The CTA 21 Radio Science Subsystem — Non-Real-Time Bandwidth Reduction of Wideband Radio Science Data

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The concept of a centralized facility at JPL to reduce the bandwidth of wideband digital recordings originated with the Pioneer Venus Differential Long Baseline Interferometry (DLBI) Experiment. This article presents a functional description of the resulting facility – the CTA 21 Radio Science Subsystem (CRS), located within JPL at the Compatibility Test Area (CTA-21). Particularly emphasized is a mathematical derivation and description of the digital filter process which comprises the core of the CRS.

I. Introduction

In December 1978, the Pioneer Venus Multi-probe Mission Spacecraft will encounter the planet Venus, and at that time the Differential Long Baseline Interferometry Experiment will attempt to measure the wind velocities in the atmosphere of Venus as four probes descend through the atmosphere. The fundamentals of the experiment are described in Reference 1. The end product at each of the involved tracking stations will be a wide bandwidth digital recording (magnetic tape) covering the entire bandwidth of interest, which includes five spacecraft signals (the spacecraft bus and the four descending probes). Plans to mid-1976 had assumed that the deliverable to the experimenter, located at the Massachusetts Institute of Technology (MIT), would be the actual wideband recordings produced at these tracking stations. This plan involved the Project procuring for the experimenter recorders capable of playing back these wideband recordings, and required that the experimenter implement and operate a system to convert the wideband recordings into a usable computer-compatible form. Estimates by MIT of the resources required to implement and operate this conversion process turned out to be a very significant portion of the total processing costs at MIT for the experiment. This problem resulted in the evolution of the concept of a centralized facility at JPL ("CTA 21 Radio Science Subsystem") to reduce the bandwidth of the wideband digital recordings and supply the experimenter with the bandwidth reduced data on computer-compatible magnetic tape. In the following sections, the functional characteristics and operation of the CTA 21 Radio Science Subsystem will be described.

II. Functional Description of the CTA 21 Radio Science Subsystem

A. Definition

The CTA 21 Radio Science Subsystem, a dedicated and integral element of the DSN Radio Science System, performs the following functions:

(1) Reduces the digitally recorded output of the wideband open-loop receiver to a narrow bandwidth centered about a predicted frequency profile.

(2) Interprets the timing information included with the digitally recorded wideband open-loop receiver data, and appropriately time-tags the bandwidth-reduced output data.

(3) Provides the time-tagged bandwidth-reduced output data and the corresponding predicted frequency profile on computer-compatible magnetic tape for distribution to the appropriate Radio Science Experimenters.

CTA 21 Radio Science Subsystem functions and interfaces are presented in Figure 1.

B. Key Characteristics

The key characteristics of the CTA 21 Radio Science Subsystem are as follows:

(1) Hardware and software are compatible with the DSN Mark III configuration.

(2) Processing is fully digital and automated:

(a) A posteriori frequency profile obtained from project navigation-DSN prediction system via high-speed data (HSD) interface.

(b) Processing proceeds at wideband tape sample rate.

(c) Playback of output tape detects signal presence.

(3) Bandwidth reduction filter is an integrate-and-dump, with dump performed by computer.

(a) Output sample rate is adjustable from 1/200 to 1/4000 of input sample rate.

(b) Maximum tracking rates accommodated by variation of output sample rate.

(4) Timing information recorded with the wideband input data is interpreted and used to time-tag the output data.

(5) Output tape quantity is dependent upon user-selected sample rate.

(6) A computer-compatible tape, which includes the bandwidth-reduced data and the corresponding a posteriori frequency profile, is provided to the Experimenters.

C. Functional Operation

The CTA 21 Radio Science Subsystem (CRS) functions and data flow are presented in Figure 2. A magnetic tape, containing wideband open-loop receiver data which have been recorded by the Digital Recording Assembly of the DSS Radio Science Subsystem, is received at CTA 21 in nonreal time via Network Information Control (NIC). Additionally, an a posteriori frequency profile is received via high speed data line (HSDL) from the NOCC Support Subsystem, and is stored. The wideband open-loop receiver data is played back via the Digital Recording Assembly within the CRS, and the Bandwidth Reduction Assembly performs the bandwidth reduction process, using an integrate-and-dump digital filter which is preset to the starting sample and the predicted frequency and phase (presetting the filter with a predicted starting phase allows the processing to occur in segments, if necessary). The processing proceeds at the wideband tape sample rate, and results in a bandwidth reduction of 1/200 to 1/4000 of the input bandwidth. The integrate-and-dump routine provides an effective filter of $\sin (N\pi f/2f_0)/\sin(\pi f/2f_0)$ where N is the decimation ratio and f_0 is the input bandwidth. Figure 3 is a functional block diagram of the Bandwidth Reduction Assembly.

The appropriately time-tagged, bandwidth-reduced data and the a posteriori phase information are written on computer-compatible tape for delivery to the Experimenters. As a final step, the output tape is played back for signal detection and validation.

III. Analysis of the Bandwidth Reduction Assembly Signal Processing

A mathematical analysis of the signal processing performed by the bandwidth reduction assembly is given in this section. Effects of noise and quantization are not considered.

A simplified block diagram of the signal processing involved in the bandwidth reduction is shown in Figure 4, where

$\phi_a(t)$ = actual (probe) phase

$\phi_p(t)$ = predicted (probe) phase

Δt = (input) data sample interval $= 1/2(2\,1/12 \times 10^6) = 0.24\ \mu\text{sec}$

The digital filter input sequences $x(n\Delta t)$ and $y(n\Delta t)$ are given by

$$\begin{aligned} x(n\Delta t) &= A \sin \phi_a (n\Delta t) \cos \phi_p (n\Delta t) \\ &= \frac{A}{2} \left\{ \sin [\phi_a (n\Delta t) - \phi_p (n\Delta t)] \right. \\ &\quad \left. + \sin [\phi_a (n\Delta t) + \phi_p (n\Delta t)] \right\} \end{aligned}$$

$$y(n\Delta t) = A \sin \phi_a (n\Delta t) \sin \phi_p (n\Delta t)$$

$$= \frac{A}{2} \left\{ \cos [\phi_a (n\Delta t) - \phi_p (n\Delta t)] - \cos [\phi_a (n\Delta t) + \phi_p (n\Delta t)] \right\}$$

Note that the first term in the final expressions for $x(n\Delta t)$ and $y(n\Delta t)$ above is a sampled signal of frequency $\omega_d(t) = \dot{\phi}_a(t) - \dot{\phi}_p(t)$ while the second term is a sampled signal of frequency $\omega_s(t) = \dot{\phi}_a(t) + \dot{\phi}_p(t)$. If $\phi_p(t)$ is properly computed $\omega_d(t) << \omega_s(t)$. The low frequency term is the desired output of the digital filters.

The frequency response of the digital filters can be determined by noting that if

$$x(n\Delta t) = e^{j2\pi f n \Delta t}$$

then

$$u(n\Delta t) = \overline{H}(f) e^{j2\pi f n \Delta t}$$

where $\overline{H}(f)$ is the frequency response of the filter. Computing $u(n\Delta t)$ yields

$$u(n\Delta t) = \sum_{k=0}^{N-1} e^{j2\pi f(n-k)\Delta t}$$

$$= \left(\sum_{k=0}^{N-1} e^{-j2\pi k f \Delta t} \right) e^{j2\pi n f \Delta t}$$

and thus

$$\overline{H}(f) = \sum_{k=0}^{N-1} e^{-j2\pi k f \Delta t}$$

As is to be expected, $\overline{H}(f)$ is periodic with period $1/\Delta t$. Summing the series yields

$$\overline{H}(f) = e^{-j\pi(N-1)f\Delta t} \frac{\sin \pi N f \Delta t}{\sin \pi f \Delta t}$$

the magnitude of which is sketched as a function of $f\Delta t$ for N = 7 in Figure 5.

Note that in general the first zero of the frequency response occurs at $f\Delta t = 1/N$. If $\phi_p(n\Delta t)$ is properly computed $f_d \Delta t = \omega_d \Delta t / 2\pi < 1/2N$. Since the sampling interval $\Delta t = 1/2B$ where B is the input bandwidth (Nyquist rate)

$$f_d < \frac{2B}{2N} = \frac{B}{N}$$

corresponding to a bandwidth reduction factor of at least N. This in turn means that the output samples need only be computed at intervals of $N\Delta t$ (corresponding to an "integrate and dump" filter) resulting in a significant reduction of data. The ratio N of the input sample rate to the output sample rate is called the "Decimation Ratio." Of course, care must be taken that $f_s \Delta t = \omega_s \Delta t / 2\pi$ corresponds to a point of high attenuation in the filter response relative to $f_d \Delta t$.

As an example, the actual bandwidth reduction assembly has the following specifications:

$$\text{Input bandwidth} = 2\ 1/12 \text{ MHz} = B = \frac{1}{2\Delta t}$$

$$\Delta t = \frac{1}{2\,(2\ 1/12 \times 10^6)} = 0.24\ \mu\text{sec (Nyquist rate)}$$

Decimation Ratio N adjustable from 200 to 4000 (corresponding to the number of samples summed)

Computing the first zero of the filter response for $N = 200$ and 4000 yields output bandwidths of approximately 1 kHz to 20 kHz as shown below:

$\underline{N=200}$

$$f = \left(\frac{1}{200}\right)\left(\frac{1}{\Delta t}\right) = \frac{1}{200} \times (4\ 1/6 \times 10^6) = 20.83 \text{ kHz}$$

$\underline{N=4000}$

$$f = \left(\frac{1}{4000}\right)\left(\frac{1}{\Delta t}\right) = \frac{1}{4000} \times 4\ 1/6 \times 10^6 = 1.04 \text{ kHz}$$

Note, as discussed above, that f_d must be less than half the value of the first zero of the filter response if the Nyquist rate for the output signal is to be maintained.

Finally, it is of interest to compare the digital filter with the corresponding analog filter employing the same integration time. It is easily shown that the frequency response of the running integration filter shown in Figure 6 is given by

$$H(f) = e^{-j\pi f T}\, T\, \frac{\sin \pi f T}{\pi f T}$$

Note that this filter (or its digital counterpart) need not be strictly realizable since processing is not done in real time. Setting $T = (N - 1)\,\Delta t$ yields

$$H(f) \doteq (N-1)\Delta t e^{-j\pi(N-1)f\Delta t} \frac{\sin \pi(N-1)f\Delta t}{\pi(N-1)f\Delta t}$$

$$\frac{H(f)}{\Delta t} = e^{-j\pi(N-1)f\Delta t} \frac{\sin \pi(N-1)f\Delta t}{\pi f \Delta t}$$

Concentrating on the region bounded by the first zero of the response $0 \leqslant f\Delta t \leqslant 1/N$ and assuming $N >> 1$ so that $\pi f\Delta t \simeq \pi/N << 1$ allows use of the approximation $\sin \pi f\Delta t \simeq \pi f\Delta t$ and thus over this region

$$\frac{H(f)}{\Delta t} \simeq \bar{H}(f)$$

Alternatively note that

$$\bar{H}(f) = \sum_{k=0}^{N-1} e^{-j2\pi kf\Delta t} = F\left\{\sum_{k=0}^{N-1} \delta(t - k\Delta t)\right\}$$

where $F\{-\}$ denotes the Fourier transform of the quantity contained within the braces and $\delta(t)$ is the impulse or Dirac delta function.

Defining

$$p(t) = \begin{cases} 1 \text{ if } 0 \leqslant t \leqslant (N-1)\Delta t \\ 0 \text{ otherwise} \end{cases}$$

$H(f)$ can be written in the form

$$\bar{H}(f) = F\left\{p(t) \sum_{k=-\infty}^{\infty} \delta(t - k\Delta t)\right\}$$

Using the fact that the Fourier transform of a product is the convolution of the Fourier transforms and the relation

$$F\left\{\sum_{k=-\infty}^{\infty} \delta(t - k\Delta t)\right\} = \frac{1}{\Delta t} \sum_{k=-\infty}^{\infty} \delta\left(f - \frac{k}{\Delta t}\right)$$

yields

$$\bar{H}(f) = (N-1)\Delta t\, e^{-j\pi(N-1)f\Delta t} \frac{\sin \pi(N-1)f\Delta t}{\pi(N-1)f\Delta t}$$

$$* \frac{1}{\Delta t} \sum_{k=-\infty}^{\infty} \delta\left(f - \frac{k}{\Delta t}\right)$$

where * indicates convolution. Performing the convolution gives the result

$$\bar{H}(f) = (N-1) \sum_{k=-\infty}^{\infty} e^{-j\pi(N-1)(f-k/\Delta t)\Delta t}$$

$$\times \frac{\sin \pi(N-1)\left(f - \frac{k}{\Delta t}\right)\Delta t}{\pi(N-1)\left(f - \frac{k}{\Delta t}\right)\Delta t}$$

Thus $H(f)$ is simply the superposition of an infinite series of $\sin x/x$ functions shifted by integral multiples of the sampling frequency $1/\Delta t$.

IV. Planned Implementation Schedule

The planned implementation schedule to meet the Pioneer-Venus DLBI experiment requirements is as follows:

CTA 21 Radio Science Subsystem	
First demonstration	15 November 1977 to 15 January 1978
Transfer to operations	1 April 1978

CTA 21 Radio Science Subsystem Interface with Experimenter	
Output tape in correct format	1 October 1977
Output tape generated from a tone	1 January 1978
Output tape generated from an ALSEP[1] signal	7 February 1978

[1]Apollo Lunar Surface Experiments Package

Reference

1. Miller, R. B., "Pioneer Venus 1978 Mission Support," in *The Deep Space Network Progress Report 42-31*, pp. 11-14, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1976.

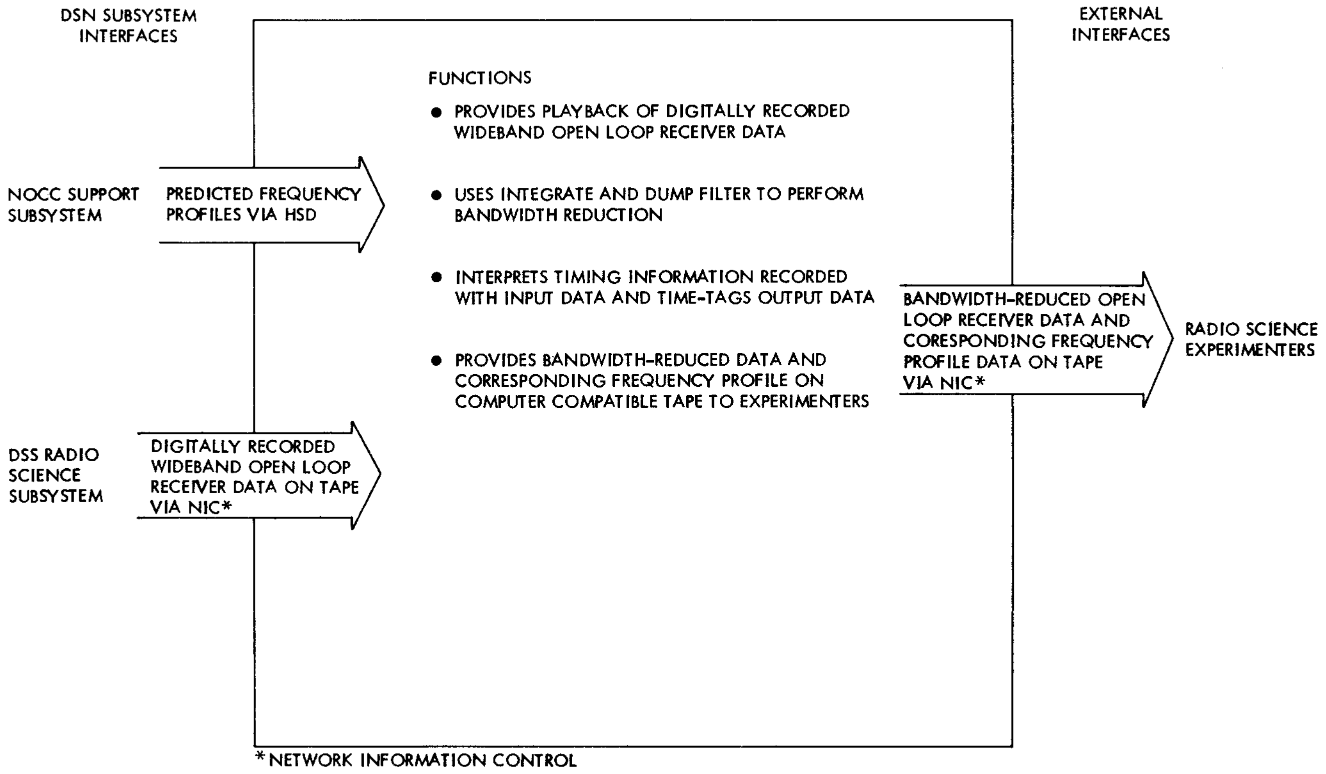

Fig. 1. CTA 21 radio science subsystem functions and interfaces

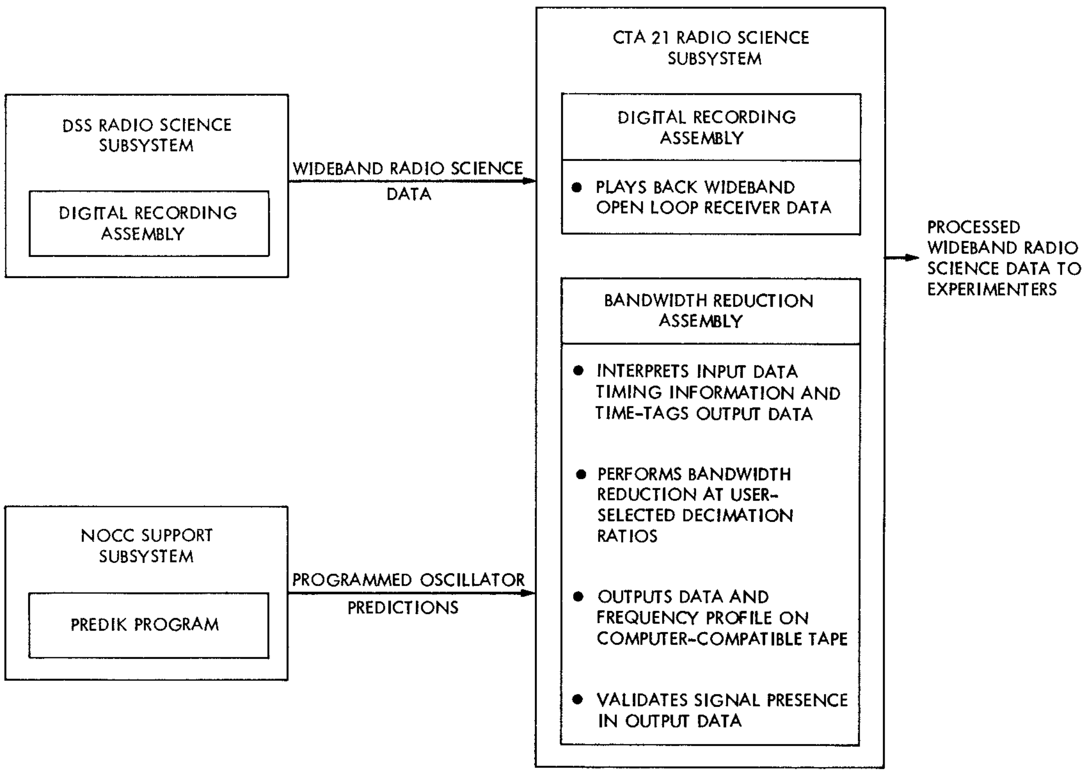

Fig. 2. CTA 21 radio science subsystem functions and data flow

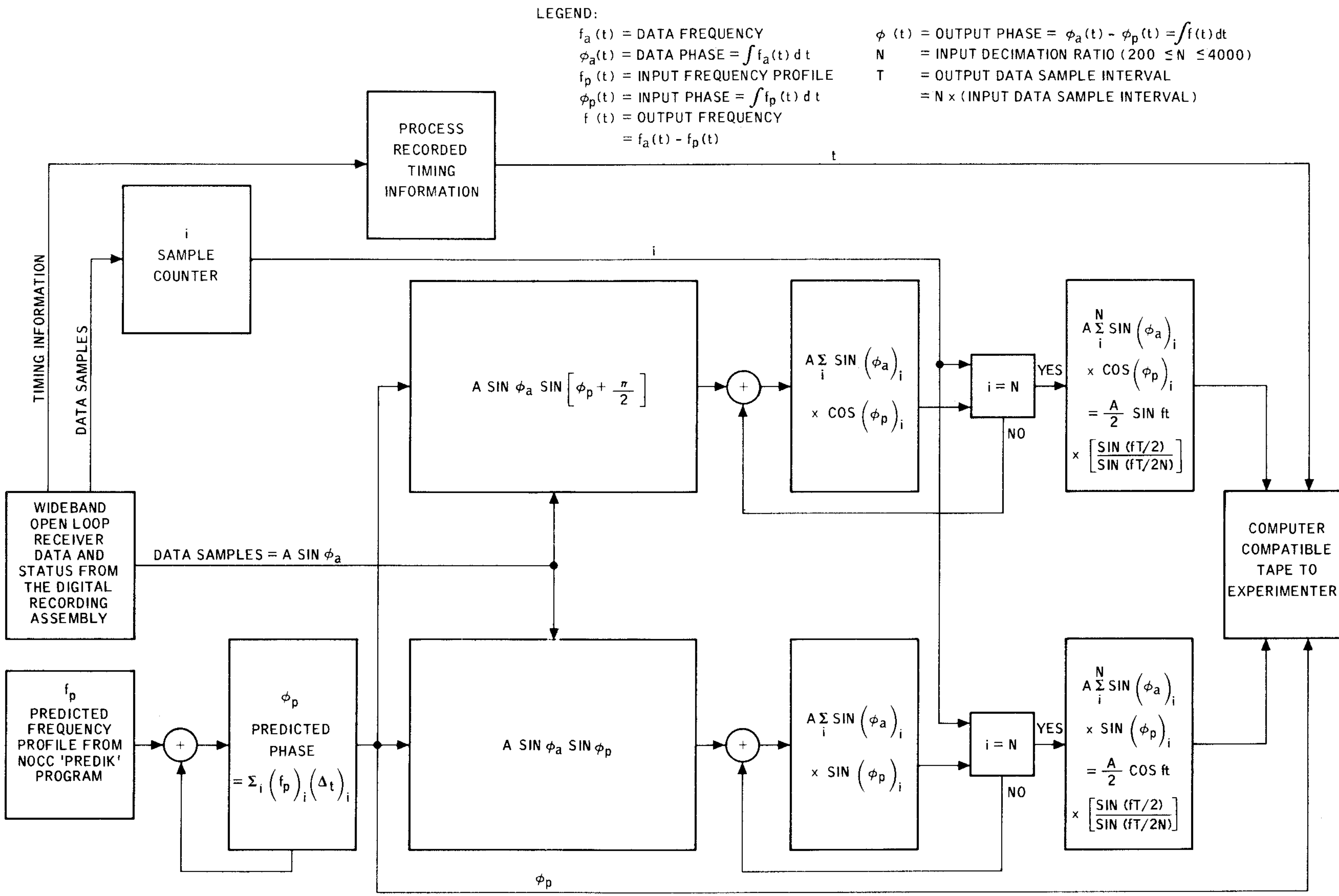

Fig. 3. Bandwidth reduction assembly functional block diagram

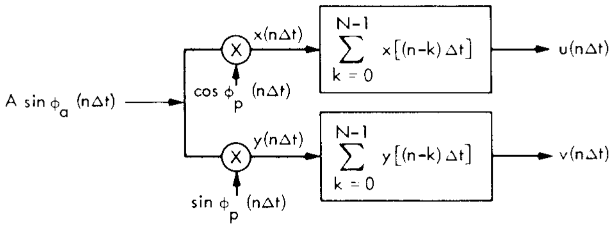

Fig. 4. Block diagram of bandwidth reduction signal processing

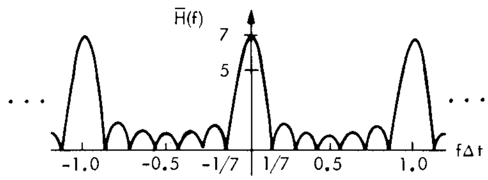

Fig. 5. Frequency response of the digital filter for $N = 7$

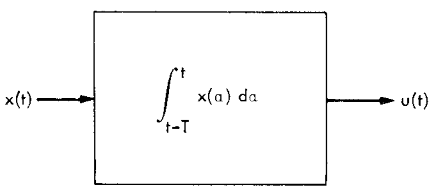

Fig. 6. Running integration filter