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Full L-S Band Telemetry System

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Abstract
Recent changes in spectrum availability as well as higher demands for spectrum have motivated the development of telemetry transmit systems capable of fully operating over both L and S telemetry bands. However, enabling operation within these two bands poses new problems in system design. This report presents a prototype system capable of operating between 1.4 and 2.4 GHz, which supports continuous phase modulation (CPM) waveforms such as pulse code modulation (PCM), frequency modulation (FM), and shaped offset quadrature phase shift keying (SOQPSK). The system architecture is detailed, and the prototype performance is discussed.

1. Telemetry Transmitter

One aspect of the standard paradigm for flight test is continuous monitoring of the aircraft via real-time telemetry [1]. Key air vehicle, system functionality, and pilot health information is relayed to facilitate real-time and post-mission analyses. The telemetry is typically accomplished over a radio frequency (RF) link on dedicated portions of the L-Band (1435-1525 MHz) and the upper S-Band (2310-2390 MHz). Air vehicles are assigned specific frequency channels within these bands, with bandwidth allocated according to the unique mission requirements. Existing telemetry transmitters and antennas are restricted to particular bands or, even worse, to discrete frequencies within a given band.

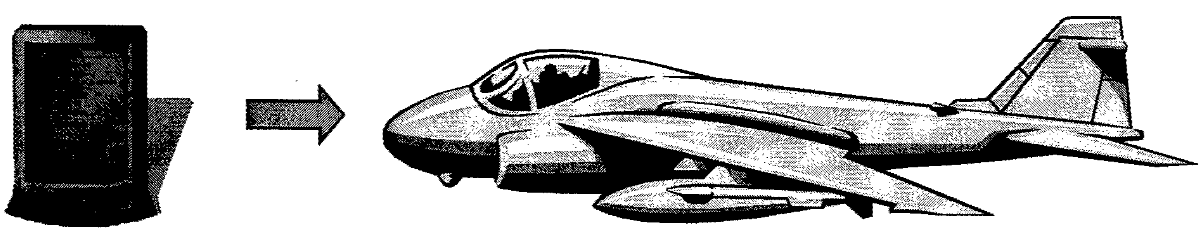

Figure 1: Concept of using a personal digital assistant (PDA) or laptop computer for reconfiguring the frequency channel assignment for an aeronautical telemetry transmitter.

Due to recent changes in spectrum allocation for telemetry and communications, the current hardware infrastructure poses problems in terms of channel assignment and scheduling for air vehicle telemetry [2]. For example, due to the apparently insatiable demand for RF spectrum in the private sector, portions of the telemetry bands have been reassigned for commercial use. Specifically, congressional actions such as OBRA 93 and BBA 97 have both decreased the bandwidth available for telemetry and fragmented the available channels over the L and S bands. Due to the inflexibility of current hardware, it has become impractical to continue the methods used in the past for channel assignment and scheduling. As a result of this need, new telemetry transmitters must be developed that allow rapid reconfiguration of the transmit band using a laptop computer or personal digital assistant (see Figure 1).

In this report, we discuss the development of a prototype transmitter architecture operating over the L and S bands. The implementation uses commercial off-the-shelf components coupled with custom software. This presentation includes information concerning the system design and performance. We also discuss work that has grown out of this effort that will solve additional problems encountered during air vehicle flight tests.

1.1 Transmitter Architecture

Historical and future trends in aeronautical telemetry suggest that appropriate transmitters be capable of continuous phase modulation (CPM) schemes. Specifically, transmitters should support pulse code modulation (PCM), frequency modulation (FM), and shaped offset quadrature phase shift keying (SOQPSK). Additionally, in order to support operation in both the L and S bands, extreme care must be exercised in generation of the modulated RF signal in order to avoid out-of-band emissions or unwanted in-band signals.

Traditional telemetry transmitters make use of a voltage-controlled oscillator (VCO) whose frequency tuning port is driven both by a center frequency control voltage as well as the modulating baseband data. The architecture used in this prototype is shown in Figure 2. In this design, a programmable phase-lock loop (PLL) subsystem is used in conjunction with a stable 20 MHz reference oscillator in order to accurately control the output frequency of the VCO. The PLL can be controlled directly by the host or through the intermediary of a simple microcontroller. The output power amplifier is typically controlled by the PLL system, being turned on only after the system has acquired lock in order to minimize the transmission of out-of-band signals. The loop filter is designed to remove unwanted signals from the VCO control voltage. Its bandwidth controls the PLL acquisition time and the locked oscillator phase noise performance. In telemetry applications, the system is typically not required to change carrier frequencies during communication. Therefore, the acquisition time is relatively unimportant, and a narrow band loop filter is used in order to optimize the phase noise performance.

The telemetry data are added to the loop filter output voltage in order to modulate the VCO output. The ideal VCO output signal can be expressed as

$$s(t) = A\cos[\omega_o t + \phi(t,\alpha) + \phi_o] \tag{1.1}$$

where the carrier frequency $\omega_o = K_o V_{PLL}$, K_o is a VCO-dependent constant, and V_{PLL} is the DC voltage at the loop filter output. The data-dependent phase is given as

$$\phi(t,\alpha) = 2\pi h K_o \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} \alpha_k g(\tau - kT)\,d\tau \tag{1.2}$$

where *h* is a modulation index that depends on the amplitude of the modulating voltage and *g(t)* is the unity-area single-symbol pulse shape of duration *T*. For PCM and FM, we use $\alpha_k \in \{-1,+1\}$ with *T* equal to the symbol period. For SOQPSK, we use $\alpha_k \in \{-1,0,+1\}$ with *T* equal to one-half of the symbol period and *h* = ¼ [3]. Therefore, this simple circuit provides the desired CPM waveform provided that the modulating data are properly formatted before its application to the transmitter.

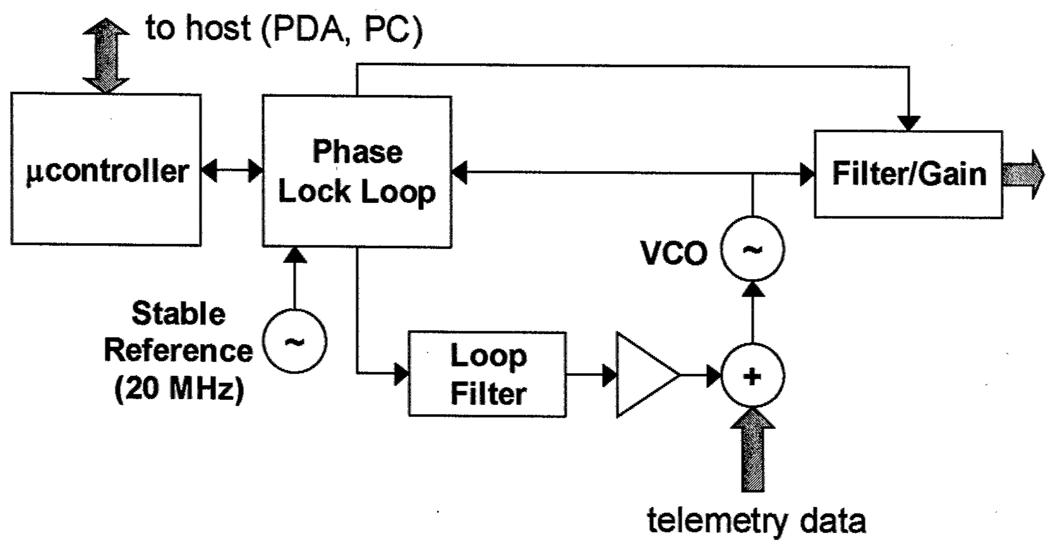

Figure 2: Block diagram illustrating a simple directly modulated voltage controlled oscillator transmitter architecture.

1.1.1 PLL Subsystem

The PLL subsystem consists of the programmable PLL chip, loop filter, 20 MHz reference oscillator, and RF power divider. For this prototype, the LMX2326 PLL chip from National Instruments has been chosen. This chip offers operation between 100 and 2800 MHz with a very high frequency resolution (50 KHz resolution is used for the prototype). Chip programming is accomplished using a serial data interface. The 20 MHz reference signal is an Epson SG-615P crystal oscillator with a frequency stability of $\Delta f / f_o = \pm 100 \times 10^{-6}$.

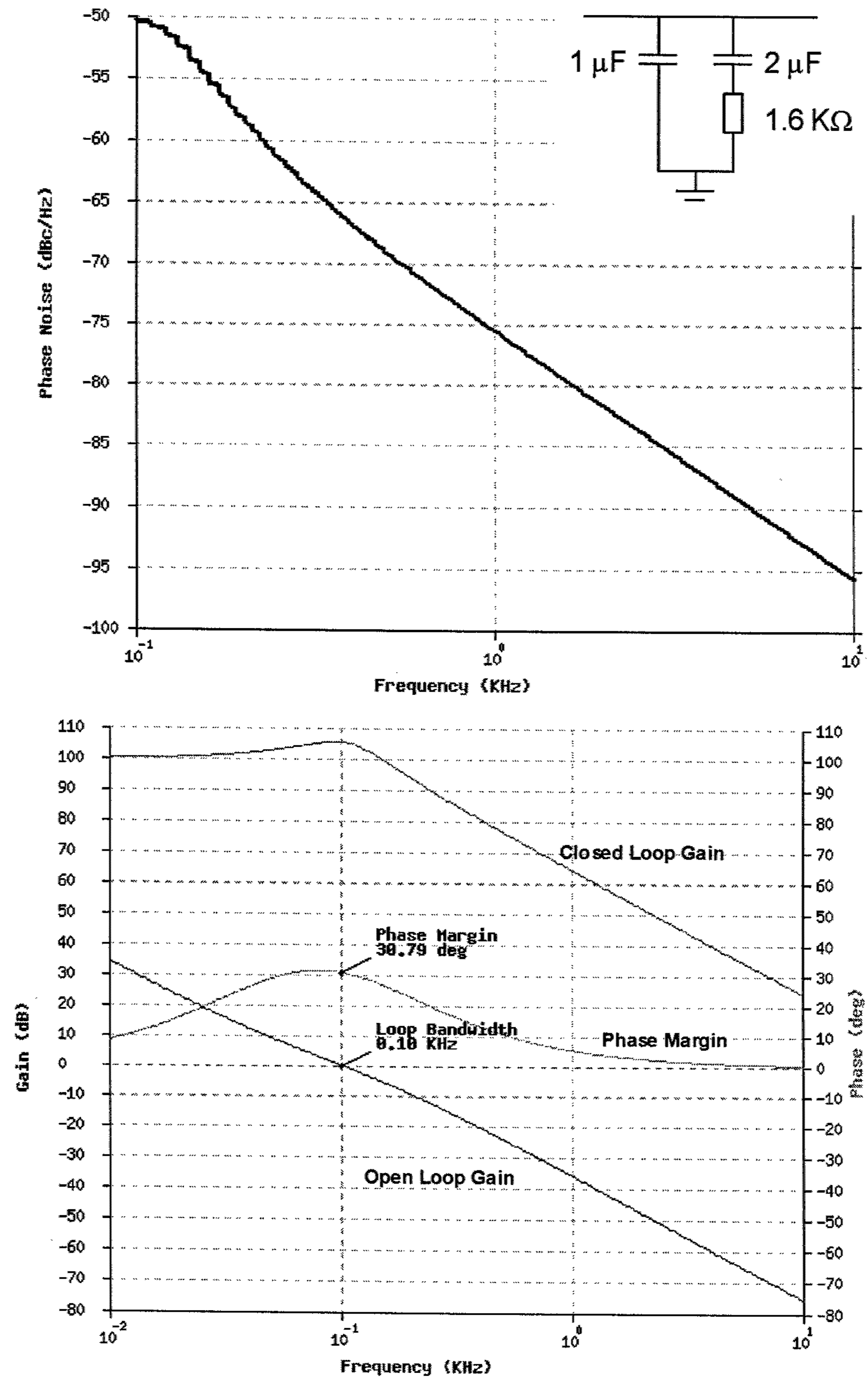

Figure 3: Loop filter design along with predicted phase noise performance and frequency response.

The key design portion of the PLL subsystem involves the loop filter. This filter was designed using standard techniques [4] for a 0.1 KHz loop bandwidth and a 48-degree phase margin. A schematic of the filter, a plot of its frequency response, and a plot of its phase noise performance are shown in Figure 3. As can be seen, the corner frequency is relatively low, which accounts for the excellent phase noise performance. This also results in the relatively long full-scale acquisition time of roughly 70 μS (VCO starts at 1400 MHz and must be locked at 2400 MHz).

The RF power divider is used to split the signal from the VCO between the output port and the RF input to the PLL chip. This has been designed using a simple resistive network such that only -5 dBm of the available 10 dBm output from the VCO is fed back into the PLL chip.

1.1.2 VCO Subsystem

A very wide band VCO is required in order to allow operation over the L and S bands. Fortunately, the ELCO-MS-148/248-01 VCO from Emhiser Research meets the specifications. This surface mount device requires a tuning voltage between 1 and 17 volts for a frequency range of 1430 to 2400 MHz. An op-amp is therefore used to amplify the output of the loop filter to the proper range. The loop filter output is summed with the telemetry data using a simple capacitive/resistive summing circuit. For this prototype, the data signal is generated using a square wave generator, although a more sophisticated system would be utilized in a practical system.

1.1.3 Control Subsystem

A microcontroller is integrated into the programming loop in order to facilitate automatic start-up configuration of the device. The Rabbit 2000 device is chosen, due mainly to the availability of useful and easy-to-use programming tools. A software interface that runs on a personal computer has also been developed to allow simple programming of the device. For the prototype, this software allows full-control of the PLL chipset, although an operational device would implement much of the basic chipset configuration using the automatic start-up sequence at instrument power up. Of most importance is the ability to set the center frequency as well as the device frequency resolution. Figure 4 shows the software interface window.

1.2 System Performance

The entire system was fabricated using surface mount construction on GIL-1000 material (30 mil thickness, 3.26 dielectric constant) and conductor-backed coplanar waveguide technology for the RF interconnects. Once fully integrated, the system achieved a tuning range from 1.14 to 2.48 GHz. The measured phase noise turned out to be approximately –25 dBc at 1 MHz offset, which represents a significant degradation compared to the theoretically computed performance. However, it is known that the spectrum analyzer used to measure this performance suffers from inaccuracies at fine frequency resolution, and therefore further testing is underway to more accurately measure this phase noise performance.

The modulation performance was tested by injecting a square wave (±1) into the telemetry data port. The system output was then down converted using a mixer and a local oscillator (LO). Figure 5 shows the result of this test for a system center frequency of 1400 MHz and LO frequency of 1380 MHz such that the intermediate frequency (IF) is nominally at 20 MHz. The 1 MHz modulating signal amplitude has been set to exaggerate the frequency modulation behavior. The modulation behavior is clearly very good, although some unwanted amplitude modulation behavior is present. When the modulating waveform was increased in frequency to about 18 MHz, the input capacitance to the VCO began to smooth the transition between the two output frequencies. However, in a realistic system, the telemetry data pulses will undergo shaping in order to limit the transmitted signal bandwidth. As a result, this additional filtering of the data will not significantly degrade the system performance for data rates as high as 20 Mbits per second.

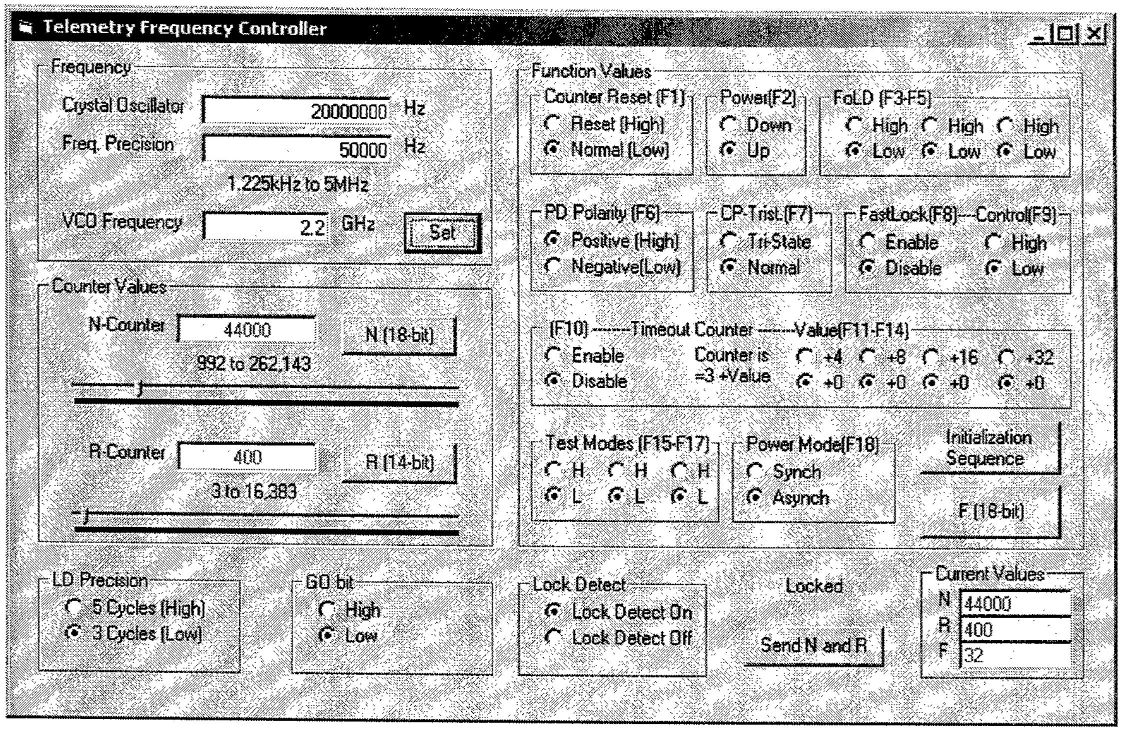

Figure 4: Control window used to program the PLL chip. This interface allows setting the VCO output frequency as well as controlling other features of the device.

1.3 Additional Considerations

1.3.1 Output Filtering and Power Amplification

One of the remaining tasks associated with development of an operational instrument based upon this design involves implementation of output filters and power amplifiers suitable for the bands of interest. Fortunately, new advances in power transistors fabricated using Gallium Arsenide (GaAs) facilitate design of power amplifiers capable of amplifying over the requisite 1 GHz bandwidth. The output filter, on the other hand, will need careful attention in order to adequately suppress out-of-band signals while passing the signals in both operational sub-bands.

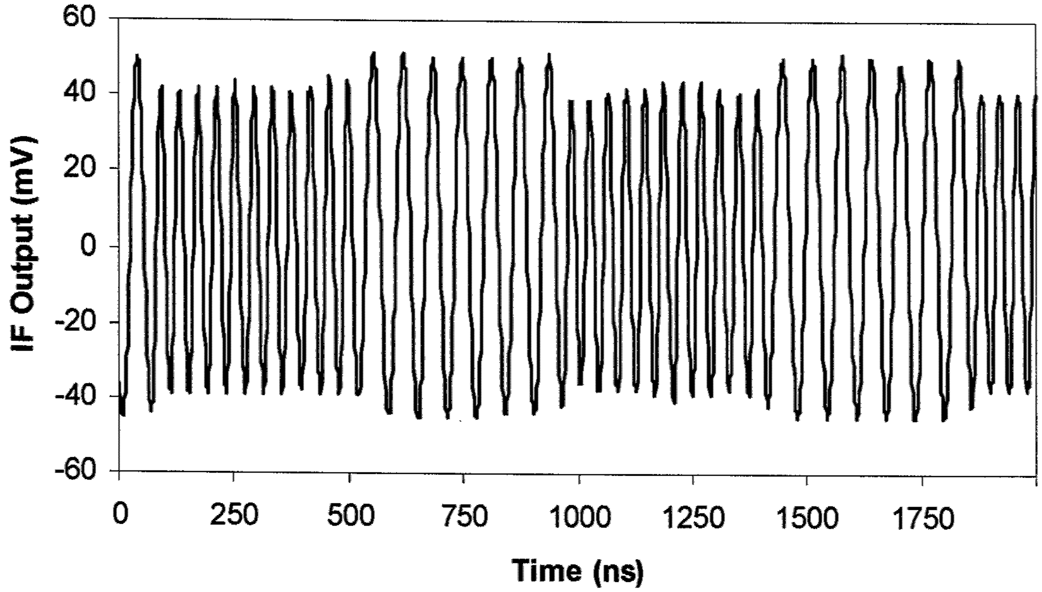

Figure 5: Output waveform resulting from down converting the modulated signal to a 20 MHz intermediate frequency.

1.3.2 Environmental Testing

One of the difficulties with the transmitter architecture examined for this effort is the effect of operational conditions such as temperature or aircraft vibrations. This latter issue is particularly important, since the large tuning range of the VCO can make it highly sensitive to mechanical stresses. As transmitters of this nature are commercialized, extensive environmental testing must be performed in order to determine the system sensitivity to operating conditions. Some of this sensitivity could be reduced by designing a loop filter with a wider loop bandwidth so that the system more quickly adjusts when external influences produce unwanted frequency deviations.

1.3.3 Potential Alternative Architectures

While the merits of the architecture discussed above have been demonstrated by years of use within the telemetry community, the analog introduction of the telemetry data can result in non-ideal output waveform characteristics. To overcome potential limitations of such systems, it is interesting to explore utilization of new technologies that can offer improved performance at reduced costs compared to traditional designs. As an example, consider the architecture shown in Figure 6. This system uses a direct digital synthesizer (DDS), field programmable grate array (FPGA), or digital signal processor (DSP) to directly synthesize the CPM waveform digitally. The In-phase (I) and Quadrature (Q) channels of the synthesized data can then be up converted either by using a programmable source similar to that discussed above or by using a sequence of multiplication stages to create the microwave signal from the IF signal created by the digital subsystem. DDS and FPGA implementations are particularly attractive, since advances in wireless communications system design have resulted in off-the-shelf components capable of producing the desired waveforms at rates in excess of 100 Mbits/s. Work is currently underway to assess the feasibility and performance advantages and disadvantages associated with using such an architecture.

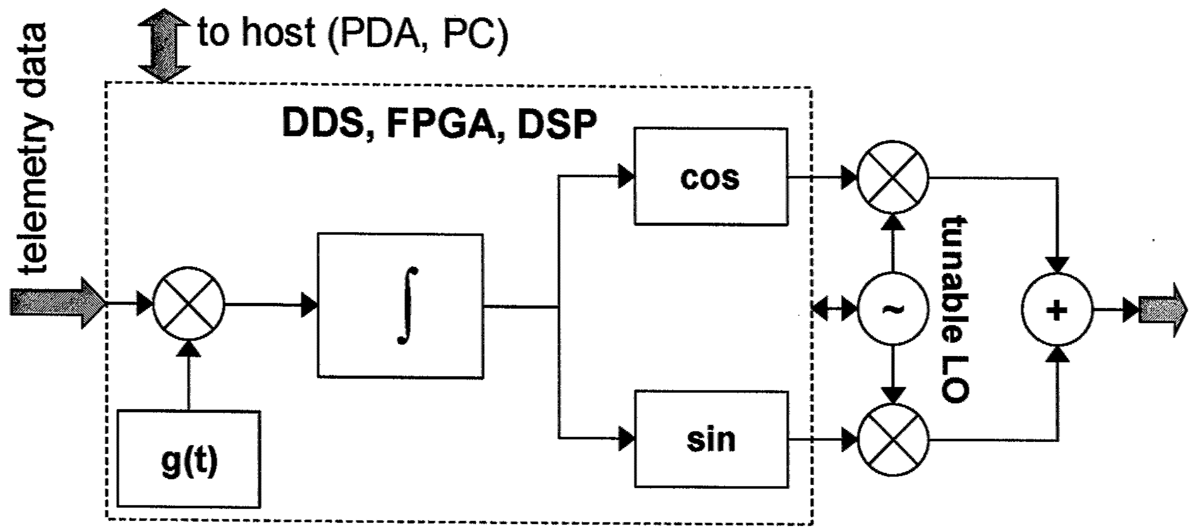

Figure 6: Potential architecture for digital generation of the baseband telemetry transmit stream.

2. Conclusions

This report has presented a prototype design for a telemetry transmitter capable of operating in both L and S bands. The system block diagram has been discussed, and the details concerning the implementation have been presented. The performance of the final system was found to meet the specifications for flight test telemetry transmission. Successful implementation of an operational version of this device would significantly increase the flexibility in scheduling frequency channels for aeronautical flight tests.

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