and arbitrary waveform generators and vector network analyzers – any device whose measurements depend in some way on its frequency accuracy. The connection usually is made through a connector on the rear panel (figure 2). Even many low-cost frequency measuring and generating test sets have an external reference input to improve their frequency accuracy.

Connecting one piece of equipment to a reference source is simple but it becomes more complicated when multiple connections are needed, mainly because of the need for power level control but also to prevent undesired interaction between the equipment. The remainder of this paper discusses the basic characteristics of a 10 MHz reference source, distribution techniques and two inexpensive distribution amplifiers, each of which may be used to connect up to eight loads to one source. Included are amplitude, spectrum and phase measurements and some comments about daily operation.

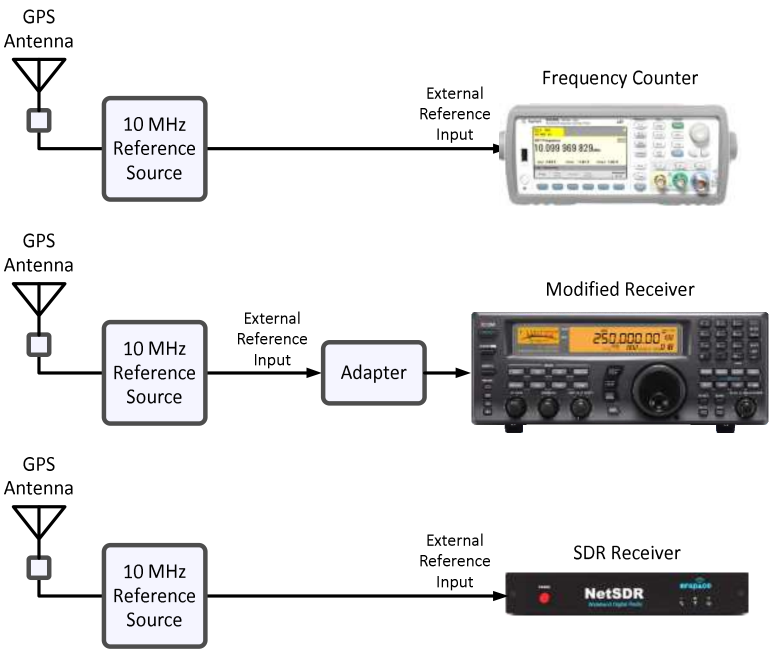


Figure 1 ~ Upper: To improve their frequency accuracy, most test equipment, such as the frequency counter shown here, have provisions for connecting an external reference source, usually through a BNC connector on the rear panel. Middle: Many superheterodyne and direct conversion receivers used by amateur radio astronomers do not have reference inputs and require modifications or an adapter, such as a frequency synthesizer, for connection and translation to the receiver oscillator frequency. Lower: Many modern software defined radio (SDR) receivers have external reference inputs. The RFSpace NetSDR shown here uses 10 MHz, but other SDR receivers may use odd external reference input frequencies such as 24 MHz for the SDRPlay RSP2 Pro. In the latter situation, a synthesizer can be used to derive the needed frequency from a 10 MHz source.

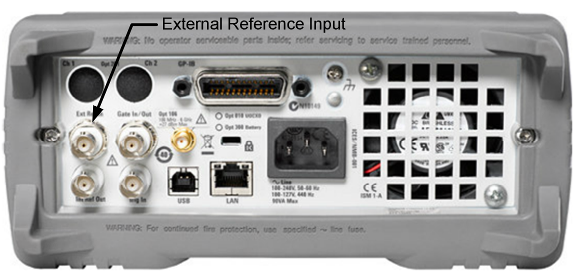


Figure 2 ~ Test equipment usually have a BNC-F connector on the rear panel for connection to an external reference source. The 10 MHz reference input on this Keysight 53220A frequency counter is labeled *Ext Ref* and is the upper connector on the far left. This frequency counter was used for the phase measurements described later.

3. 10 MHz Reference Source Characteristics

The 10 MHz reference is a sinewave RF signal most often having 50 ohms impedance and a power level of +11 to +15 dBm at the source, corresponding to a nominal voltage range 0.8 to 1.2 Vrms. The mid-range voltage is 1.0 Vrms into a 50 ohm load. Cables to equipment introduce losses, which usually are designed to be no more than about 3 dB (equivalent to about 64 m of RG-58 or 107 m of LMR-240 coaxial cable). It should be noted that some connected equipment may require intentional reduction of the input signal level. For example, if the input requires 0.5 Vrms (+7 dBm) the reference source power would need to be reduced 6 dB.

The frequency accuracy of the reference source generally should be at least an order of magnitude better than the internal oscillator in the connected equipment and usually is much better. High-quality test equipment will not accept an external source that is not at least as good as its internal oscillator.

The output signal from professional reference sources is a clean sinewave (figure 3 and 4) but non-professional sources may be heavily distorted or a quasi-square wave with high harmonic content. In this case, the end equipment must have an intermediate or input filter or a means of selecting the desired frequency from the harmonics.

In some industry applications, the phase difference between the outputs and between the outputs and input is an important parameter and normally is specified to be below some value. The actual value will depend on the standards that apply to the application, but for most amateur radio astronomy a phase difference ≤ 5° probably is adequate or more likely not important at all. Phase differences often are reduced by adjusting cable lengths.

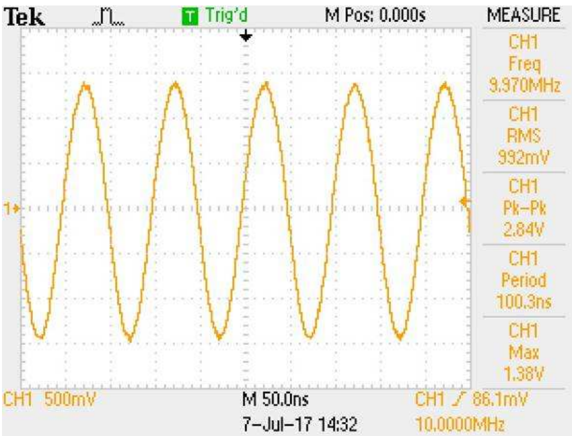


Figure 3 ~ Oscilloscope screenshot showing the waveform of the 10 MHz reference output from a Symmetricom TimeSource TS-2700 primary reference source. This measurement was taken with a 50 ohm termination at the end of a 3 m long RG-58 coaxial cable. The voltage is very close to 1.0 Vrms and the sinewave is quite clean. A Tektronix TDS2022B oscilloscope was used for these measurements. The vertical channels use 8-bit analog-digital converters (digitizers) so the sinewave appears jagged when scaled up. This scope's frequency measuring function is not particularly accurate, in this case indicating 9.970 MHz for the 10 MHz source.

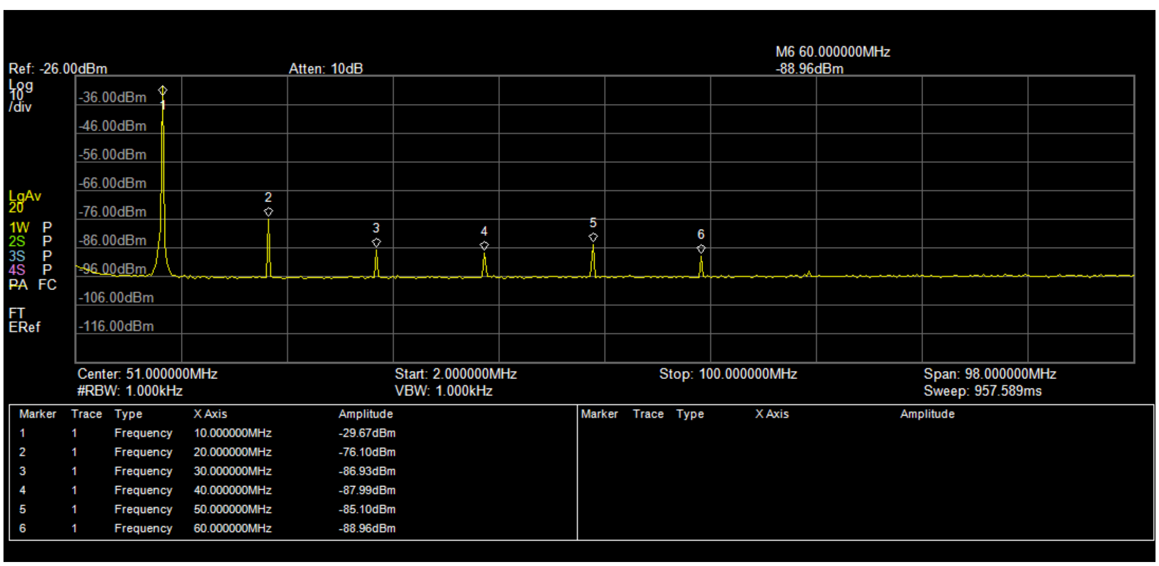


Figure 4 ~ Spectrum of the TS-2700 reference source. The first seven harmonics are visible. The 2nd harmonic at 20 MHz is about 46 dB below the 10 MHz fundamental.

4. Distribution Methods

Signal level reduction, impedance mismatch and undesired interaction caused by reflections can result if the reference signal is simply bridged to more than one piece of equipment. Rather than bridging, a passive splitter or a reference distribution amplifier is used to isolate the equipment from each other (figure 5).

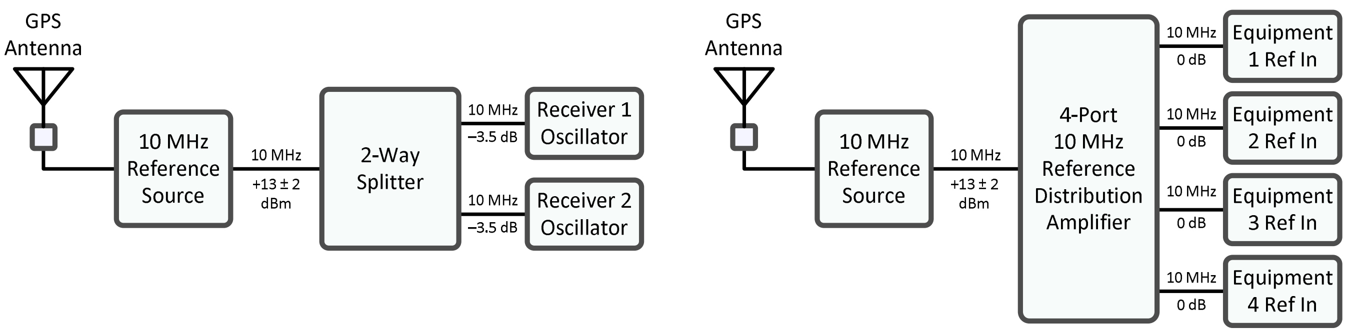


Figure 5 ~ Block diagrams of typical 10 MHz reference setups based on GPS-derived sources. Left: A 2-way splitter is used to connect the oscillators in two receivers to the 10 MHz reference source. The splitter reduces the signal level on each port by 3.5 to 4.5 dB, which may result in the signal being too low for some end equipment. Right: A distribution amplifier provides a lossless connection between the reference source and end equipment and provides isolation. In this example, a 4-port amplifier is used to connect the source to four pieces of test equipment. Any unused ports on a distribution amplifier should be terminated in a 50 ohm resistance termination.

A passive splitter introduces splitting losses that depend on the number of ports: 3.5 to 4.5 dB for 2-way; 6.5 to 7.5 dB for 4-way; and 9.5 to 10.5 dB for 8-way splitters. Port isolation typically is in the range 15 to 30 dB for transformer-type splitters. Resistive splitters are avoided because of their relatively high insertion loss and low isolation. A passive splitter may not work with some equipment because of the reduced signal level. In this case, a reference distribution amplifier is needed. A properly designed amplifier provides the necessary impedance match, isolation between ports and signal level control, and it usually includes filters to ensure a clean output signal.

I use a 10 MHz reference signal derived from a GPS disciplined rubidium oscillator in conjunction with an OCXO. In my lab this may be connected to several different pieces of lab test equipment and SDR receivers during testing and evaluation. I previously used a 2-way passive splitter and manually unplugged and plugged the equipment as required. I sometimes ran into problems when more than two loads needed connection and eventually tired of the inconveniences, so I decided to use an 8-channel distribution amplifier.

I acquired two amplifiers, one sold at the website HUPRF.com; delivered cost was about 135 USD in 2015 but it apparently is no longer available. The other is available at the Chinese website BG7TBL.taobao.com but is more conveniently purchased through eBay; delivered cost also was about 135 USD in early 2016 when purchased but is about 25% lower as of this writing in mid-2017. Both units are described below. BG7TBL also has a GPS disciplined 10 MHz OCXO that is available through eBay. I plan to compare the GPS unit to another inexpensive frequency source and to my lab frequency sources in a future paper.

5. G4HUPRF Distribution Amplifier

Description: The G4HUPRF 8-channel 10 MHz Distribution Amplifier is sold as a kit (figure 6) or fully built. I ordered the kit, which I later regretted. The assembly instructions were difficult to use and the PCB design led to assembly problems, but the amplifier did work after I spent a full but frustrating day building it. While most components are surface-mount devices (SMD) the input and output BNC connectors and a few other components are through-hole parts. Unfortunately, the annular copper rings on the component holes are too thin and difficult to solder even with a 0.2 mm conical soldering iron tip. This is especially true of the ground pads. Thermal ground pads are not used, making adequate heat transfer from a small soldering iron tip very hard to achieve.

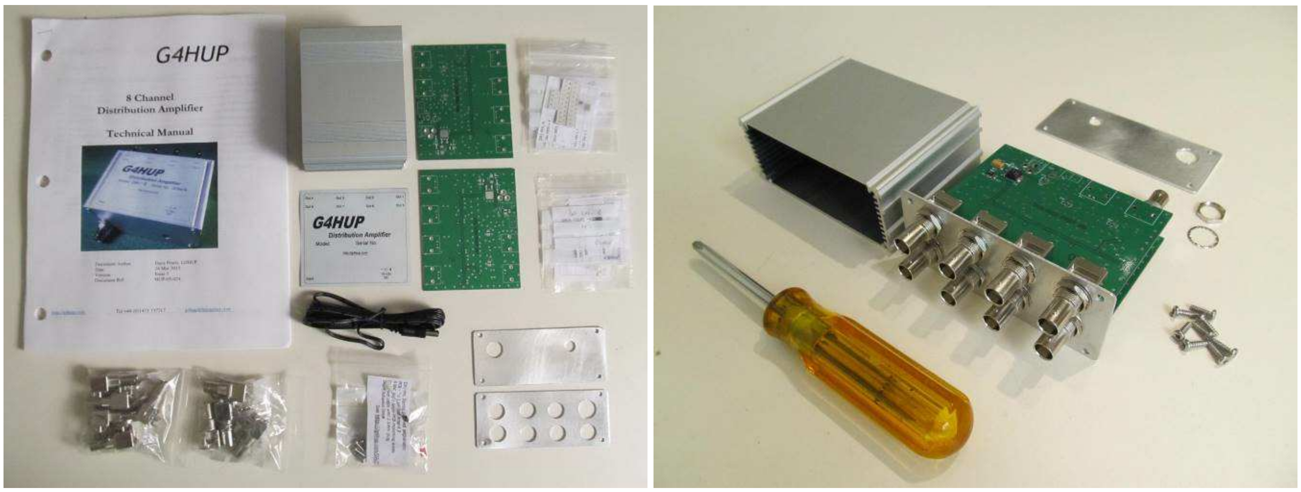


Figure 6 ~ G4HUPRF distribution amplifier kit. Left: All parts were bagged and properly labeled. The two printed circuit boards (green panels on the right) are identical but the addition of parts is slightly different. The front and rear panels, shown lower-right, are supplied blank and I cut all holes before this picture was taken. Right: After building the PCBs, the eight BNC-F connectors are mounted to the rear panel. At this point, the assembly is ready to be inserted into the rails inside the extruded aluminum enclosure at upper-left. The front panel is then attached and the unit is ready for testing. The enclosure dimensions are 109 W x 80 L x 45.5 H mm not including the connectors.

Another difficulty is the BGA616 monolithic microwave integrated circuit, or MMIC, amplifiers, which are used to equalize levels on each output. These are tiny SMDs (2 mm wide) with very small gull-wing leads on an SOT343 package (right). Unfortunately, the PCB pads are sized for reflow assembly and are too small to hand-solder without great difficulty. The PCB pads should have been made larger at least in the kit version. There are eight amplifiers, and I was very surprised after finishing assembly that all eight channels functioned properly without having to do any rework. Oddly, the SMD resistors, capacitors and inductors have larger-than-required pads and were quite easy to hand-solder, requiring only a few minutes for all those parts. I could have used my own small reflow oven but I had no current solder paste. If the fully assembled version of this amplifier is purchased, all the SMDs are pre-installed, thus avoiding these problems.

The printed circuit boards and technical manuals are “universal” and designed for multiple applications. There are 4- and 8-channel versions and these may be built for 10 MHz reference distribution or for more general RF applications with various filters and attenuators. The 8-channel version uses two identical 4-channel PCBs and the 8-channel technical manual refers to the 4-channel manual for some of the component installation. The parts supplied and their placements depend on the application and version. The technical manuals attempt to cover all situations, but there are many errors and conflicts in the information provided. Having to switch back and forth between the 8-channel and 4-channel manual and resolve the conflicts caused a lot of confusion and wasted a lot of time. I studied and reread the manual several times but still had problems to correct after assembly (a missing jumper and one resistor in the wrong location). I could have built the distribution amplifier in about 1/3 the time if it had a better manual.

The 10 MHz reference input connector and dc coaxial power jack are on the front panel and all outputs are on the rear panel. The output connectors are mounted close together and quite crowded when connecting and disconnecting cables at adjacent positions. An adhesive label is provided that shows the channel numbers. However, the label actually fits only on the bottom of the enclosure so the amplifier sits on the bench upside down, a small point because its position does not really matter. This distribution amplifier does not have an On-Off switch or any status or power indicating LEDs. Power is connected through a 2.1 x 5.5 mm coaxial power jack (center positive), and the specified input voltage range is 10 to 15 Vdc. The measured current draw at 12.0 Vdc input is approximately 560 mA. One of the reasons for the relatively high current is that each output amplifier is biased with 60 mA operating current, and there are eight of them. The enclosure runs warm but not hot.

<u>G4HUPRF Performance Measurements</u>: The outputs of the G4HUPRF distribution amplifier were measured using a Tektronix TDS2022B oscilloscope and Agilent N9342C handheld spectrum analyzer (HSA). The oscilloscope trace indicates a sinewave with no obvious distortion (figure 7). The output voltage is slightly under the minimum expected value for a reference source but within the unit's specifications listed in the technical manual. To protect the spectrum analyzer, I used a 30 dB attenuator on the distribution amplifier output. I did not offset the display; therefore, the measured power levels indicate 30 dB lower than actual (figure 8). For these measurements, the spectrum analyzer external reference input was connected to one of amplifier outputs (indicated on the left side of the screen by the notation *ERef*). When viewed over a narrow frequency range, 9.6 to 10.4 MHz, the spectrum is as expected. When viewed over a wider range, 2 to 100 MHz, which covers the first ten harmonics, some harmonic distortion becomes apparent (figure 9). The 2nd harmonic, 20 MHz, is only 27 dB below the 10 MHz fundamental, indicating that lowpass filters on each output rather than just on the input could improve the harmonic distortion. Nevertheless, the outputs probably are adequate for everything but the most demanding applications.

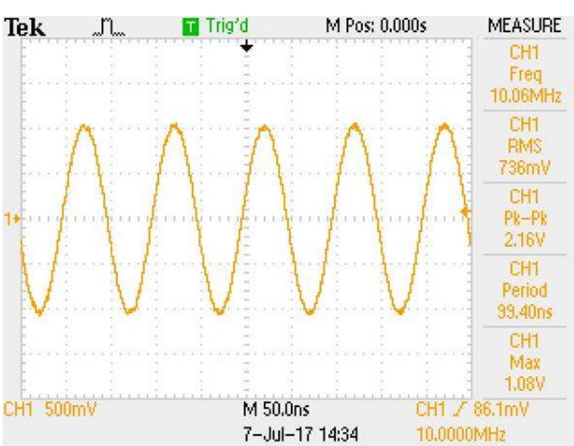


Figure 7 ~ Oscilloscope screenshot of the waveform from the G4HUPRF distribution amplifier. Note that the output is about 0.74 Vrms, slightly below what is usually considered the acceptable range at the output of a 10 MHz reference. The output was terminated with 50 ohms for this measurement.

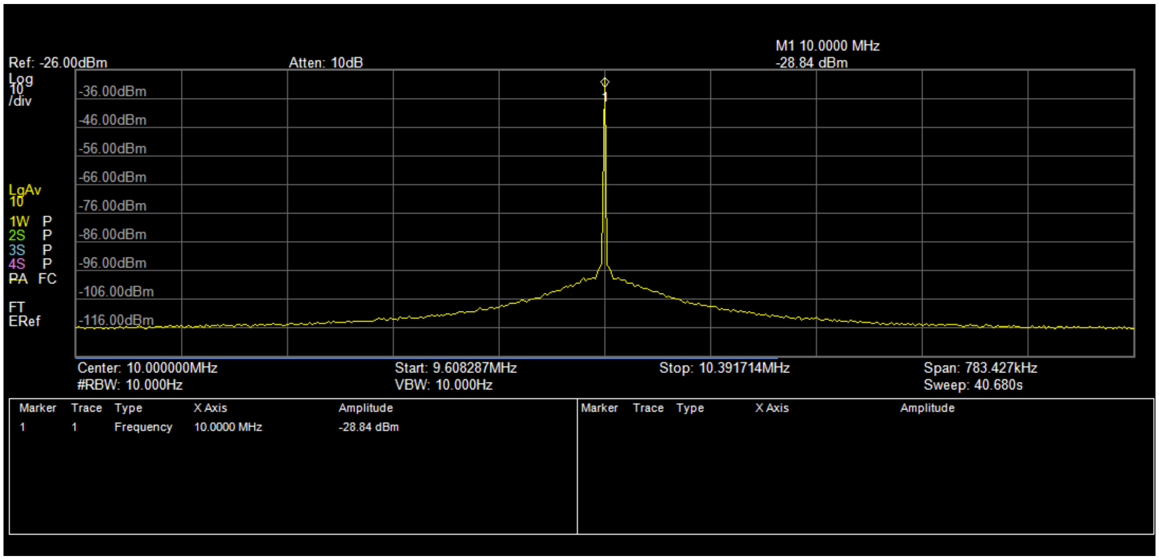


Figure 8 ~ Narrow spectrum view of the 10 MHz reference output from one of the channels of the G4HUPRF amplifier. The span shown here is about 783 kHz, which resulted from using the analyzer *Autotune* function.

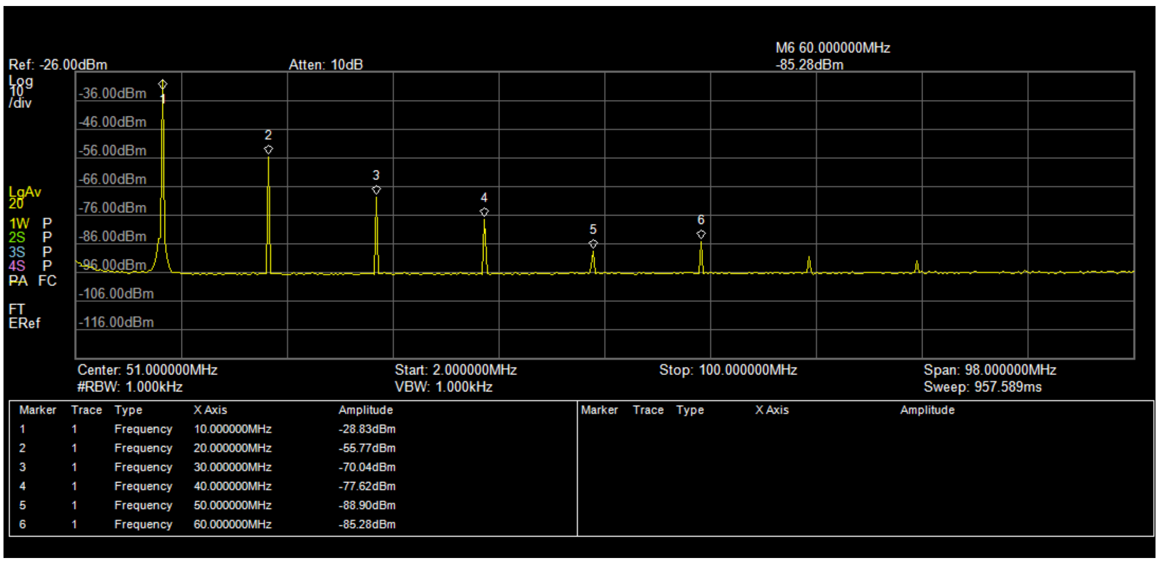


Figure 9 ~ Wider spectrum view of the same output as in the previous figure. At least eight harmonics are visible. The 2nd harmonic is about 27 dB below the fundamental.

The G4HUPRF technical manual specifies ≤ 3° phase difference between channels. Assuming phase delays are primarily due to the PCB trace lengths and the velocity of propagation on FR4 printed circuit board material is 0.5 times the propagation velocity in a vacuum, the wavelength of a 10 MHz signal on the PCB is 15 m. A phase difference of 3° would require a trace length difference of (3° x 15 m/360° =) 0.125 m, or 125 mm. The physical layouts for each channel are symmetrical and have close to the same lengths, so as a first order approximation the 3° requirement should be achievable.

I used a Keysight 53220A frequency counter for measuring the absolute phase differences between the amplifier's input and an output and between two output channels (table 1). This counter has two 350 MHz input channels (plus I have an optional 6 GHz input channel) and measures phase with 0.001° resolution. I used two LMR-240 cables of equal physical length (about 0.9 m). To measure their phase length difference, I compared each one to an arbitrary reference cable using a passive 2-way splitter. These measurements showed a difference of 0.03°, which is included in the measurements.

Table 1 ~ G4HUPRF phase difference measurements

Measurement	Phase (|°|)
Input – Channel 1 (A)	2.7
Channel 1 (A) – Channel 2 (A)	0.08

6. BG7TBL Distribution Amplifier

Description: The BG7TBL 8-channel distribution amplifier is fully assembled and ready to use (figure 10). Although its front panel is marked “10 MHz OCXO Frequency Standard – 10 MHz Distribution Amplifier” the one I purchased did not have the OCXO installed (a version is available with the oscillator). The enclosure uses an extruded aluminum body. The front panel is made from what appears to be single-sided FR4 PCB material with a solid tinned-copper back in direct contact with the enclosure body. The rear panel is sheet aluminum.

Figure 10 ~ Two views of the BG7TBL distribution amplifier. Seven of the eight output connectors are covered with rubber protective caps. The input from the reference source is on the upper-right of the front panel. Enclosure dimensions are 100 W x 103 L x 55 H mm not including connectors

A nice feature of this distribution amplifier is the set of three LEDs labeled with a silkscreen *PWR*, *EXT 10M* and *ERROR*. The EXT 10M LED indicates an active input and ERROR indicates inactive input. These would appear to be redundant, but the ERROR indicator could be an *either-or* indicator when an OCXO is installed. The front panel also has a hole to access a trimmer resistor labeled *F, ADJ*, which does nothing in the standalone amplifier but probably is used to trim the frequency when an OCXO is equipped. The unit has no On-Off switch.

The PCB is well-designed, well-marked and well-made. The PCB assembly appears to have been made using pick-place machinery and reflow soldering. All surface mounted components are on the bottom of the board. A separate amplifier integrated circuit is used on each output channel (I did not attempt to identify the brand or type of IC).

The 10 MHz reference input and all outputs of the BG7TBL unit are through closely spaced BNC-F connectors and are crowded similar to the G4HUPRF amplifier. All connections including power are on the front panel. Power is connected through a 2.1 x 5.5 mm coaxial power jack (center positive), and the measured current draw at 12.0 Vdc input is about 260 mA, one-half the G4HUPRF unit. The input voltage range marked on the front panel is quite narrow, 11.7 to 12.9 Vdc. I did not attempt to operate the unit outside this range. The PCB appears to have an on-board voltage regulator, so this range may apply only to the version with an OCXO.

I noticed that the BG7TBL distribution amplifier current draw decreased as I added 50 ohm terminations to each port, decreasing from approximately 290 mA to 260 mA with all ports occupied. I thought this may have been due to oscillations in the unterminated output amplifiers but nothing showed on the oscilloscope (it is possible the probe loading stopped any oscillation). Harmonic content on the BG7TBL outputs when terminated is considerably less than the G4HUPRF amplifier. Examination of the PCB reveals what appear to be lowpass filters on each output channel unlike the G4HUPRF amplifier that has only one lowpass filter on the input. Also, unlike the G4HUPRF amplifier the BG7TBL unit does not get warm when powered up.

<u>BG7TBL Performance Measurements</u>: Measurements were made as above using an oscilloscope and spectrum analyzer. The voltage level of the output is very close to nominal (figure 11). The spectrum over a narrow frequency range differs from the G4HUPRF amplifier only in the output level (figure 12). Over a wider range, the spectrum indicates lower harmonic power levels across the board most likely due to the better output filtering in the BG7TBL distribution amplifier (figure 13). Because of the filtering, the 2nd harmonic is lower than the fundamental by about 50 dB.

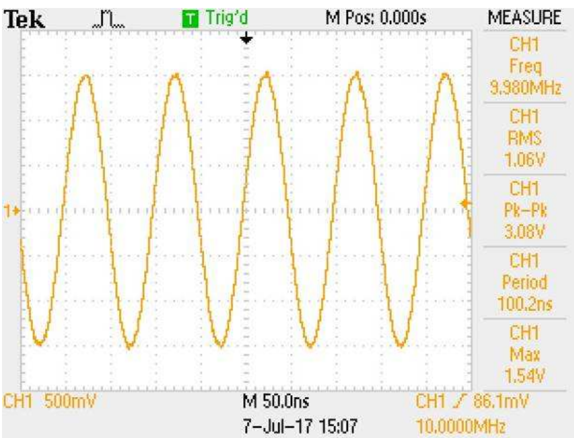


Figure 11 ~ Oscilloscope screenshot of the waveform for one output channel on the BG7TBL distribution amplifier. Note that the output is very close to the desired 1.0 Vrms nominal value. The output was terminated with 50 ohms for this measurement.

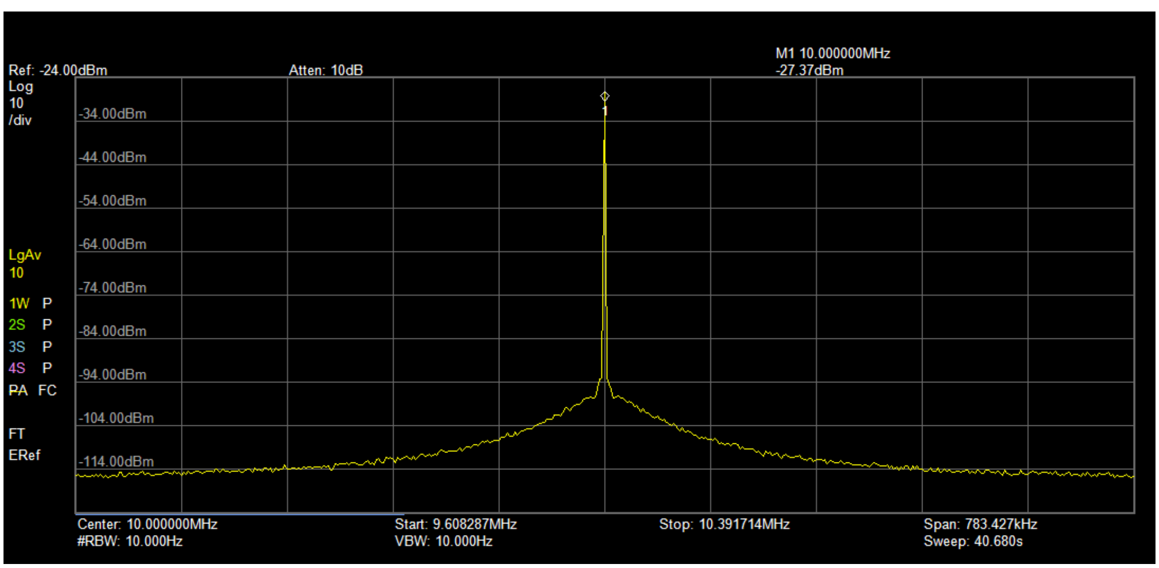


Figure 12 ~ Narrow spectrum view of the 10 MHz reference output from one of the channels of the BG7TBL amplifier. The span shown here is about 783 kHz.

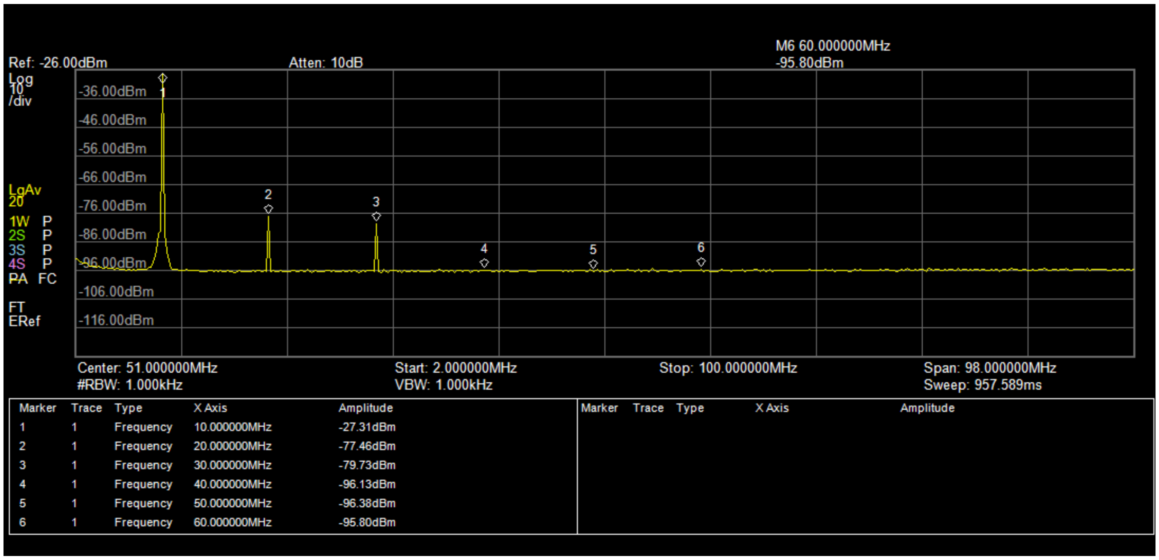


Figure 13 ~ Wider spectrum view of the same output as in the previous figure. At least six harmonics are visible. The 2nd harmonic is about 50 dB below the fundamental.

There is no specification available for the phase delay limit in the BG7TBL unit. The previous calculations of 3° phase delay for FR4 PCB material require 125 mm of trace length difference; however, examination of the single PCB in the BG7TBL unit shows a symmetrical layout with close to the same lengths on all channels. As above, I used a Keysight 53220A frequency counter for the measurements of phase difference between the BG7TBL distribution amplifier channels (table 2). It is seen that it has slightly lower channel-channel phase difference than the G4HUPRF unit, but its input-output phase difference is substantially higher. The input-output phase difference is a problem only if the reference source is connected through, say, a passive splitter to a distribution amplifier and also directly to a load that must be in-phase with the amplifier outputs. As previously mentioned this probably is not important in most amateur radio astronomy applications.

Table 2 ~ BG7TBL phase difference measurements

Measurement	**Phase (|°|)**
Input – Channel 1	133.5
Channel 1 – Channel 2	0.8

7. Daily Operation

It is clear from the above measurements that the BG7TBL distribution amplifier is overall the better amplifier, so it is the one I use daily in my lab. It is powered at all times and unused output channels are terminated with 50 ohms. Some of my test equipment does not annunciate an error when the external reference source is absent so leaving the amplifier plugged in eliminates at least one future self-caused trouble. I use a moderate-efficiency, well-regulated ac power adapter to power the distribution amplifier.

I was curious as to the cost of leaving the amplifier powered at all times. To measure the ac load including the power adapter losses and other parameters, I used a *Kill a Watt EZ* meter. This meter has an advertised accuracy of 2% but the advertisement does not say if this is achieved at all load levels. My experience with this device indicates that it works best when substantially loaded (say by a refrigerator), but it also seems to be accurate when very lightly loaded as was the case for these measurements. For the setup here, the indicated *apparent* *power* = 6 VA, *real power* = 4 W, *power factor* = 0.65 and *load current* = 0.05 A. The load is constant. My incremental electricity rate is 0.118 USD/kWh/mo. Therefore, the estimated electricity cost for the distribution amplifier and ac power adapter together is 0.004 kW x 730 h/mo x 0.118 USD/kWh/mo = 0.34 USD/mo, or about 4 USD/yr. The ac adapter output is (0.26 A x 12.0 V =) 3.12 W. For 4 W input power the calculated efficiency of the ac adapter is (3.12 W output/4 W input =) 78%.

8. Conclusions

Both the G4HUPRF and BG7TBL distribution amplifiers discussed in this paper are adequate for the purpose of distributing a 10 MHz reference signal to receivers and test equipment. However, the GB7BTL amplifier has better overall performance than the G4HUPRF amplifier, not only in the quality of the outputs but in power consumption and economy of operation. Having the amplifier in operation and permanently connected has incrementally simplified my lab operation.

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Document information

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Revision: 0.0 (Original draft started, 7 Jul 2017)

0.1 (Added images and descriptions, 9 Jul 2017)

0.3 (Additional cleanup, 10 Jul 2017)

0.4 (Added phase measurements and completed 1st draft, 15 Jul 2017)

0.5 (Added SDR info, 30 Aug 2017)

0.6 (Add'l receiver info, 03 Sep 2017)

0.7 (Completed draft, 17 Sep 2017)

1.0 (Distribution, 01 Oct 2017)

1.1 (Replaced HUPRF link, 04 Oct 2017)

Word count: 4309

File size: 4562944