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Analysis of Counting Errors in the Phase/Doppler Particle Analyzer

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Counting Error Analysis of the Phase/Doppler Particle Analyzer

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Abstract

NASA is investigating the application of the Phase Doppler measurement technique to provide improved drop sizing and liquid water content measurements in icing research. The magnitude of counting errors were analyzed because these errors contribute to inaccurate liquid water content measurements. The Phase Doppler Particle Analyzer counting errors due to data transfer losses and coincidence losses were analyzed for data input rates from 10 samples/second to 70,000 samples/second. Coincidence losses were calculated by determining the Poisson probability of having more then one event occurring during the droplet signal time. The magnitude of the coincidence loss can be determined, and for less than a 15 percent loss, corrections can be made. The data transfer losses were estimated for representative data transfer rates. With direct memory access enabled, data transfer losses are less than 5 percent for input rates below 2000 samples/second. With direct memory access disabled losses exceeded 20 percent at a rate of 50 samples/second preventing accurate number density or mass flux measurements. The data transfer losses of a new signal processor were analyzed and found to be less than 1 percent for rates under 65,000 samples/second and only increase to 3 percent at the maximum throughput of 70,000 samples/second.

Introduction

The reliable measurement of drop size distributions and liquid water content (LWC) is an important goal in icing research. Comparison of drop size instruments have been reported[1] indicating a significant variation between the measured median volume diameters (MVD) and a greater variation in their indicated LWC. A program is being pursued to develop improved calibration techniques for the drop sizing instruments now used in icing research.[2] In addition to this program, NASA is looking for advanced concepts for icing instrumentation to provide improved drop sizing and LWC measurements. The Phase Doppler measurement technique is one concept which is currently under investigation.

The Phase Doppler measurement technique has been developed into a drop sizing instrument[3-5] which can simultaneously measure the droplet size, velocity, and local mass flux. The Phase Doppler Particle Analyzer (PDPA) has been compared to other drop sizing instruments[6] and demonstrated good agreement with significantly different measurement techniques.

A comparison of the PDPA's Local mass flux measurements with other techniques has been reported[7] indicating agreement to ±10 percent, and if affects of nonparalyzable dead time are included the agreement would improve to ±5 percent. In high number density or high velocity sprays these counting errors will become more significant.

In the present study, the counting errors due to instrument dead time and droplet coincidence were analyzed for a wide range of data rates, representative droplet signal lengths, and data transfer times.

Nomenclature

E_n	Efficiency of a nonparalyzable element
E_p	Efficiency of a paralyzable element
P_k	Probability of k events in the queue
R_i	Input rate, sec^{-1}
R_o	Output rate, sec^{-1}

R_q Queueing rate, sec^{-1}

R_s Service rate, sec^{-1}

t_d Data transfer or dead time, microseconds

t_e Signal time, microseconds

t_m Minimum signal time, microseconds

u Traffic intensity

Counting Errors

The Phase Doppler Particle Analyzer is one of a class of instruments called single particle counters. These instruments all suffer from the possibility of counting errors of two main types, coincidence losses and dead time losses. To understand how these errors arise, Figures 1(a) to 1(e) are presented to illustrate five possible events as two particles pass through the sample volume.

1. Figure 1(a) illustrates the ideal case. The first droplet is detected by the system as the signal exceeds a minimum threshold. At the end of the signal the system must transfer the signal information to the computer and reset the electronics for the next event. The time period, t_d, is determined by the time period necessary to transfer the signal information into the computer memory. The processor returns to a "ready" state before the next droplet signal begins.

2. In Figure 1(b) the second droplet enters the sample volume during the data transfer period, but the end of the signal is detected after the end of the data transfer period. This partial signal is accepted because it exceeds a minimum signal time, t_m. For these two examples no counting errors occur.

3. Figure 1(c) illustrates a data transfer loss. The first droplet leaves the sample volume and the data transfer is initiated. During this time another droplet passes through the sample volume. This signal is not detected by the system and does not affect the transfer period or any other aspect of the system.

4. Figure 1(d) illustrates an event similar to that illustrated in 1(c) except that the second signal ends after the end of the data transfer time, but does not exceed a minimum signal time. This event triggers a hardware reset by the processor, but has no other affect on the system.

5. A coincidence loss is illustrated in figure 1(e). The second droplet enters the sample volume before the signal from the first droplet has dropped below the threshold. The system does not detect the second particle as a separate event, only as a continuation of the first event. Coincident events cause counting errors, and if the signal is accepted, may result in sizing errors.

In the instrument sampling process the arrival of droplets at the sample volume can be treated as a Poisson process. A Poisson process is a process where the probability of an event only depends on the length of the time period, is independent of when the time period occurs, and is independent of the past history of the system.[8]

The PDPA processor has both paralyzable and nonparalyzable elements.[9] The process of transferring signal information into computer memory is a nonparalyzable element because once the process is initiated, a fixed time period, t_d, will elapse before the processor returns to a ready state. The return to a ready state is independent of any events occurring during this time period. A paralyzable element is one that, once triggered into an active state, remains in an active state for a time period, t_e. Additional events occurring during this time period extend this active state until a time period of t_e has passed with no events.

Coincidence Losses

The PDPA processor has no defined fixed time period, t_e, which is activated or reset as additional events occur. However, the resemblance to a coincident event described above is obvious. The processor, upon being triggered by a droplet signal into an active state, stays in this state until the end of the signal. Additional droplet signals beginning before the end of the previous signal will extend this active state.

The counting efficiency of a paralyzable element given random inputs with a mean rate of R_i is the Poisson probability of having zero events in its time period. The efficiency of this process is given by

$$E_p = e^{(-R_i \cdot t_e)} \qquad (1)$$

where t_e is the average signal time.

In cloud measurements, the signal time and mean input rate are a function of several physical variables. The signal time, which is the time for a particle to traverse the sample volume, is mainly a function of droplet velocity and sample volume size. But, this signal time is also influenced by the droplet size and droplet trajectory through the sample volume. Signal times tend to be shorter with high velocity droplets and small sample volumes, and conversely, longer with low velocity particles and larger sample volumes. The input rate is primarily a function of the drop number density and sample volume size. However, the droplet size and number density also influences the sample volume size.

Because of the many physical variables which influence the droplet signal time, the analysis of coincidence losses is presented only in terms of the signal time and counting rate. In figure 2 the efficiency versus output rate of the PDPA is given for a series of signal times. A signal time of 5 microseconds is equivalent to a beam diameter of 160 microns and a droplet velocity of 35 meters/second. This signal time enables counting rates up to 10,000 samples/second with only a 5 percent loss. In contrast, a droplet velocity of 2 meters/second would result in a transit time across the same sample volume of 80 microseconds resulting in a 5 percent loss at only 600 samples/second.

These curves can be used to estimate the magnitude of coincidence losses and possibly permit correction for losses up to approximately 15 percent. As the loss increases the curves become vertical making a reliable correction impossible. These results need to be experimentally verified and the affect of coincident signals on the size distribution should be thoroughly understood before routinely implementing large corrections.

Data Transfer Losses

The transfer of signal data into the computer memory is the nonparalyzable element of the system. For a nonparalyzable element, the dead time is simply $R_o \cdot t_d$, and the efficiency of the system is the fractional live time given by

$$E_n = 1 - R_o \cdot t_d = \frac{1}{1 + R_i \cdot t_d} \qquad (2)$$

where R_i is the mean arrival rate and t_d is the data transfer time as presented in Reference (9).

The data transfer time in the PDPA is a determined by the time needed to transfer the signal information into computer memory. At the end of a signal there are 16 bytes of data which must be transferred to the computer. The PDPA was designed to use an IBM PC for processing this signal data utilizing the direct memory access (DMA) capabilities to transfer the data into computer memory. The DMA controller in the PC operates at 4.77 Mhz and one 8 bit transfer requires 5 clock cycles resulting in a transfer in 1.05 microseconds. The total data transfer time needed to make 16 transfers using a PC is about 18.5 microseconds which includes approximately 2 microseconds for controller latency. Latency is the average time period for the DMA controller to begin executing a DMA transfer. If the PDPA is interfaced to an IBM PC/AT the data transfer time is increased to 28.5 microseconds because the DMA controller only operates at 3 Mhz. The DMA controller in an AT compatible being used with the PDPA at NASA operates at 5 Mhz reducing the DMA transfer time to 18 microseconds. A Compaq DESKPRO 386™ is being considered for use as a processor to reduce the data analysis time. The DMA transfer time for the Compaq is the same as the IBM PC/AT at 28.5 microseconds.

The PDPA can be run with the DMA capability turned off. In this mode, signal information is transferred to the computer, validated, and the size is determined before the signal processor can accept the next event. This mode increases the dead time considerably resulting in a large reduction in counting efficiency. When operating with the DMA off the dead time losses become dependant on the particular computer and the version of the PDPA analysis software in use. The dead time for an IBM PC/AT using PDPA System Software Version 2.6 is about 1.7 milliseconds. The latest system software released, Version 3.4.7, increases the dead time to 4 milliseconds. It is estimated that using a Compaq DESKPRO 386™ as a processor would reduce the dead time to 1.3 milliseconds.

Figure 3 clearly illustrates the severe reduction in counting efficiency resulting from not using the DMA capability. Using a AT with the latest version of the software with the DMA off results in a 10 percent loss at an input rate of 25 per second. In contrast, with the DMA on, a 10 percent loss does not occur until an input rate of 4000 per second. Turning the DMA off, permits the data point to consist of a large number of droplet events which is not restricted by the total computer memory available. However, this prevents reliable number density and mass flux measurements.

When the droplet event times are of the same magnitude as the dead time, equation (2) must be modified to account for droplet signals which begin during the dead time, but are counted because the signal ends after the data transfer time. This process is illustrated in figure 4. The second droplet enters the sample volume during the data transfer period t_d. At the end of this period, the system detects the signal which is accepted as a valid signal if it exceeds a minimum number of fringe crossings which can be considered a minimum signal time t_m. The efficiency of the processor with respect to data transfer losses is given by

$$E_n = 1 - R_o(t_d - (t_e - t_m))$$

$$= \frac{1}{1 + R_i(t_d - (t_e - t_m))} \tag{3}$$

where

$$t_e - t_m \geq 0$$

and

$$t_d - (t_e - t_m) \geq 0$$

The minimum number of fringe crossings is normally set to one-half the nominal number of fringes in the sample volume and therefore, nominally $t_m = .5t_e$.

Figure 5 shows the effect of considering the signal time. These results are based on a data transfer time of 28.5 microseconds, t_e from 0 to 80 microseconds, and $t_m = .5t_e$. In general, considering the signal time reduces the effective dead time. For a signal time of 80 microseconds there are no dead time losses because one-half the signal time, 40 microseconds, is greater than the data transfer time of 28.5 microseconds.

Data Transfer Losses in a New High Speed Processor. Recently, under NASA contract, Aerometrics has designed a new signal processor for performing measurements in high speed flows in support of NASA's icing research program. The main requirement of this processor is to accept Doppler burst frequencies of up to 20 megahertz. In addition to the speed improvement, two features were incorporated to reduce data transfer losses. First, DMA transfer now take advantage of the 16 bit bus of the PC/AT. Signal data is passed into computer memory using 8 word transfers, instead of 16 byte transfers used in the original design, resulting in a data transfer time of 14.25 microseconds. Second, because the DMA transfer rate has been the limiting factor to obtaining low dead time losses, the new processor uses a first-in, first-out (FIFO) data buffer as a fast temporary storage for the signal information.

The efficiency of this system is analyzed by treating it as a queueing problem. The performance equations for a queueing system with a Poisson input, exponential service time, one server, and a limited queue length,[10] is used to approximate the efficiency of this system. The rate at which events enter the queue is given by

$$R_q = (1 - P_k)R_i \tag{4}$$

where

$$P_k = \frac{(1 - u)u^k}{1 - u^{k+1}} \quad \text{if } R_i < R_s \tag{5}$$

and

$$P_k = \frac{1}{k + 1} \quad \text{if } R_i = R_s. \tag{6}$$

The quantity R_q is the actual rate into the queue which equals R_o since all events entering the queue will be processed. The quantity u is the traffic intensity, which is the ratio R_i/R_s. The probability, P_k, is the probability that there are k events in the queue (the queue is full) resulting in lost events.

Figure 6 plots the input rate versus output rate for the system using a data buffer with a data transfer time of 14.25 microseconds. For comparison, the curve for the previous design without a data buffer and a data transfer time of 28.5 microseconds is presented. Losses are less than 1 percent up to an input rate of 65,000 samples/second and losses only increase to about 3 percent at the maximum throughput of 70,000 samples/second.

Concluding Remarks

The counting errors of the Phase Doppler Particle Analyzer were analyzed for a range of data rates, signal times, and data transfer times. In general, the analysis supports the following conclusions.

1. Given the average signal time, the magnitude of coincidence errors can be estimated. Reliable corrections can be applied to losses less than 15 percent, however, the affect of coincident signals on the droplet size distribution needs to be investigated to assure that this distribution is still representative of the actual cloud.

2. Data transfer losses can be estimated and corrected. With the direct memory access enabled the losses are less than 5 percent for input rates under 2000 samples/second and losses increase only to 20 percent for a rate of 10,000 samples/second.

3. Data transfer losses increase drastically when the DMA is disabled. Losses exceed 20 percent for a very low input rate of 50 samples/second. Accurate number density and mass flux measurements can not be obtained if the PDPA is operated in this mode.

4. Incorporation of a data buffer in a new signal processor design virtually eliminates data transfer losses for all input rates less than the maximum throughput of 70,000 samples/second.

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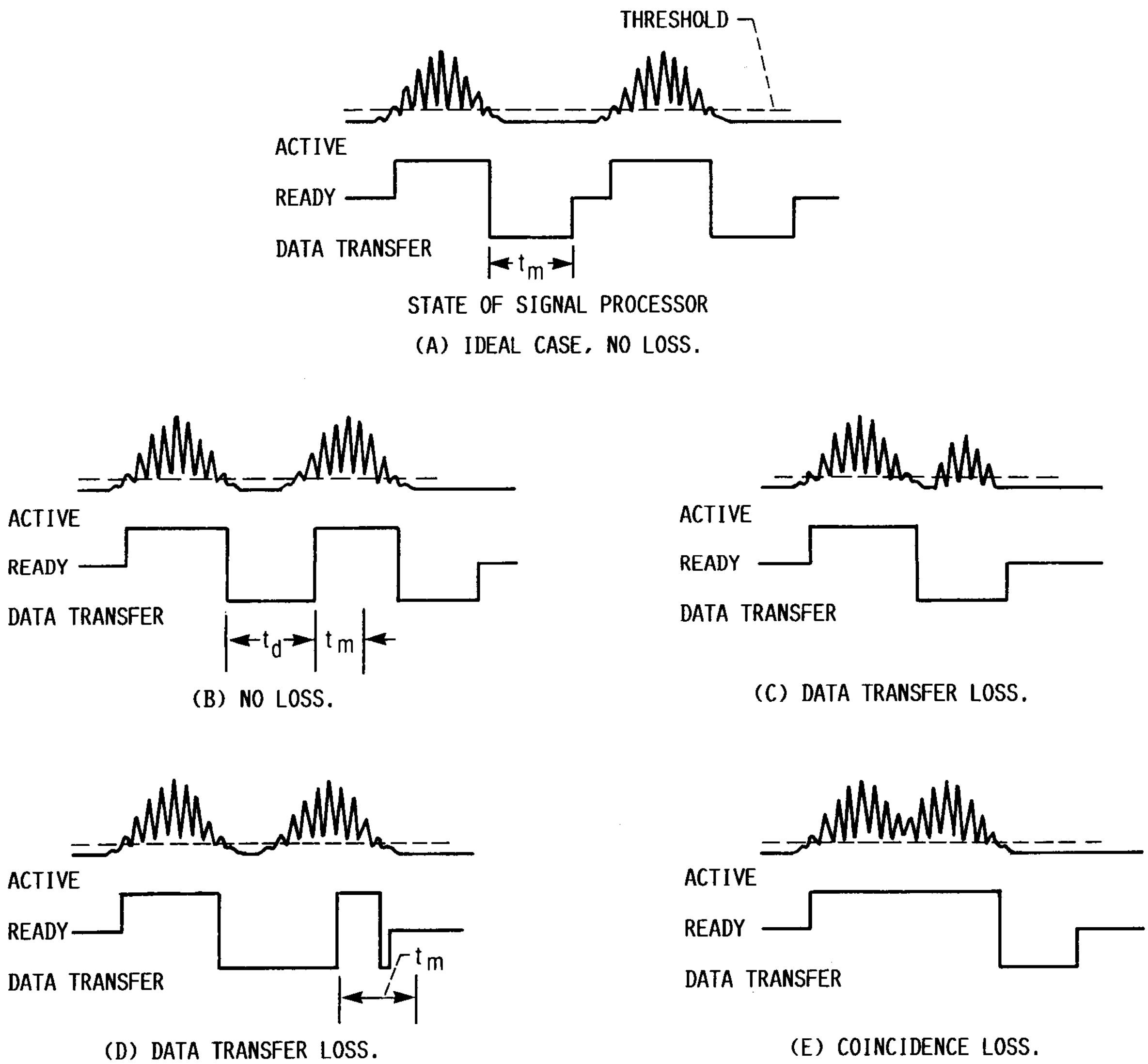

FIGURE 1. - ILLUSTRATION OF FIVE POSSIBLE EVENTS AS TWO PARTICLES PASS THROUGH THE SAMPLE VOLUME.

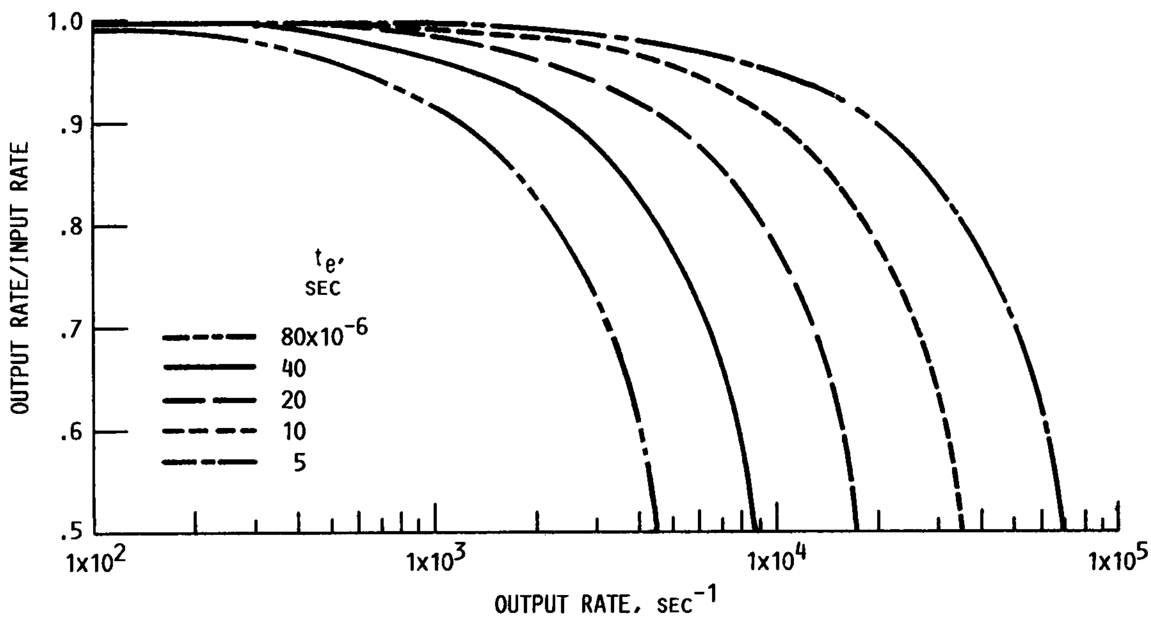

FIGURE 2. - COUNTING LOSSES DUE TO DROPLET COINCIDENCE.

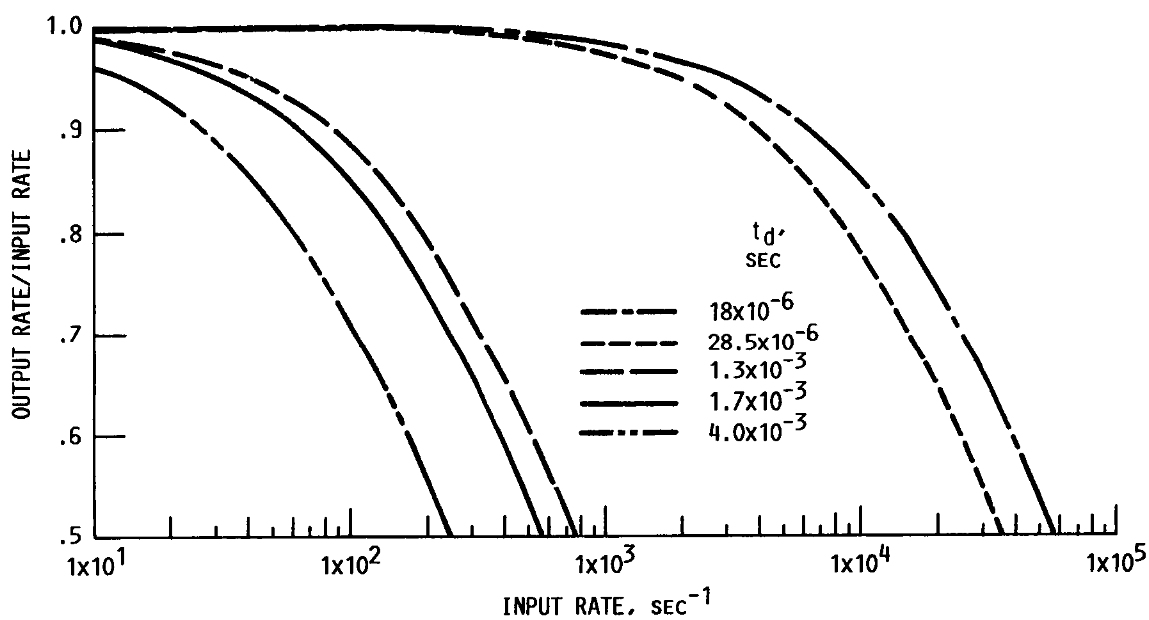

FIGURE 3. - COUNTING LOSSES DUE TO DATA TRANSFER.

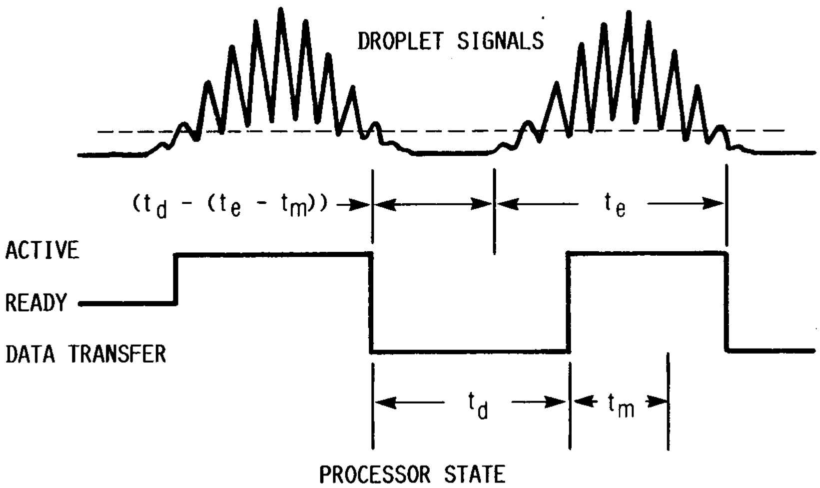

FIGURE 4. - ILLUSTRATION OF REDUCTION OF THE EFFECTIVE DATA TRANSFER TIME WHEN THE DROPLET SIGNAL TIME IS OF THE SAME MAGNITUDE AS THE DATA TRANSFER TIME.

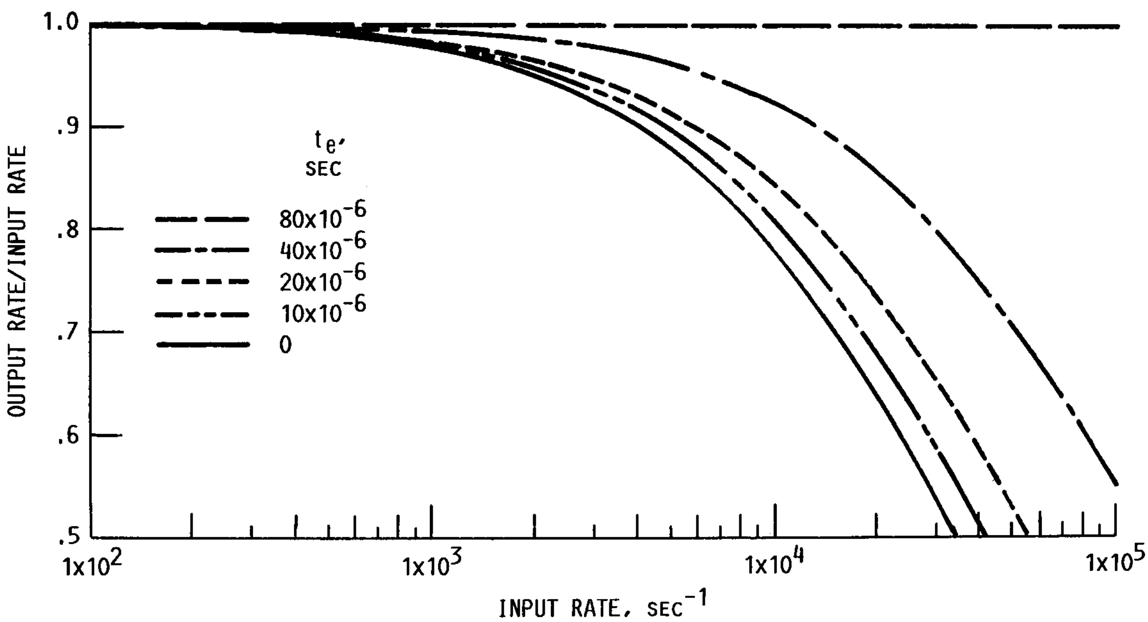

FIGURE 5. - EFFECT OF SIGNAL TIME, t_e, ON DATA TRANSFER COUNTING LOSSES WITH t_d = 28.5 MICROSECONDS AND t_m = 0.5 t_e.

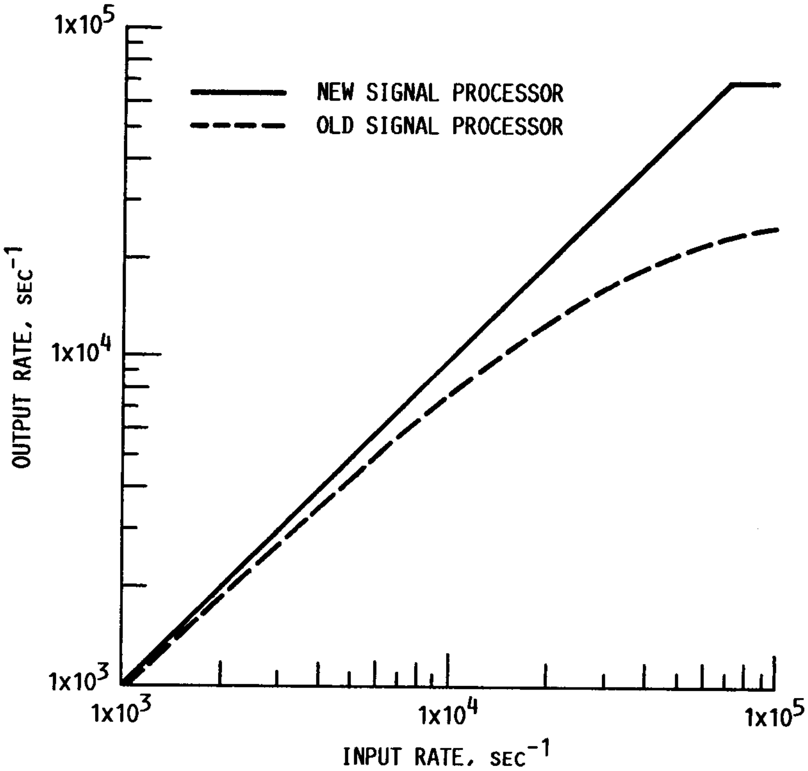

FIGURE 6. - COMPARISON OF NEW SIGNAL PROCESSOR USING A DATA BUFFER AND t_d = 14.25 MICROSECONDS TO A PROCESSOR WITHOUT A BUFFER AND t_d = 28.5 MICROSECONDS.

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