CARRIER PHASE MODULATION USING DIRECT DIGITAL SYNTHESIS FOR AN S-BAND UPLINK

George Burgess William Murphy
Stanford Telecommunications, Inc.
2421 Mission College Blvd.
Santa Clara, CA 95056-0968

ABSTRACT

Phase modulation has traditionally been performed in analog hardware. A new product will be described that implements this function using a phase-modulating NCO IC. The modulating signal is sampled and added digitally to the phase of the carrier generated by the NCO. This method produces an output spectrum with highly accurate modulation control, low spur levels and minimal distortion. The effects of generating sampled phase-modulated signals will be described. The selection of the clock and output frequencies are critical to ensuring a clean spectrum. Resulting output spectra are shown.

INTRODUCTION

Phase modulation has commonly been used to transmit commands, data, and telemetry on a carrier to and from satellites. In particular, SGLS uplinks containing commands and ranging, data, and telemetry utilize phase modulation on S-band carrier frequencies. Phase modulation has traditionally been implemented using analog hardware. This approach has had problems with modulation index accuracy, drift, and repeatability. Recent advances in speed and density of digital logic have made digital implementations of phase modulation feasible. Digital designs offer the advantages of precise frequency and mod index control, excellent repeatability, and relatively little drift. The STel 5310 RF Modulator chassis was designed using digital phase modulation because of these considerations.

5310 RF MODULATOR

The 5310 RF Modulator was designed to operate as either an RF uplink signal generator for a SGLS ground station, or as an RF downlink simulator for SGLS satellites. The unit can transmit on any of the 20 channels for uplink, and can simulate any of the 20 carrier I downlink channels. The channel frequencies range from 1.7 to

1.8 GHz on the uplink, and 2.2 to 2.3 GHz on the downlink, as shown in Table 1. The complete specifications for the RF Modulator are shown in Table 2. The basic function of the 5310 is to input commanding, ranging and telemetry signals in digital format, generate the baseband signals, and phase modulate them on a selected RF carrier frequency. The mod index for each signal and the carrier frequency are selectable on the front panel or through a remote RS-232 link. An analog baseband input can also be modulated on the carrier with a predefined sensitivity (3 radians/volt). The interfaces are shown in the block diagram in Figure 1.

The ranging modulator adjusts the voltage levels generated for a 0 or a 1 using a precision D/A converter (DAC). The resulting mod index is a function of the ranging signal voltages, the A/D converter range, and the bits used by the modulation NCO. The command modulator generates a unique frequency tone for each of the 0, 1, or S inputs, and amplitude modulates this FSK signal with a triangular ramp synchronized to the clock signal with a selected phase offset. The resulting signal is shown in Figure 2. The voltage level of the command signal is also adjusted using a DAC to set the modulation index. The BPSK subcarrier modulator modulates a 1.024 MHZ subcarrier with the telemetry input, and sets the voltage level using a DAC. The subcarrier can also be selected as 1.25 MHZ or 1.7 MHZ.

The baseband spectrum is formed by summing the outputs of the three modulators and the separate analog baseband input. The baseband signal is low-pass filtered prior to A/D conversion. These digital samples are used to phase modulate a carrier in the baseband modulator using the STel 1175 Phase-Modulating NCO chip. The selection of the sample rate and the NCO output frequency will be discussed in a later section.

The NCO output is converted to analog using a DAC and an LPF, and this signal is mixed up to a nominal frequency of 69.75 MHZ for the uplink generator or 70 MHZ for the downlink simulator. These frequencies were selected because of the availability of SAW bandpass filters at a 70 MHZ center frequency. The SAW BPF is used to reject any spurs or harmonics outside of a ± 3 MHZ band. The nominal uplink frequency could not be 70 MHZ because the synthesizer generates RF mixing frequencies in increments of 2 MHZ for the uplink, so any remainder when the channel frequency is reduced modulo 2 MHZ must be generated by the IF. The uplink IF can thus range from 69.721 MHZ to 69.795 MHZ.

The RF synthesizer module uses a PLL to generate the RF mixing frequency from a 10 MHZ reference. The upconverter module mixes this local RF with the IF from the baseband modulator to produce the S-band output. This signal is then bandpass filtered and the output level set to the selected value using an amplifier and a step attenuator. This output can be routed to either the uplink equipment or a downlink receiver for loop-back testing.

Table 1. SGLS Frequencies

SGLS CHANNEL	UPLINK TRANSMISSION FREQUENCY. MHZ	DOWNLINK RECEPTION FREQUENCIES. MHZ (NOMINAL)
	$\left[f_{o\ uplink}\right]$ (±0.002%)	$\left[\frac{256}{205} f_{o\ uplink}\right]$
1	1763.721	2202.500
2	1767.725	2207.500
3	1771.729	2212.500
4	1775.733	2217.500
5	1779.736	2222.500
6	1783.740	2227.500
7	1787.744	2232.500
8	1791.748	2237.500
9	1795.752	2242.500
10	1799.756	2247.500
11	1803.760	2252.500
12	1807.764	2257.500
13	1811.768	2262.500
14	1815.772	2267.500
15	1819.775	2272.500
16	1823.779	2277.500
17	1827.783	2282.500
18	1831.787	2287.500
19	1835.791	2292.500
20	1839.795	2297.500

Table 2. RF Modulator Specification

PARAMETER	PERFORMANCE
Output Power	10.0 dBm to -53.5 dBm ±.5 dB in .5 dB steps
Carrier Frequency	Any of 20 SGLS uplink or Carrier I downlink channel frequencies • Can be offset by ± 1 MHZ with 1 Hz resolution
Spurious Levels (Unmodulated Carrier)	• Harmonics of carrier < -50 dBc • Other spurs outside F_c ± 2 MHZ < -60 dBc • Spurs inside F_c < -43 dBc
Phase Noise	Less than 2º RMS when integrated from F_c +500 Hz to F_c + 1 MHZ
Phase Modulation Index	• .01 to 1.99 rad for ranging, command, or subcarrier • Linearity = ± 8%
Command Tone Modulation	• Baud rate = 1 kbps or 2 kbps • Tone Frequencies: "1" 95.00 kHz ± .01% "0" 76.0 kHz ± .01% “S” 65.0 kHz ± .01% • AM modulation percentage = 50% ± 5% • Sync phase from .55 to .70 in .025 increments (± 10%)
Subcarrier Modulation	• Frequency selectable from 1.024, 1.25, 1.7 MHZ (±40 Hz) • Offset selectable from -99 Hz to +99 Hz in 1 Hz steps • BPSK modulated by input data clock
Analog Baseband Modulation	Modulation sensitivity = 3 rad / v
Control	• Front panel menu selection • RS-232 remote interface
Mechanical	• 3.5" rack height • 40 lbs

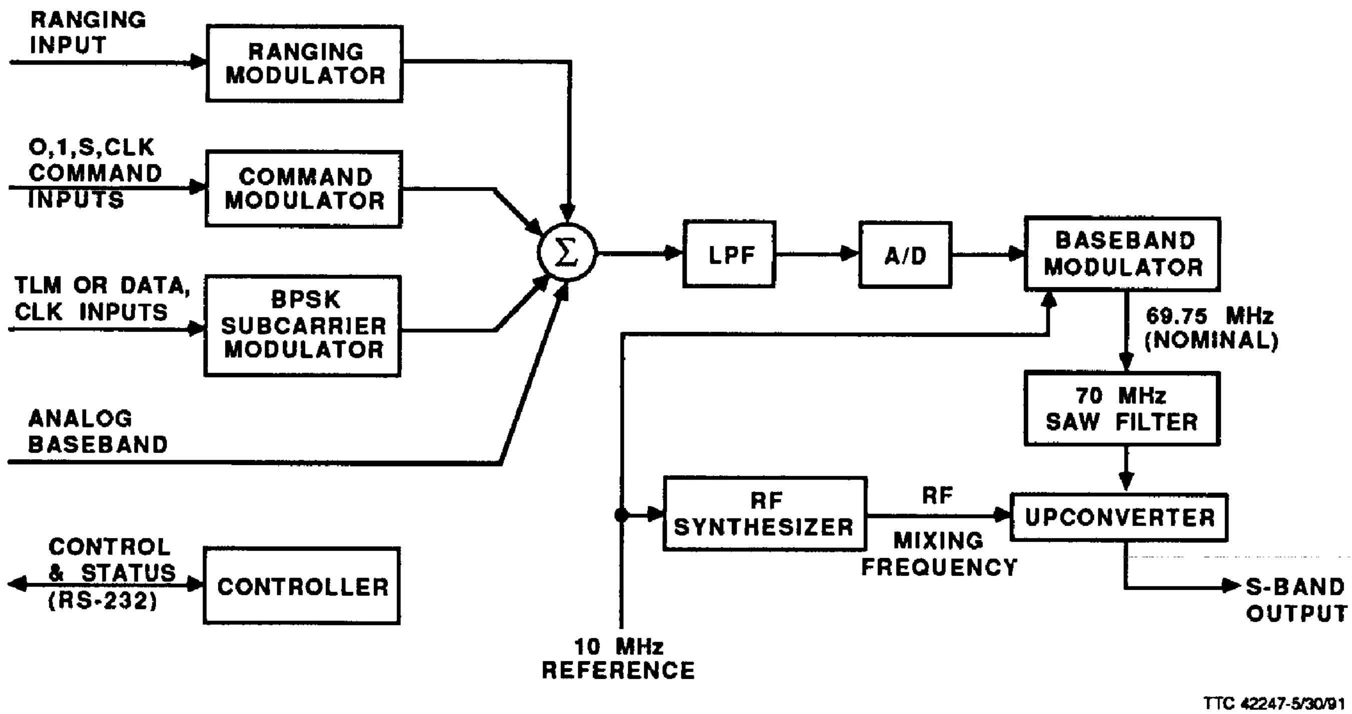

Figure 1. RF Modulation Block Diagram

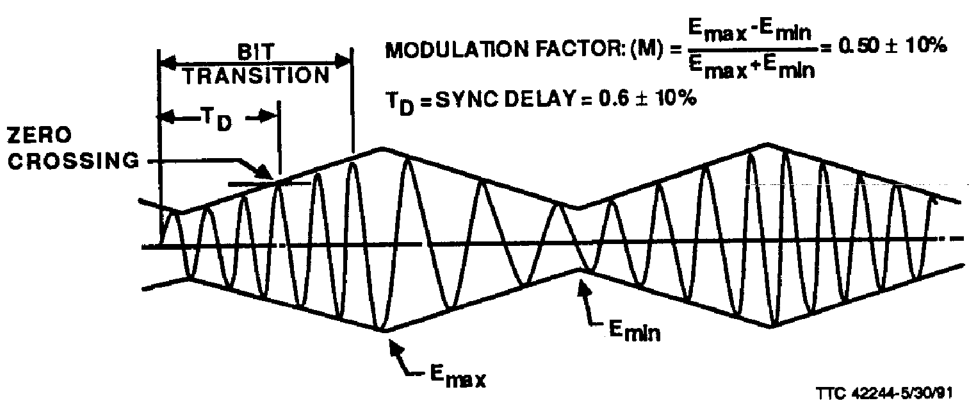

Figure 2. Typical Command Signal

The controller board provides the chassis interfaces to the front panel and remote control. The controller presents parameter selection menus on a 4 line by 40 character display for a local user, and configures the hardware based on these selections. A serial remote interface is also provided to select the same parameters and to receive status. The controller stores the configuration in EEPROM allowing the last state to be reconstructed upon powering up the chassis.

Mechanically, the 5310 occupies a rack height of 3.5". The baseband modulator and controller boards are both 6 U VME form factors, and plug into a common backplane. The controller board is the standard depth of 160 mm, while the baseband modulator is 280 mm. The RF synthesizer and upconverter modules are separate enclosed boxes mounted inside the chassis. The rear panel uses a combination of multipin circular connectors, BNC and N-type connectors.

PHASE-MODULATING NCO

The primary innovation in the design of the 5310 was the use of a digital phase-modulating NCO chip, the STel 1175, in the baseband modulator board. To discuss the design constraints on using this method, the chip design must first be understood. A block diagram of the 1175 is shown in Figure 3.

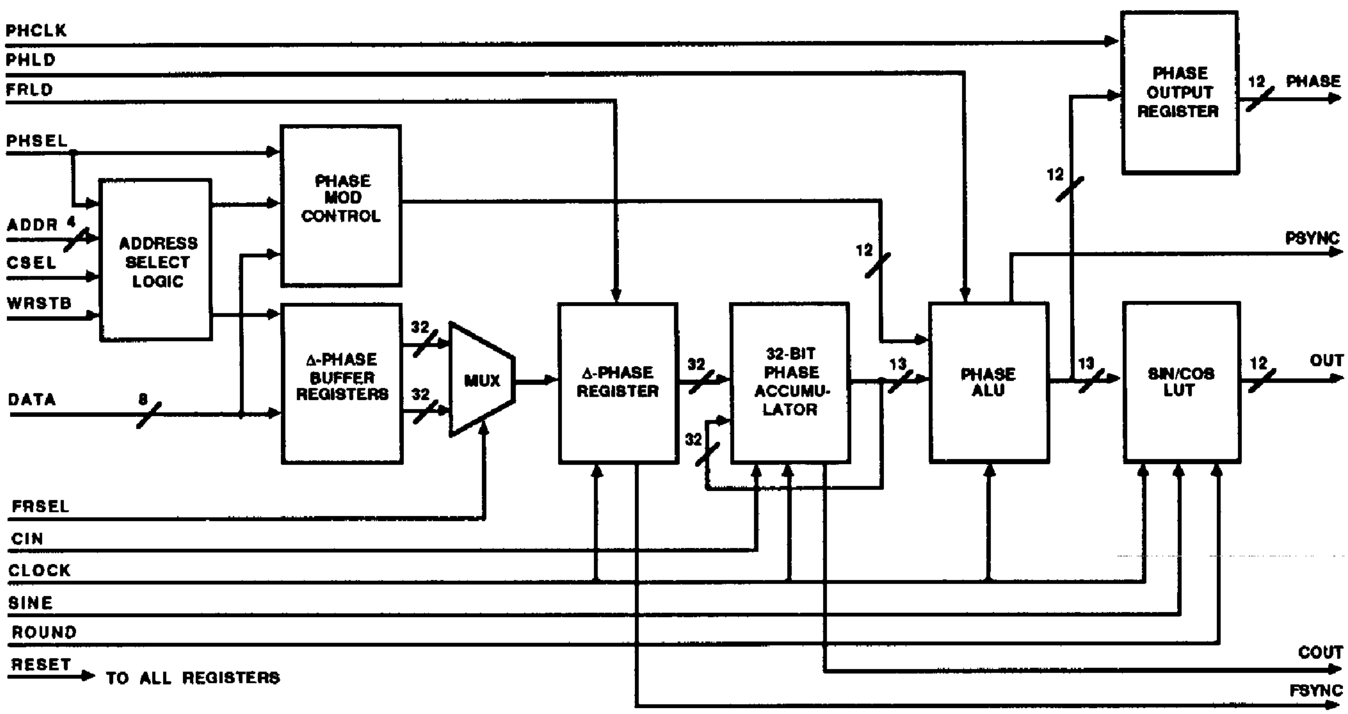

Figure 3. STel 1175 Phase-Modulating NCO

The heart of the 1175 is a 32-bit phase accumulator. This accumulator has the value in the delta-phase register added to its contents every clock cycle, at a rate of up to 60 MHZ. The recycle or overflow rate of the accumulator defines the carrier output center frequency. Every clock cycle the 32-bit accumulator contents represent the current phase of the output frequency. This phase is converted to a sinusoidal signal level by performing a table look-up on the highest 13 bits of the accumulated phase to map to a 12-bit signal level. The 12-bit phase is also available as a direct output.

The delta-phase register can be loaded synchronously from one of two delta-phase buffers. This mechanism also provides the capability to frequency hop or FSK the carrier. The delta-phase registers are loaded over an 8-bit microprocessor bus. The center frequency of the output can be determined by the formula

$$F_{out} = F_{clk} \times \frac{\Delta phase}{2^{32}},$$

where F_{clk} is the accumulator clock frequency, F_{out} is the output frequency, and Δ_{phase} is the value in the delta-phase register. The highest recommended output frequency is 25 MHZ, based on a maximum F_{clk} of 60 MHZ.

The phase modulation occurs at the output of the phase accumulator. 12-bit phase offsets are added to the 13 high-order bits of the accumulator after appending a 0 as the lowest bit of the offset. This provides the ability to increase the phase by 0 to 2 π radians (or $-\pi$ to $+\pi$) in steps of 1.53 millirad. The phase offset can change at a rate up to 25% of the accumulator clock rate. The 13-bit result of this addition is used in the sinusoid look-up table and output directly.

The center frequency of the NCO can be set with a resolution of 14 MHz at a 60 MHZ clock rate. The output spectrum of the unmodulated carrier should have no spurs higher than -75 dBc in theory. The actual spectral purity depends on the performance of the DAC used to convert the 12-bit sinusoid samples. In the baseband modulator, a small printed circuit module was used which includes the 1175, a 10-bit SONY DAC, and CMOS/ECL level shifters. This package, the STel-1375A, provides a spurious level of < -65 dBc.

SPECTRAL EFFECTS OF DIGITAL PHASE-MODULATING

The basic effects of sampling the modulating signal are shown in Figure 4. If the pre-sampled modulating signal appears as in (a), ideal sampling with impulses will produce the spectrum shown in (b). The modulating signal is replicated at multiples of the sampling frequency F_s. In actual practice, a sample-and-hold technique is used, which is equivalent to scaling the ideal spectrum by a sinc function with nulls at multiples of the sampling frequency. This function is shown as a dotted line in (b). The resulting spectrum of the sampled modulating signal is shown in (c). The sinc function produces residual asymmetric components centered at multiples of the sampling frequency.

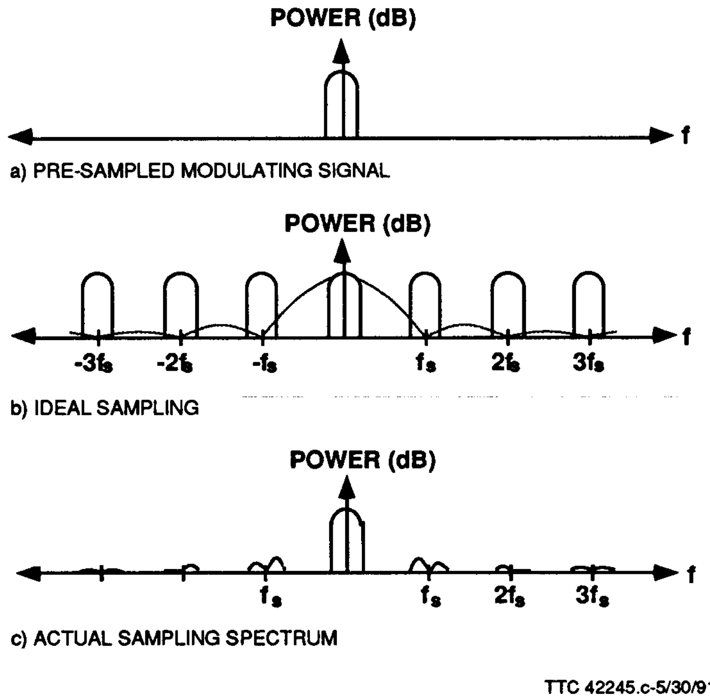

Figure 4. Sampling of Modulation Signal

The samples of the modulating signal are added to the phase accumulator output to create a phase-modulated carrier. The modulation index is determined by the voltage level of the modulating signal before sampling, and the bits/V sensitivity of the A/D converter. The ideal phase modulation output spectrum is shown in Figure 5(a). Only the first-order PM harmonics are shown, but these are the most significant. The desired signal is shown as a carrier at F_c with the modulating signal centered about that frequency. The reflected images of the residual components occur at multiples of F_s away from the complementary PM output at F_c. If the sampling and carrier frequencies are not chosen carefully, these components will fall in the band of interest around F_c, which for this design was ± 3 MHZ.

The actual phase modulation process generates samples of a continuous signal, so the resulting spectrum will be the product of replicating the ideal spectrum at multiples of the output clock frequency and scaling by a sinc function with nulls at those same frequencies, as shown in 5(b). The shape of the sinc function causes some distortion in the desired output due to larger attenuation for higher frequencies. The goal of the frequency plan is thus to select clock and output frequencies such that image effects and distortion am minimized.

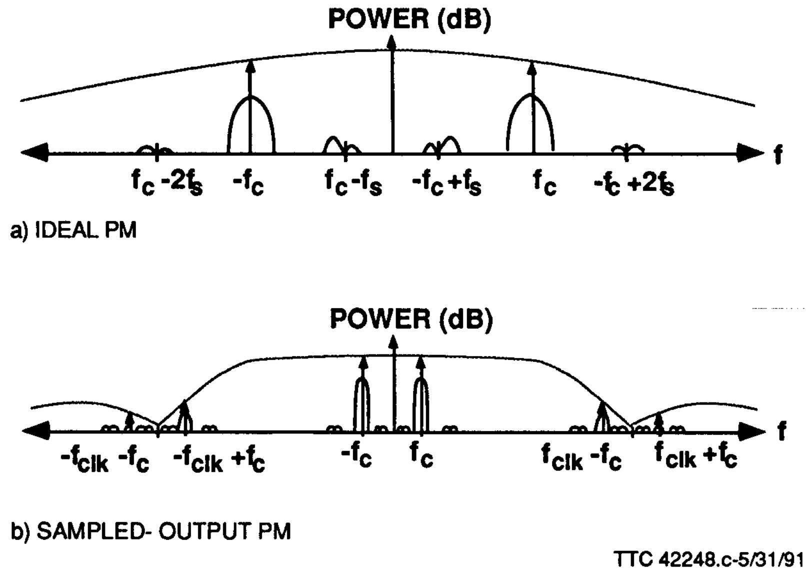

Figure 5. Phase Modulation Output

FREQUENCY PLAN FOR BASEBAND MODULATOR

A principal requirement was that the frequencies used were to be synthesized from a 10 MHZ reference. The number of unique synthesizers on the board should be minimized, however. The modulating NCO accumulator clock should be kept as close to 60 MHZ as possible to maximize isolation from reflected images about the clock frequency. Combined with a nominal output frequency of about 70 MHZ, these constraints led to the design shown in Figure 6. The same frequency is used to clock the NCO accumulator and to mix the NCO output up to ~70 MHZ. There is a single phase-locked synthesis loop, which generates both the NCO accumulator clock and the sampling clock. The sampling clock was selected to be 1/4 of the NCO clock.

The frequencies selected were 58.75 MHZ for the NCO and mixing frequencies, and 14.6875 MHZ for the sampling frequency. This implies an NCO output frequency of 11 MHZ for the uplink, and 11.25 MHZ for the downlink. The images at $-F_c + F_s$ and $-F_c$ + 2Fs are located at 3.6875 MHZ and 18.375 MHZ, which places them over 7 MHZ from the carrier frequency. Since the signal bandwidth of interest is about ± 3 MHZ about the carrier, the images will be rejected by the SAW BPF. The distortion over the bandwidth due to the NCO clock sinc function is about .6 dB, which is acceptable. Note that the NCO output has an image of the modulated carrier at the desired frequency of 69.75 MHZ, but the sinc function causes the power level to be 16 dB lower and the distortion to be >3.6 dB, so this output is unusable.

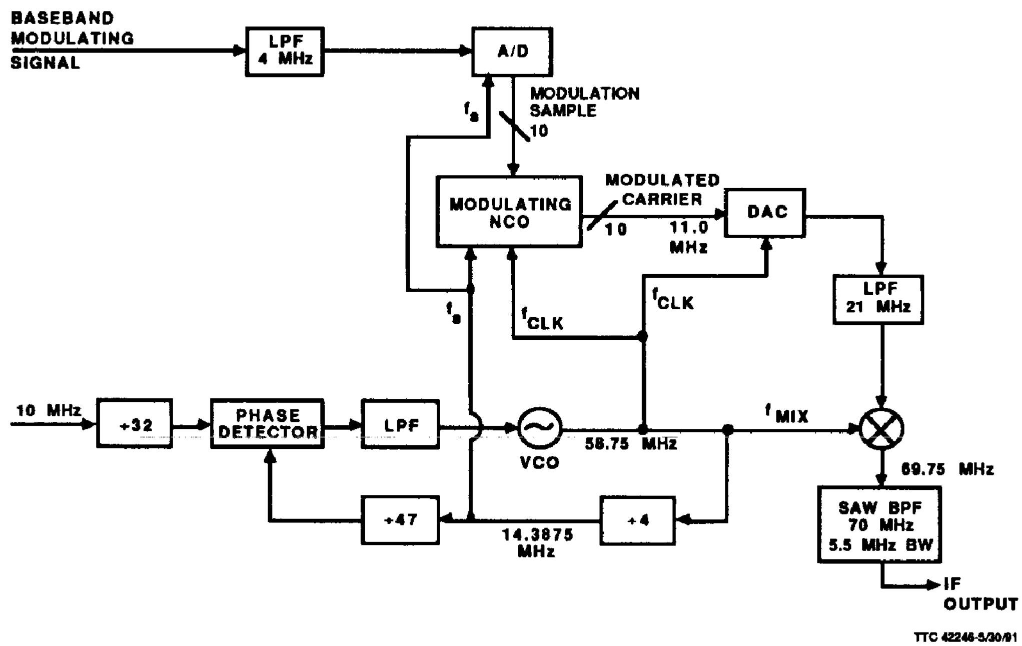

Figure 6. Baseband Modulator

Another important design consideration for the baseband modulator is the selection of the A/D converter that samples the modulating signal. The NCO can input 12-bit samples, but no A/D converter was found that could generate 12-bit samples at a 15 MHZ clock rate. 10-bit A/DCs were found that could operate at those rates, so the parts were evaluated and a Comlinear CLC920 was selected. The 10 sample bits were mapped into the high 10 bits of the 12-bit input of the NCO, and the 2 low bits were set to zero. This provides a resolution of .006 rad, which for the lowest mod index of .1 rad implies a resolution error of ± 3%. For linearity of ± 8%, the ADC must not vary by more than 1 bit for a constant input voltage.

TEST RESULTS

The 5310 met all of the requirements shown in Table 2. Examples of unmodulated and modulated spectra are shown in Figures 7-10. Figure 7 shows the unmodulated carrier at the NCO and RF outputs. The highest spurs are shown to be 65 dB down from the carrier. Figure 8 shows command tone modulation at .1 rad. The three tones are clearly distinguishable on either side of the carrier, and the start of the second harmonics can be seen about 30 dB down at twice the frequency. The added phase noise on the RF output is due to synthesizer phase noise. Figure 9 shows the ranging signal modulated at .3 rad. Figure 10 shows an unmodulated 1.024 MHZ subcarrier modulated onto the carrier at 1.65 rad. At this mod index, the carrier level falls below that of the first sidebands. The spurious tone between the second and third harmonics are reflections from the images on each side of the carrier (±7 MHZ).

SUMMARY

The digital approach to phase modulation has distinct advantages over analog methods in the areas of accuracy, stability, and repeatability. The digital design must take into account the constaints on frequency selection to avoid unwanted in-band images. The STel 5310 RF Modulator has been designed using carefully selected frequencies in the phase modulator to provide a clean output spectrum with digital phase modulation. The 5310 is designed for the SGLS uplink and Carrier I downlink channels, but this approach can easily be extended to other frequency bands and baseband data types.

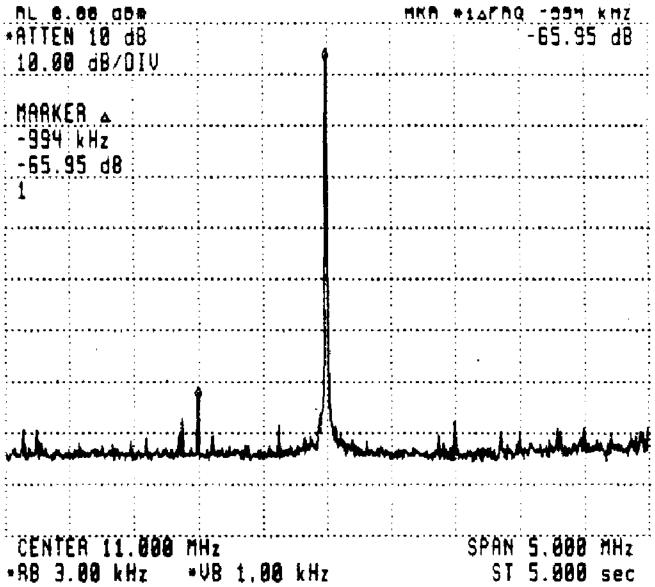

Figure 7a. Unmodulated Carrier - NCO Output

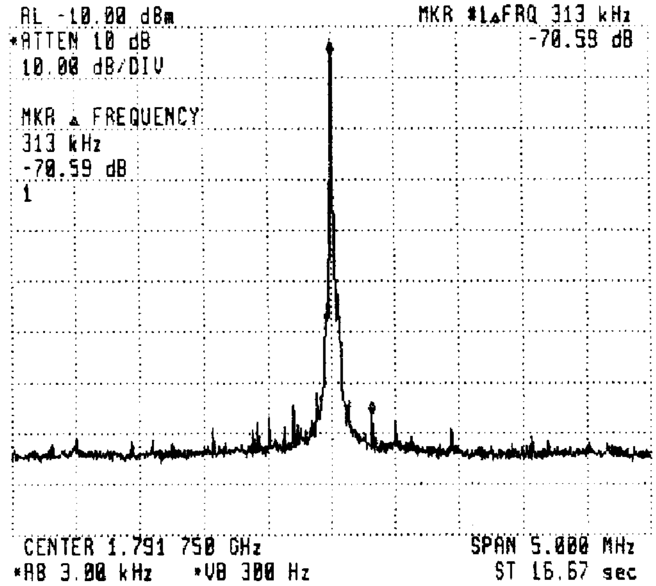

Figure 7b. Unmodulated Carrier - RF Output

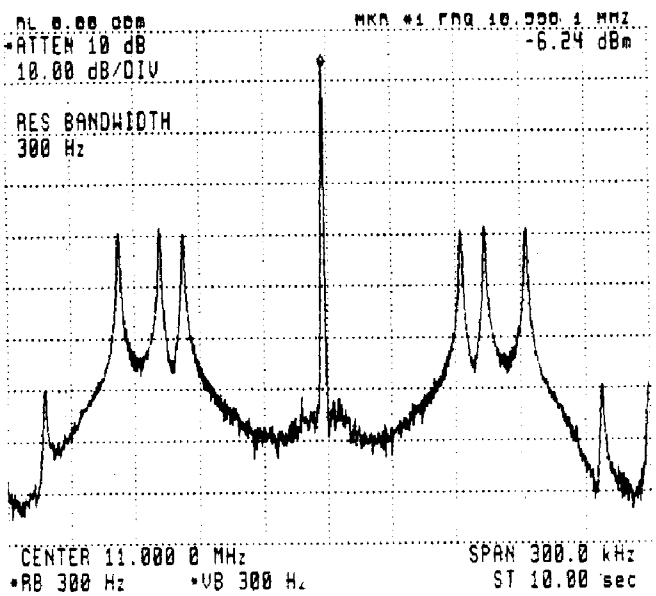

Figure 8a. Command Tone Modulation at .1 rad - NCO Output

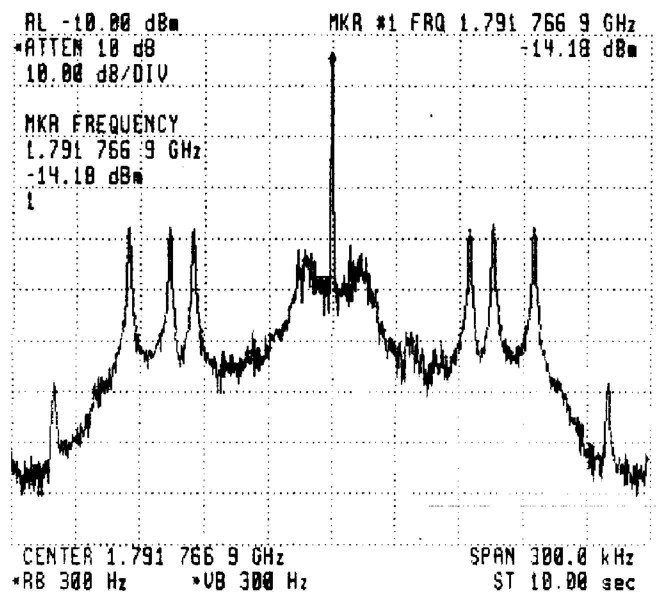

Figure 8b. Command Tone Modulation at .1 rad - RF Output

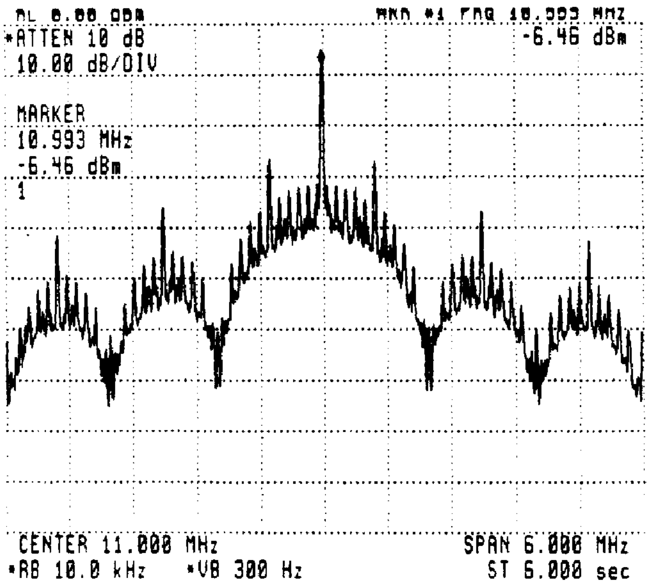

Figure 9a. Ranging Modulation at .3 rad - NCO Output

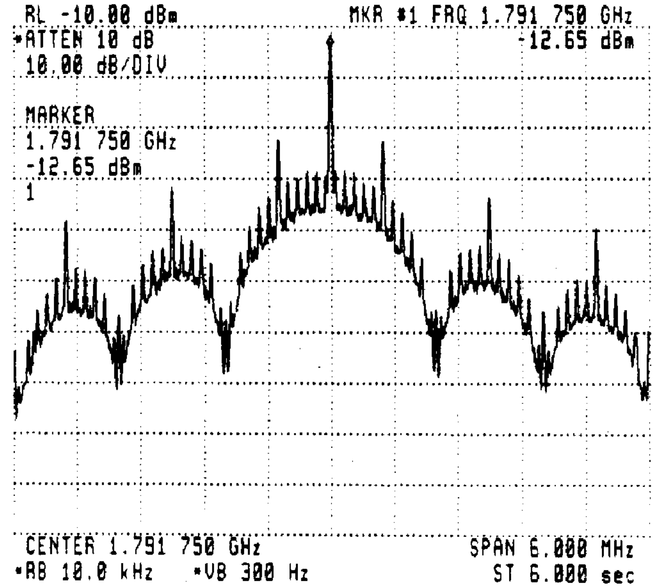

Figure 9b. Ranging Modulation at .3 rad - RF Output

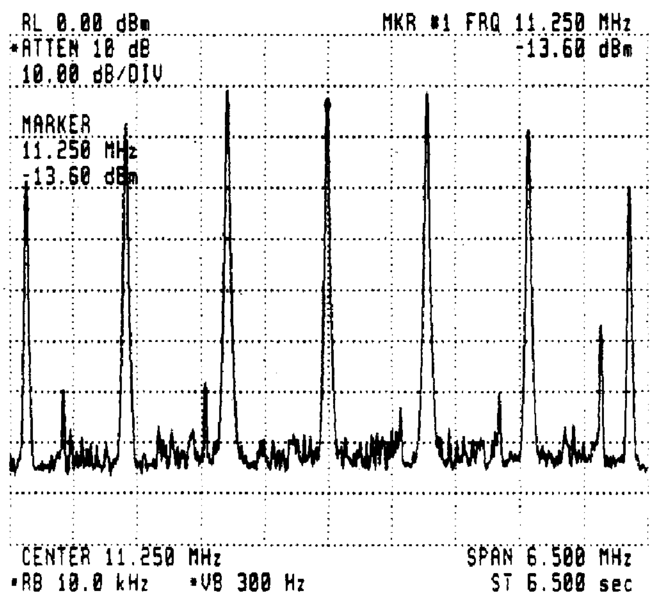

Figure 10a. Carrier PM with Unmodulated 1.024 MHz Subcarrier at 1.65 rad - NCO Output

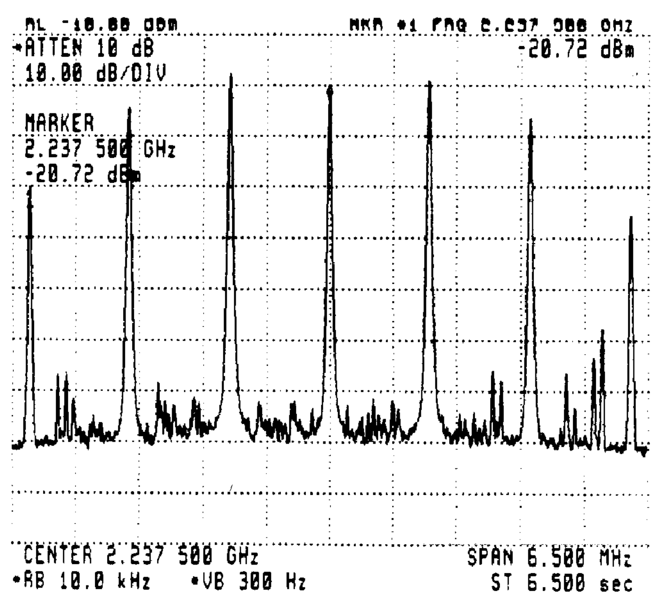

Figure 10b. Carrier PM with Unmodulated 1.024 MHz Subcarrier at 1.65 rad - RF Output