NOVA AND GEOSAT COMPUTERS

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ABSTRACT

Two computers, utilized on-board the Navy satellites NOVA, launched in May 1981, and GEOSAT, to be launched in early 1984, are reviewed. The NOVA computer is an extension of the TRIAD design presented at the 1972 Government Microcircuit Applications Conference. The NOVA computer is the third generation digital data handling system for the Navy Transit Navigation Satellites. Covered in this paper is the computer architecture, hardware design, and relation to other satellite systems. The design of the NOVA computer software and its in-orbit performance is covered in a companion paper. The NOVA computer is an integral part of the on-board data handling system. It formats the Transit navigation message, stores and analyzes telemetry, and executes commands to extend the autonomous operation time of the satellite. The GEOSAT computer is a signal processor for a satellite born radar altimeter. It is an extension of the SEASAT-A design presented at the 1977 JBIS Symposium on Computer Techniques for Satellite Control and Data Processing. Its principal design feature is the incorporation of a microprocessor. The GEOSAT computer performs return signal acquisition, range tracking, receiver gain control, calibration, ocean wave height estimation, telemetry formatting, and command decoding. This paper gives a brief description of the GEOSAT computer functional performance, hardware, and software.

INTRODUCTION

Two types of on-board computers are described. The first is a sixteen bit word length computer designed specifically as a data formatter and controller for the NOVA Navy Navigation Satellite. The history that led to its development and a brief hardware description is given. Its software implementation and its in-orbit performance is covered in a companion paper. The second computer is a 8085 microprocessor based design. This computer is utilized to perform radar altimeter processing on-board the Navy GEOSAT oceanic satellite. An introduction to four related satellite born radar altimeter designs, SEASAT, NOSS, TOPEX, and GEOSAT is presented. Then a description is given of on-board data processing for a satellite radar altimeter.

HISTORY OF NAVSAT COMPUTER DEVELOPMENT

The Navy Navigation Satellite System is one of the earliest programs designed to put space systems to practical use(1). It established a navigation capability through the use of artificial satellites. The program was conceived and developed by The Johns Hopkins University Applied Physics Laboratory. The development started in 1959 and became operational under the control of the Navy Astronautics Group in 1964. The Navy Navigation Satellite System is a worldwide, all-weather system that provides accurate position fixes from data collected during a single pass of an orbiting satellite.

First Generation

The first generation navigation satellite was launched in 1962. The on-board data processor consisted of magnetic-core diode circuitry used to perform logic and also to drive a 24,000 bit core memory array. The design of the first generation system established the navigation message data format currently in use.

The Second Generation

The second generation data processor was launched on-board a navigation satellite in June of 1965. This processor was the first application of integrated circuits on-board a Navy Navigation Satellite. It utilized series 51 RCTL integrated circuits to perform logic and a core memory array driven with hybrid semiconductor circuits. Three of this generation of satellites have been operational for more than 10 years. These satellites now have predicted life expectancies in excess of 13 years.

The TRIAD Satellite

In September 1972, the first in a series of three experimental/operational satellites designed to test improvements to the Navy Navigation Satellite System was launched(2,3). This satellite is three bodied and called TRIAD. It contains as new systems a disturbance compensation system (DISCOS), a pseudo random noise (PRN) experiment, an incremental phase shifter (IPS), and a general purpose programmable computer. TRIAD consists of three bodies interconnected with booms. The center body contains the DISCOS used to sense and compensate for air drag. The upper body contains the satellite power system. The lower electronics body contains the computer. The TRIAD computer is the first general purpose computer utilized on-board a Navy Navigation Satellite. The computer is designed as an integral part of the data handling system. It functions as a real-time controller operating under prioritized interrupts, storing the navigation message and delayed commands, reading out the navigation message and commands, monitoring and storing telemetry data, monitoring and storing data on the operation of the DISCOS and its propulsion system, and processing data for IPS and PRN. The basic architecture of the TRIAD computer is the forerunner of the NOVA computer. The TRIAD computer processor is designed utilizing type 54 and 54LS TTL integrated circuits. The computer utilizes a 4096 word X 16 bit core memory.

The TIP-2 and -3 Satellites

The second and third of the series of experimental/operational satellites, designed to test improvements to the Navy Navigation Satellite System, are TIP-2 launched October 1975 and TIP-3 launched September 1976. The TIP-2 and -3 satellites are prototypes for the new series of NOVA satellites to replace the older generation Navy Navigation Satellites. The TRIAD satellite, considered the first TIP satellite, employs a three axis DISCOS. A axis DISCOS is used on TIP-2 and -3 providing capability orbit of ±85 meters for a minimum 7-day period. The TIP-2 fly the first prototypes of the NOVA computer.

THE NOVA COMPUTER

The NOVA computer consists of two redundant central processing units complete with input/output logic and two redundant 16,384 word memory units. Either or both memory units may be used with either of the redundant central processing units. Computer function (Figure 1) includes operation to control the incremental phase shifter to track oscillator drift, position solar blades after deployment, control satellite spin up, store telemetry, and control the orbit adjust thruster firing to establish the desired orbit. During satellite operation the flight computer stores, formats, and transmits up to five days of NAVSAT messages without ground support.

Design features of the NOVA computer include cross-coupled subsystem redundancy between computers and other satellite subsystems, cross-coupled redundancy between processors and memories with switched power so that a single processor can operate with either memory or with both memories in series, and memory capacity of 16,384 16-bit words per memory subdivision. The logic circuitry for the processor (Figure 2) and also the memory are packaged on multilayer printed circuit boards with plated-through hole construction. The board layout and routing were accomplished by computer control. Each processor and memory are separately housed in a magnesium casting. A processor-memory set occupies 2,998 cc . The voltage regulators are
to the processors and memories. A single computer weighs 3.18 kg. The computer power is: (a) 4 W standby, and (b) 30 W at 100% duty cycle access to core memory.

Processor

The NOVA processor is a sixteen-bit parallel organization. A status register contains the carry, overflow, input-output flags, power mode control bits, and eight interrupt marks. The processor, in addition to an accumulator and index register, contains a real-time clock register. Operations that are performed with the accumulator can also be performed with the clock register. The program address register is also part of the general register set. The control section of the processor contains the instruction register, state register and iteration counter. The major considerations used to determine the machine architecture were:

1. Low overhead for entry into the exit from short data formatting tasks,

2. high program storage efficiency,

3. fast reaction time to interrupts,

4. NAVSAT output formatting primary bench mark,

   and

5. total power shutdown capability.

SATELLITE RADAR ALTIMETERS

The first Applied Physics Laboratory space borne radar altimeter design began in 1973. This effort led to the design of the radar altimeter for the SEASAT mission(4). The National Aeronautics and Space Administration has supported the development of progressively more accurate satellite radar altimeters as part of the Earth and Ocean Physics Applications Program. Altimetry was first proposed as a tool for extending our knowledge of the geoid, obtained from precision doppler tracking of satellites. The design of an altimeter sufficiently precise for geodesy was found also to be capable of resolving surface topographic features of oceanograph interest including ocean currents, tides, waveheights and coastal upwellings. Since the launch of the SEASAT-A spacecraft in 1978 the Applied Physics Laboratory has been engaged in the design of a radar altimeter for both NASA and Navy oceanic use.

The SEASAT Altimeter

The SEASAT satellite is designed to provide all-weather, global monitoring of the sea surface temperature, wind speed and direction, and departures from the marine geoid corresponding to ocean dynamic processes(5). The radar altimeter, designed and fabricated at the Applied Physics Laboratory, is one of the five sensors installed on the SEASAT satellite. The SEASAT satellite also contains a synthetic aperature radar, a fan-beam scatterometer, a scanning multifrequency microwave radiometer and a visible and infrared radiometer. The performance requirements of the SEASAT radar altimeter is a one year mission life, limited mainly by the 2 kW peak power traveling wave tube. The altimeter design is required to measure the height above the ocean to an accuracy of ±10 cm and measure wave height of the area surface beneath the satellite to an accuracy of ±10% or 0.5 meters. The effective footprint diameter of the SEASAT altimeter is 1.7 km.

The two primary outputs of the SEASAT altimeter are the precision height from which the ocean geoid and surface topography are determined and the wave height estimate. Both are calculated via the altimeter computer(6). The on-board computer performs return signal acquisition, range tracking, receiver gain control, calibration, ocean wave height estimation, telemetry formatting, and command decoding. The computer hardware utilizes the 8080 microprocessor with 4096 bytes of program memory and 2048 bytes of scratch pad memory. It performs tasks on three interrupt levels utilizing eighty-five percent of its maximum processing capability.

SEASAT was launched successfully on 27 June 1978. The satellite operated successfully for three months reporting continuously on changing ocean conditions such as wave height and direction, surface winds, water temperature, current and tide patterns, and ice field locations, when a power system failure terminated its operation.

The NOSS Altimeter

The National Oceanic Satellite System (NOSS) radar altimeter is to be part of the instrument complement of the NOSS satellite(7). The purpose of NOSS is to provide improved long-range weather forecasting for both ocean and continental areas. The NOSS altimeter design is similar to the SEASAT altimeter with changes and improvements required to meet the NOSS performance specifications. Preliminary design of the on-board data processor began in December 1979. The technical plan was completed in March 1981. The NOSS program was scheduled as a 1982 NASA start until eliminated from the 1982 Congressional budget.

A significant design innovation over SEASAT for the NOSS satellite is to make the radar altimeter on-board computer ground programmable. To allow for post launch changes in the software, a capability for program loading via command uplink is specified. This would allow for optimization of altimeter performance and facilitate experimental modes during the three year mission. This, as a change to the SEASAT design, required, as a minimum, additional read-write memory, a faster version of the 8080 microprocessor, and a standby power supply to prevent loss of stored software during altimeter power cycling.

Additional software requirements for the NOSS satellite included:

1. A rainfall detection capability utilizing an unchirped pulse mode time shared with the normal track chirp pulse.

2. A new seastate (wave height) computation to correct a bias at low wave height.

3. A continuous collection of statistics (min, max, mean, standard deviation) on selected parameters to help pinpoint problems in a timely fashion.

4. The implementation of a shorter automatic gain control (AGC) time constant when passing over rain cells.

5. Shifting of the track point from the center of the filter bank to an early filter to obtain more of the total signal in the waveform samples.

   and

6. Changes in telemetry format to aid in ground processing.

An 8085 based on-board data processor was incorporated early in the NOSS altimeter-design. As the design progressed, and the processing requirements matured, the newly Joint Army-Navy (JAN) rated 8086 microprocessor replaced the 8085.

The TOPEX Altimeter

The Ocean Topography Experiment (TOPEX) altimeter will be part of a satellite instrument complement which will provide global measurements of the ocean surface conditions(8). The TOPEX altimeter preliminary study was started April 1980 and is currently in the development phase. The performance specification requires twice the SEASAT precision, a five year lifetime, tolerance of a 1.5 degree attitude control system and adaptive resolution. The primary mission of the altimeter is to measure the surface signature of oceanographic phenomena including currents, gyres, eddies, and rings. The altimeter will also determine wave height, wind speed, rain rate and ionospheric electron content. The TOPEX altimeter is a dual frequency design providing the capability of ionospheric disturbance correction. Variable resolution capability is made possible by a digital chirp pulse generation technique which enhances the ability of the altimeter to maintain track over rough slopping terrain.

The dual frequency radar channels of the TOPEX altimeter, essentially doubles the on-board data processing requirement. Each radar return chirped pulse is processed by twice the number of filters as the SEASAT altimeter, again doubling the processing load for most of the track algorithms. The processing rate requirement for TOPEX totals to more than 5 times SEASAT. The high data processing rate requirement of TOPEX is a major factor in the choice of a data processor.

The choice of a data processor for the TOPEX radar altimeter preliminary study is influenced by the following, sometimes conflicting requirements.

1. Most of the processing structures and algorithms match SEASAT, and SEASAT processing is coded in 8080 assembly language.

2. The incorporation of post launch reprogramming capability makes it essential that a software development approach be taken that produces programs which can be easily understood and modified.

3. The TOPEX satellite may be flown at a higher altitude than SEASAT, 1334 km versus 800 km, significantly increasing the radiation hazard.

   and

4. The fivefold increase in processing rate requirement, compared to SEASAT, drastically limits the choice of computers.

Candidate computers for the TOPEX altimeter include designs based on the 9445, 9989, and the 8086 microprocessors.

The GEOSAT Altimeter

The principal purpose of GEOSAT is to provide the Navy a large quantity of oceanographic data with at least the SEASAT quality(9). The GEOSAT design plan was presented to the Navy in December 1979. The scheduled program start date is October 1981. The GEOSAT satellite will consist essentially of a SEASAT type altimeter and a control module derived from the GEOS satellite series developed at the Applied Physics Laboratory. The GEOSAT satellite will use the GEOS structure and launch vehicle interface for a Delta rocket. Doppler-beacons developed for the GEOS satellites will be used to determine the orbit of GEOSAT. The GEOS power system will be extended to meet the radar altimeter power requirements. The real-time command system designed for the NOVA satellite will be incorporated into the GEOSAT design. A fixed format telemetry will interface with NASA standard 5×10^8 bit tape recorders. The Applied Physics Laboratory, Howard County, Maryland, satellite injection station will provide the primary ground support. The backup ground support will be provided by the Navy, Point Mugu, California, injection station.

The GEOSAT altimeter computer hardware design will focus on reliability improvements for a long mission requirement. The point-to-point welded wire fabrication technique utilized at the Applied Physics Laboratory allows microprocessor and memory type substitution without effecting component board artwork. The CMOS 8085 microprocessor currently under development at Sandia Laboratories will be incorporated in the design if it is available on the GEOSAT time schedule. Otherwise, a HMOS 8085 microprocessor design will be utilized. Read-write memory selection will be made with attention to susceptibility to cosmic-ray-induced soft errors.

RADAR ALTIMETER DATA PROCESSING

The signal interface between an on-board computer and other units of a radar altimeter is shown in Figure 3. The digital filter converts the chirped mode radar return signal into a series of sample points representing the return signal waveform (Figure 4). The number of sample points ranges between 64 and 128. The digital processor then sums each sample vector (array of points) over a group of radar return waveforms, typically 50, to accomplish post detection filtering. After waveform smoothing the result is released for the next processing step as a new group of radar return waveforms are summed. Each ocean return sample point is digitized by the digital filter to 8 or 9 bits in length. The samples are summed into 16 bit length words. The return signal waveform outputted by the digital filter appears as a noisy filtered step function (Figure 4). The beginning of the step signifies the beginning of the ocean signal return. The slope of the step is a function of the ocean wave height. The sample points are spaced along the waveform at approximately 3 ns intervals giving a total sample window of approximately 200 ns.

Gate Formation

The smoothed sample points are processed, as shown in Figure 4, to form normalized early, middle and late gates by summing adjacent sample points along the return signal waveform before the return signal step, during the return signal step and after the return signal step respectively. An effort is made to keep the number of sample points summed a power of 2 so normalization may be accomplished by right shifting. A normalized gain control gate is also formed by summing all the sample points. From these gates running averages of the late gate minus the early gate, and a running average of the gain control gate minus the middle gate are maintained. From these processed gates, a range tracking error, a wave height estimate, and a receiver gain control value are derived. A test for track lock is also performed. The set of gates used for range tracking error and wave height estimation is selected as a function of ocean wave height. The higher the ocean waves the longer the rise time of the return signal, and the wider the early middle and late gates are selected. To accomplish gate width selection, processing is actually performed concurrently on six or more different sets of early middle and late gates. Running averages of the difference between late and early gate samples are maintained for all sets of gates. The widest gate width late-minus-early running average is used to normalize the other running averages. The normalized late-minus-early running average closest to the optimum value is selected for wave height determination. Wave height determination is made utilizing a lookup table for the selected gate set.

To determine range error the gain control gate is subtracted from the middle gate. This result is properly scaled to form a signal proportional to the tracking loop misalignment. The generation of a gain control signal is derived by summing and scaling all sample points giving the average value of the ocean return. The gain control loop drives this average value to a preset constant. The time constant of the gain control loop is selectable in the range of one half second to several seconds.

Alpha-Beta Tracker

A tracker of the alpha-beta type is implemented to smooth the range error measurement developed from the adaptive gate selection process and form the range and range rate predictions. The alpha-beta tracker maintains range and range rate words which are updated by the range error word generated as part of the adaptive gate selection process. That is:

New Range ← Old Range + alpha x Range Error,

and

New Range Rate ← Old Range Rate + beta x Range Error.

The scaling of the range error is selected as a function of gate selection, which is a function of the estimated wave height, to maintain optimum tracking loop bandwidth and damping over the range of wave height measurements required. The alpha-beta track process is completed at the radar pulse repetition rate by developing the predicted height word for each radar return pulse to place track gates at the correct position. That is:

New Range ← Old Range + Range Error.

Signal Acquisition

The computer controls the signal acquisition process. One method used for signal acquisition is to place the altimeter in the unchirped mode and measure the time between transmit pulse and return pulse with an interval counter. In the unchirped mode the receiver gain control loop is closed to drive the probability of return detection to fifty percent. Continuing the gain control loop, detection ranges are collected and the average range computed. Using the unchirped pulse gain control word and the unchirped average range an initial estimate of range and receiver gain control is computed for the chirped pulse mode. The radar is then switched from the unchirped to the chirped mode and the range gates are set ahead of the predicted chirped range. The chirped waveform window is then moved in approximately 50 nanosecond increments each 50 milliseconds until the return signal is recognized and signal acquisition is established.

Calibration

Calibration modes are implemented as a means of accurately calibrating the range measurement itself. The most complex calibration mode involves the switching of the calibration reference signal on one tenth of a second every five seconds while the altimeter is locked onto the return ocean signal. Ocean tracking loop coast calculations are performed while obtaining calibration signal tracking data. A calibration signal attenuator is adjusted such that the gain control signal for ocean return matches the gain control signal for calibration.

Telemetry Formatting

The scientific data which is necessary to realize the altimetry and wave height measurement requirements is formatted and outputted 10 to 20 times per second to the satellite interface. This data includes the range, range rate, the range error, the ocean wave height, the receiver gain control word and the averaged waveform sample points. In addition to the scientific data, engineering data consisting of power supply voltages, temperatures, and status information is also outputted.

Command Decoding

The computer processes commands received via the satellite interface. For one implementation, ten bit data commands are interpreted to place the altimeter in the desired mode. The ten bit command word is divided into an eight bit field and a two bit field. The two bit field defines four classes of command. The first class of command is executed without an interruption of the altimeter timing allowing uninterrupted telemetry formatting and a smooth transition from one mode of operation to another. The second class of command causes the initialization of the altimeter, and a self check on the computer and memory before switching to the commanded mode. The third class of command allows the loading of a memory dump location and block length information to be used in conjunction with telemetry format modes. The fourth class allows the loading of track and acquisition parameter options allowing the changing of bandwidths, time constants and thresholds. Command types are standby, calibrate, track modes, a traveling wave tube fault reset, and test modes. Option bits in the command word allow the automatic cycling through of a calibration mode every hour, or every five seconds, or a memory dump sequence.

CONCLUSION

The choice of small and medium scale bipolar logic integrated circuits for the NOVA computer design was necessitated by environmental and extremely long life (10 years plus) requirements. A 1982 design of the NOVA computer would probably yield only marginal benefits from recent advances in semiconductor technology. This is not the case with radar altimeter computer design. Processing algorithms for acquisition, track, wave height determination, and the telemetry format continue to change. A move to a high level language to produce software that can be more easily understood and modified is essential to facilitate post launch reprogramming. The trend here is toward the most capable on-board computer consistent with environmental and reliability requirements provided by new developments in very large scale integrated circuit technology.

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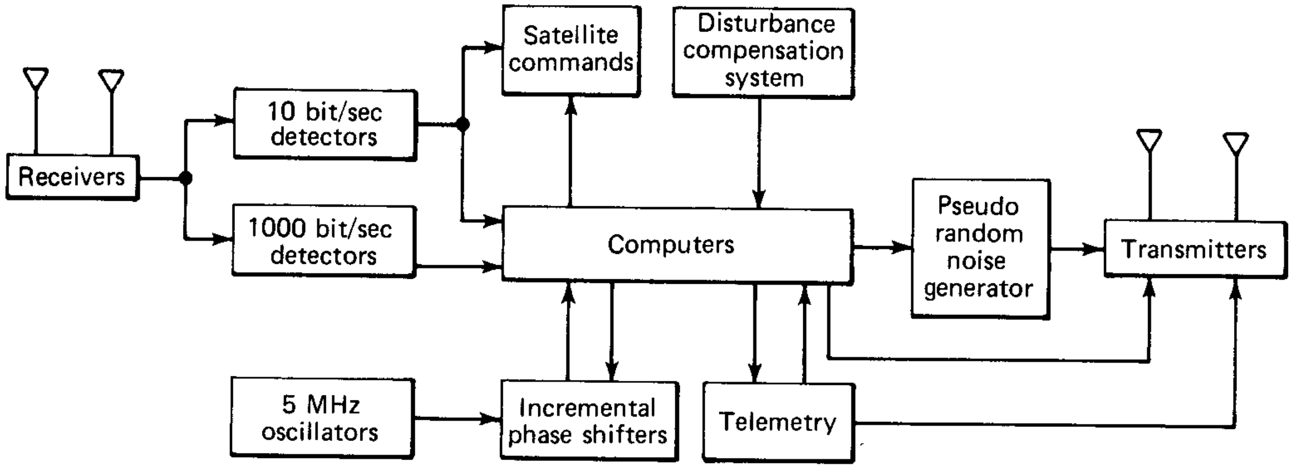

Fig. 1 NOVA computer relation to other satellite systems.

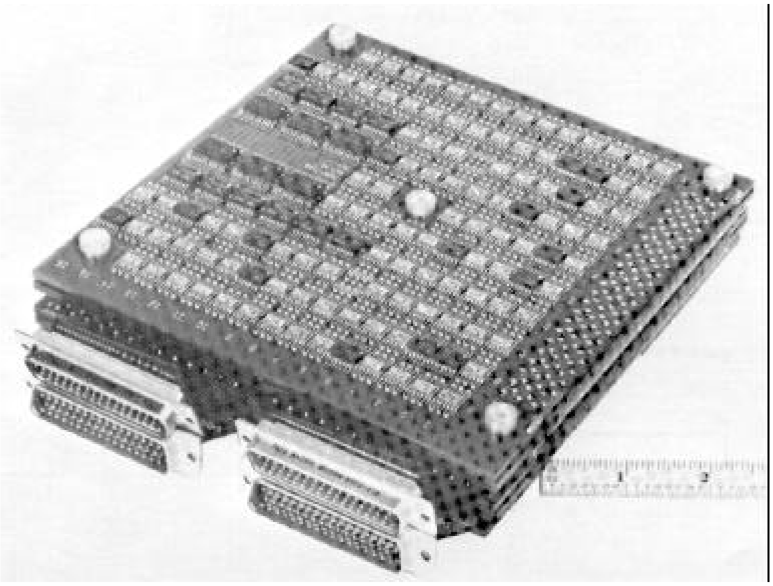

Fig. 2 NOVA computer processor.

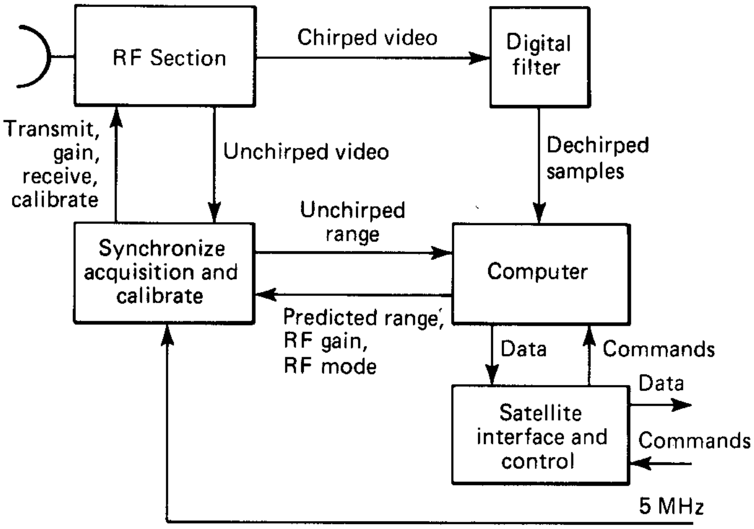

Fig. 3 Computer interface to altimeter.

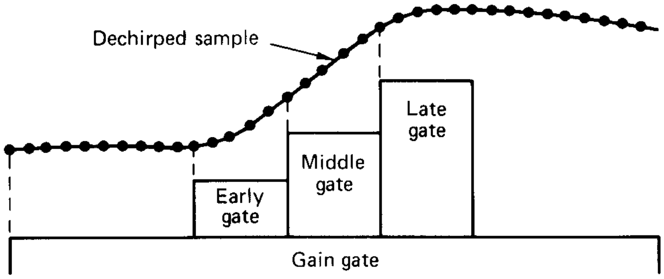

Fig. 4 Dechirped signal waveform.