A bit synchronizer for telecommunication with a balloon-borne experiment

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Received 9 November 1998; revised 26 March 1999; accepted 8 April 1999

The bit synchronizer forms an important component of a telemetry ground station for receiving on-line information from a space-borne experiment. A new bit synchronizer for a pulse code modulation (PCM) telemetry system which was developed for use with the TIFR 100 cm balloon-borne far-infrared telescope payload has been described. This system performed satisfactorily during recent balloon flight experiments.

1 Introduction

Most space-borne experiments require two-way communication between the payload and the ground station. For active on-line control of the experimental parameters during the mission, it is necessary to (i) assess the present status of the experimental sub-systems and (ii) to modify any parameter, if needed, to optimize the science goal from the given space-borne experiment. Whereas the former is the responsibility of the telemetry downlink (payload-to-ground station communication), the latter is provided by the telecommand system. Decisions made at the ground station are uplinked by the ground station to the payload communication channel.

Pulse code modulation (PCM) telemetry is widely used as the downlink in several kinds of applications requiring high accuracy, varying degree of sampling of signals with differing characteristics, etc. This kind of modulation has advantages over other competing schemes, viz., (i) capability of handling analogue as well as digital signals, (ii) flexibility in the number of channels, (iii) a wide range of sampling rate and (iv) better noise immunity in the radio frequency (RF) tuner.

The onboard telemetry encoder collects various information as data sampled at regular intervals of time [most likely through an analogue to digital converter (ADC) for analog information] and expressed in digital (binary) form. These data are then time multiplexed and converted into a serial stream of bits. This well formatted and repetitive stream, in turn, is used to modulate an RF carrier by a transmitter. The bit stream has bits, words, frames, sub-frames as the units at different levels of hierarchy.

The major responsibility of the ground station is data recovery with as high a reliability as possible. The RF receiver regenerates the modulating signal stream (along with various noises) from the RF carrier. The first and the most important task at the ground station is to recover the bit timing (bit synchronization) from this analogue signal. The data cannot be regenerated/detected reliably without accurate recovery of the frequency and phase of the bit clock. Having accomplished the bit clock recovery, the actual bits of data have to be retrieved as accurately as feasible depending on the prevailing signal-to-noise ratio (SNR) in the signal channel. After having detected the bits, the later processing for word, frame and sub-frame synchronization becomes relatively simpler as they involve only digital logical decision making. Thus, in the entire chain of data recovery from the telemetry stream after the RF receiver stage, bit synchronizer is the most crucial stage of signal processing.

In the present paper, we describe a new bit synchronizer which has been designed and fabricated for use with the existing as well as the upgraded PCM-PM telemetry system of the balloon-borne far-infrared astronomy payload. The design of the present bit synchronizer is, somewhat, similar to the one developed earlier for a lower frequency application.

2 Bit synchronization

The most crucial aspect of bit synchronization is the detection of bit timing boundaries in the signal...
stream. Once the beginning and the end of each bit interval has been identified, the detection of the bit value involves either the sampling of the waveform at the middle of the bit duration (sampling detection) or the integration of the waveform over the bit period (integration detection). The latter, being much more superior in noise rejection capabilities, has been used in the present process.

There are several methods to derive the bit timings, viz., (a) use of the same master clock at both the transmitting and the receiving stations (used mainly in wired links), (b) use of an independent clock channel (additional channel capacity gets blocked) and (c) having the bit timing implicitly embedded in the signal by appropriate choice of the modulation scheme, the details of which are described elsewhere. The last method is the most efficient one for wireless links used between a space-borne payload and the ground station.

There exist many schemes of extracting the bit phase information based on the transitions between the bit values 0-1 or 1-0. In these schemes, bit transitions are identified and used to drive a phase locked loop (PLL) which is implemented by a combination of phase detector and a voltage controlled oscillator (VCO). However, this has an inherent weakness in the event of long sequences of 1’s or 0’s, which do not provide adequate bit timing information.

This weakness has been avoided here, by using a bit demodulation scheme of Bic-L. By virtue of this modulation, the high-to-low (or low-to-high) transition rate is guaranteed to be within a narrow range of 50%-100% of the fundamental bit clock frequency. It is to be noted that this does not introduce any inefficiency in the channel capacity or penalty in the form of loss of number of information bits (e.g. synchronization pattern, parity bits, etc.). The details of the implementation of the bit synchronizer are given in Sec. 2.1.

There are two other telemetry equipments (commercial units, which also perform the bit synchronization operation) which have been in use in the ground control segment of the TIFR balloon facility at Hyderabad. These are: (i) an EMR-720 PCM bit synchronizer, manufactured by Fairchild Weston Systems Inc. (Schlumberger); hereafter referred to as EMR, and (ii) the CDS d/pad telemetry data processor, manufactured by the Conic Data Systems (a subsidiary of Loral); hereafter referred to as CDS. Whereas the EMR unit performs only the bit synchronization, the CDS unit is a complete telemetry signal and data processing equipment, including not only the bit synchronizer, but also frame and sub-frame synchronizer and decommutator. Both these units are for general purpose and, hence, user programmable (e.g. bit rate, type of modulation, code, data polarity, etc).

In the present telemetry application, the most important specifications are the locking threshold and the level up to which the lock can be maintained once the lock has been achieved. Other specification regarding the sensitivity to the change in clock frequency, etc. is not important to us, since our onboard transmitter uses a crystal (whose temperature is quite stable). Hence, in the following, we compare the specifications of the above commercial units relevant to our application. Although, EMR has a synchronization threshold (search-to-lock) SNR of 3.5 dB and minimum SNR required to maintain the lock is 0 dB, this equipment has always performed several (3-5) dB inferior to the above specifications. The CDS unit also has identical specifications and has been performing (during 1980-1996) quite close to these specifications. However, due to aging and non-availability of adequate spare boards/components, the CDS unit functions only intermittently at present.

Against the above backdrop, it was decided to reduce the dependence of flight missions on the above commercial units. As a result we designed and implemented an indigenous bit synchronizer, which is dedicated to one specific balloon-borne experiment (100 cm far-infrared telescope). This also ensures that as and when the onboard telemetry system is upgraded for the need of higher communication bandwidth, the ground station bit synchronizer can also be modified accordingly. With the indigenization, this is practicable within the in-house know-how and other resources.

2.1 Specifications of new bit synchronizer

The telemetry link losses between the space-borne transmitter and the ground station antenna and receiver system, vary with time due to the (i) change in line-of-sight distance, (ii) change in the elevation angle of the payload with respect to the ground station (thereby leading to different atmospheric losses and ground wave interference), (iii) change in orientation of the onboard transmitter antenna (since
it is mounted flexibly for ease of launching), etc. Hence the signal-to-noise ratio of the demodulated signal (at the input of the bit synchronizer) is expected to vary too. The specifications for the new bit synchronizer (NBS) must consider all these aspects.

The new bit synchronizer was developed with the following specifications/design goals in mind:

(i) The NBS must operate satisfactorily with the old (existing) bit rate of 5 kbits/s, so that it is compatible with the old telemetry system of the far-infrared astronomy payload\(^5\,^4\). This requirement follows the anticipation of re-run of past experiment's raw telemetry receiver output stored in Ampex analogue tapes. In addition, the NBS should replace the old bit synchronizer even during the upgradation phase of the onboard telemetry system, which may last about one year.

(ii) The NBS must operate satisfactorily with the new bit rate of 10 kbits/s.

(iii) For any input signal-to-noise ratio of 6 dB (or better), the NBS must attain the 'lock' status from the 'search' mode.

(iv) Once in the 'lock' mode, the synchronization must not be lost as long as the input signal-to-noise level does not deteriorate below 0 dB level.

(v) The bit error rate (BER) must remain below the level of \(1 \times 10^{-6}\) while in the 'lock' mode.

(vi) The NBS must accept a dynamic range of the input signal level of 20 dB (volts), as dictated by the feeding RF receiver.

(vii) In order to optimize items (iii) and (iv) under different noise conditions at the input level, the facility for effectively controlling the NBS bandwidth must be present.

(viii) There should be adjustability of the centre frequency of the VCO of the PLL.

(ix) Diagnostics in the form of display of the offset between the centre frequency set and that actually found by the signal processing from the input signal, should be available.

### 2.2 Description of the bit synchronizer

The RF telemetry signal (136.25 MHz) transmitted by the balloon-borne payload's omnidirectional antenna is picked up by a ground station yagi antenna. This yagi is made to track (manually) the payload line-of-sight in azimuth and in elevation using the aspect information made available at regular intervals from a nearby radar or as derived from the onboard global positioning system (GPS) information relayed in the telemetry data. This yagi feeds to a Microdyne receiver (Model 1100-AR) which is a double superheterodyne with the first IF at 50 MHz and the second IF at 10 MHz. The plug-in unit covers the frequency range of 105-155 MHz, and has a nominal noise figure of 4.5 dB (maximum noise figure = 5.5 dB) with a transfer bandwidth of 3 MHz. The image rejection of the receiver is 60 dB min and the IF rejection is 80 dB min.

The Microdyne output is fed to the NBS described here. The block diagram of the bit synchronizer is shown in Fig. 1. The demodulated output of the Microdyne receiver which is in the Big-L format is fed to the input of the bit synchronizer where the signal is attenuated to a level of 1 V (peak-to-peak) to ensure linear operation of the circuitry. A d.c. rejection circuit with a cut-off frequency of 80 Hz helps in reducing the low frequency drifts, 1/f noise, etc. The signal is then buffered and passed through a low pass filter with a cut-off frequency of 20 kHz and a pass band gain of 1.3. This low pass filter can be switched into or out of the circuit from the front panel and is used only in cases of extremely noisy signals. From this point on, the signal is divided into two paths, namely, the 'clock channel' which extracts the clock information and the 'data channel' which extracts the data bits from the signal using the extracted bit clock.

The signal processing chain for the 'clock channel' is also described. A comparator shapes the high pass filter output into a square wave and clamps the output voltage to transistor-transistor logic (TTL) levels. This is then fed to a monoshot circuit which is triggered by both the edges of the pulses. The output pulse (width = 2.5 μs) is used to trigger a phase locked loop (PLL) which has a centre frequency of either 5 kHz or 10 kHz depending on the telemetry system under use. The centre frequency of PLL can be adjusted interactively within a range of ±10 % of the designed value of the centre frequency. The 10 kHz (5 kHz) PLL is designed to have a lock range of 6.6 kHz (3.3 kHz). The error output of the phase detector portion of PLL is also fed to a centre-zero current meter for visual display which is useful in interactive adjustment of the centre frequency of PLL. The output of VCO portion of PLL is delayed by a small amount to take care of the delays occurring in the signal path. The clock signal is delayed (by 1.6 μs) to ensure that the data are stable before the
arrival of the clock edge. This output is termed as the ‘delayed clock’ of NBS. The clock signal is also fed to a chain of monoshots to produce a data detection pulse (2 μs wide) and the bit integrator discharge pulse (16 μs wide), which are used in the data extraction channel.

The data extraction channel consists of a phase sensitive detector (PSD) which extracts the data bits from the signal which has been extracted by using the clock signal as described above. The data are then integrated over a bit period to improve the signal-to-noise ratio. The output of this integrator is sampled at the end of the bit period. Thereafter, the integrator is discharged. The data are then converted to the return-to-zero (RZ) and the nonreturn-to-zero (NRZ-L) formats by using logic circuits using a set of flip-flops. Further details of the hardware implementation are given in Sec. 3.

3 Hardware implementation

The actual circuits corresponding to the entire new bit synchronizer, implementing the schematic block diagram of Fig. 1, are shown in Figs 2 and 3.

The input to NBS (coming from the telemetry receiver) is filtered and attenuated using operational amplifiers of type LM 741 and pulse shaped using LM 710 (Fig. 2). Further digital processing of the clock signal uses TTL monoshots (74121s). The PLL used is LM 565. In the data extraction channel, the phase sensitive detector (PSD) stage is implemented by two analog switches from the CMOS IC CD4066 and low input bias/offset current operational amplifier LM 308. The latter is also used for implementing the integrator stage. An analog switch (CD 4066) is used for discharging this integrator. The flip-flops used are of TTL 7474 type, and all logic
units are implemented using the TTL 7400 gates (Fig. 3).

4 Qualification tests and performance during balloon flights

All sub-units of the new bit synchronizer (NBS) system (e.g. filters, PLL, PSD, etc.) were separately tested in the laboratory to ascertain that they functioned within the designed tolerances. The fully assembled bit synchronizer was then tested for all its specifications. These tests involved simulations of RF receiver output with different SNR conditions, which was synthesized using pattern generating circuits and test instruments like function generators, noise generators, etc. The noise spectrum, power and bandwidth were varied as required during the qualification tests. Finally, the tests were repeated with live as well as recorded real telemetry signals before certifying the NBS to be fit for on-line application during a balloon flight. The bit synchronizer was found to lock onto the signal at an SNR of 4.6 dB and it remained locked up to an SNR of 0 dB which is better than the design specifications.

This NBS has been used during two actual balloon flights so far. This NBS is now an important constituent of the ground station set-up for the TIFR’s balloon-borne far-infrared (FIR) astronomy payload (which is a 100-cm diameter telescope). This FIR telescope payload was launched during winter 1995 (12 Nov. 1995) and summer 1998 seasons (8 Mar. 1998). Whereas the former mission used the slower bit rate telemetry (5 kHz), the latter used the new faster telemetry system (10 kHz). During both the missions, NBS performed satisfactorily as per its specifications.

During a typical ground test/flight campaign, NBS was used to feed a frame synchronizer and decommutator (FSD) which, in turn, drives a hub of three PCs. The FSD is a microprocessor based system designed and developed at TIFR. These PCs used the telemetered data asynchronously for continuous controlling and monitoring the far-infrared telescope payload. The controlling involved changing the aspect of the telescope, observational parameters, etc., as and when desired. The monitoring involved several crucial sub-systems of the payload requiring
constant watch on their behaviour (done through software modules written in high level languages like Fortran and C). Based on NBS usage and performance during the aforesaid two balloon flight campaigns (including ground tests; field calibration; all phases of the balloon flights, viz., ascent, float and descent), it may be concluded that the bit error rate (BER) was lower than $1 \times 10^{-7}$. This is far better than the target specification for NBS.

The following comments are found to be in order here, when NBS is compared with the other two commercial units, viz., EMR and CDS systems. Whereas the EMR and CDS systems are for general purpose covering a wide range of user selectable parameters, the present NBS is for a specific application only. Comparing the technical specifications alone, both EMR and CDS systems are marginally superior to NBS. However, as mentioned earlier (Sees 2 and 4), in practice, during bench tests, simulations and real time flight signal processing, the NBS has proved to be much more vitally useful (since NBS has performed even better than its specifications, whereas EMR and CDS have underperformed).

5 Conclusions

From the above discussion, it is clear that a new bit synchronizer has been successfully developed and commissioned for telecommunication from the ground station to a balloon-borne payload. This bit synchronizer has already given satisfactory performance during two balloon flight missions, and will be used regularly for future balloon flights of the TIFR 100-cm far-infrared telescope for astronomical studies.

Acknowledgements

The authors thank all the members of the Infrared Astronomy Group of TIFR, Mumbai, as well as the members, particularly Shri S Sreekumar, of Control Instrumentation and Balloon Support Group at TIFR.
Balloon Facility, Hyderabad, for their cooperation and help during the course of work.

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