AN NNSS SATELLITE TIMING RECEIVER

BY

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ABSTRACT

The U.S.Navy Navigation Satellite System termed as NNSS offers a unique worldwide facility for the precise Time Synchronisation. To take the advantage of such a facility for tracking Indian Satellites, Space Applications Centre (SAC) has developed a simple Timing Receiver. Using this Timing Receiver first the internal time consistency of NNSS was studied and then its performance to synchronise time was compared with that of National Time Standard. This paper describes in detail the methodology of data analysis, results and the various sources of error which affects the time transfer accuracy. The main source of error was found to be the receiver delay which varies with signal strength. It is possible to apply this delay correction empirically provided signal strength is recorded.

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INTRODUCTION

The Navy Navigation Satellite System (NNSS) is a fully operational navigation system that enables the Navy Fleet or commercial users to accurately obtain their position any where on the Globe, day or night and in any weather. The NNSS commonly known as TRANSIT, consists of a constellation of five operational satellites in fixed circular polar orbits at an altitude of approximately 1100 km. The TRANSIT system requires accurate time to accomplish its navigational mission. For this reason the satellites transmit a precisely timed fiducial time mark (FTM) every two minutes. The transmission of FTM has provided a unique world wide facility for time Synchronisation. In fact Trasit satellites are like unattended flying clocks and user can tap precise time as and when the satellites come on the horizon with a proper type of receiver. This unique facility has become a bonanza to users of precise time even in remote areas. Maintanance of precise time is as difficult as keeping an Olympic Flame. In case of failure it would be necessary in either situation to go back to the source. But the TRANSIT has solved this problem and 5 operational satellites provide excellent service reliability.

To take advantage of NNSS facility for maintaining time at ISRO Telemetry & Tracking Command Network (ISTRAC) Space Applications Centre (SAC), Ahmedabad under took the fabrication of a simple Timing Receiver. This receiver after getting locked to 400 MHz satellite carrier detects FTM and sets the 1PPS of the local clock. The path delay correction to 1PPS is applied using broadcast ephemeries and ground station coordinates manually.

TIME TRANSFER METHODOLOGY - SATELLITE FRAME TO GROUND FRAME

The time mark in the satellite signals are referenced to UTC (Universal Coordinated Time maintained by U.S. Naval Observatory). The time mark consists of a "Zero", 23 "ones" and a "Zero", followed by a 400 Hz beep signal and is shown in fig. 1. The exact point of transition between the final binary zero and the beginning of 400 Hz beep is the exact two minute mark. This time mark is known as Fiducial Time Mark (FTM). In every two minute, synchronised with FTM, the satellites also transmit 26 orbital words. The first 8 words are known as variable parameters and the rest are known as fixed parameters. The fixed parameters describe the satellites nominal orbit where as the variable parameters describe the fine structure in the satellite nominal orbit as a function of time. The accuracy of the satellites position derived from these parameters (known as Broadcast Ephemeris) are 25 m in-track, 15 m cross-track and 10 m in radial direction.

The NNSS Timing Receiver detects the FTM and synchronises 1 PPS of its internal clock. The correction to this 1PPS is given by:

Correction	=	$D_o + R/C$
Where Do	=	Mean receiver delay at a given signal strength.
R	=	Slant range of the satellite from receiver antenna in km.
C	=	Velocity of electromagnetic waves in km.

The satellite transmits the five orbital parameters viz. semi-major axis (a_{t_p}), eccentricity (e), inclination (i), argument of perigee (ω_{t_p}) and right ascension of the ascending node (Ω_{t_p}), the precession rate of ω and Ω ($\dot{\omega}$ & $\dot{\Omega}$), the mean motion (n) and Greenwich sidereal time ($GAST_{t_p}$) at a certain time t_p along with Δa, ΔE and η where Δa and ΔE are the corrections to be applied to the semi-major axis and the eccentric anomaly and η is the out of plane component.

The satellite coordinates at any instant t with respect to the orbital coordinate system are

$$\begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix} = \begin{bmatrix} a_t \ (\text{Cos } E_t - e) \\ a_t \ \text{Sin } E_t \\ \eta_t \end{bmatrix}$$

where a_t = semi-major axis at time t

$= a_{t_p} + \Delta a_t$

E_t = Eccentric anomaly at time t

$= M_t + e \text{ Sin } M_t + \Delta E_t$

M_t = Mean anomaly at time t

$= n \ (t - t_p)$

The transformation of the satellite coordinates from the orbital plane system to the equatorial coordinate system is accomplished by three rotations viz

(i) the rotation in the x-y plane by ($-\omega_t$)

(ii) the rotation in the y-z plane by ($-i$)

(iii) the rotation in the x-y plane by ($-\Omega_t$)

where

ω_t = argument of perigee at time t

$$= \omega_{t_p} - |\dot{\omega}| (t-t_p)$$

Ω_t =right ascension of ascending node at time t

$$= \Omega_{t_p} + \dot{\Omega}(t-t_p)$$

The rectangular geocentric coordinates are, therefore,

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = R_1(-\omega_t) \cdot R_3(-i) \cdot R_1(-\Omega_t) \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$$

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = \begin{bmatrix} \cos\omega_t & -\sin\omega_t & 0 \\ \sin\omega_t & \cos\omega_t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \begin{bmatrix} \cos\Omega_t & -\sin\Omega_t & 0 \\ \sin\Omega_t & \cos\Omega_t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$$

In order to obtain the coordinates in the earth fixed system, a sidereal rotation by an angle equal to the Greenwich sidereal time at the instant is applied,

i.e. $\lambda_t = GAST_t = GAST_{t_p} + \omega_e (t-t_p)$

ω_e = rotation rate of the earth

Thus
$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = \begin{bmatrix} \cos\lambda_t & \sin\lambda_t & 0 \\ -\sin\lambda_t & \cos\lambda_t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix}$$

The coordinates of the station are expressed in terms of the geodetic latitude ϕ and longitude λ. They can be transformed into cartesian coordinates by the formulae,

$$X_o = (\nu + N + h) \cos\phi \cos\lambda$$
$$Y_o = (\nu + N + h) \cos\phi \sin\lambda$$

$$Z_o = \left\{(1-e^2)\,\nu \;+N+h\right\} \sin\phi$$

where,

$$\nu = \frac{a_e}{(1-e^2 \sin\phi)^{1/2}}$$

a_e = equatorial radius of the earth

e = eccentricity of the earth

$N+h$ = height of the station above the reference ellipsoid.

Knowing the station position and the satellite position at any time t, we can calculate the slant range as follows:

$$R = \left\{(X_s-Y_o)^2 + (Y_s-Y_o)^2 + (Z_s-Z_o)^2\right\}^{1/2}$$

Using above relation slant range is determined. The mean receiver delay is added with the propagation delay and clock correction factor is obtained in microsecond. The clock is advanced by this clock correction factor.

EXPERIMENTAL SET UP

The Timing Receiver developed at Space Applications Centre is a single channel phase locked receiver operating at 400 MHz. The orbital data is stored in receiver memory and read manually for computing propagation delay. The receiver design was kept extremely simple in order to develop a concept for time transfer.

The experimental set up used to study the internal consistency of NNSS as well as the capability of receiver to transfer time with respect to National Standard is shown in fig. 2. In the first case for studying the internal time satellites was found to be around ±75 microsecond (1 sigma level) and is shown in fig. 3A. This one sigma (1σ) level value may improve after applying the receiver delay correction for each data point (Delay variation with signal strength).

(ii) For studying the performance of Timing Receiver to transfer time with respect to National Standard maintained at National Physical Laboratory, New Delhi, data were taken from 9th to 12th February 1981. The one sigma value for time transfer accuracy was found to be about ±70 microsecond and is shown in Fig. 3B.

(iii) The internal consistency of NNSS is found to be as good as the time transfer accuracy of Timing Receiver with respect to National Standard.

SOURCES OF ERRORS.

The accuracy to which time can be transferred from the satellite clock to the user's clock using an NNSS Timing Receiver depends on many factors. The following sources of error limit the overall accuracy of the system.

(i) Time jitter in FTM detection
(ii) Offset in FTM transmitted by satellite
(iii) Receiver delay variation with signal strength.
(iv) Ionospheric & Tropospheric delay

The error due to factor No.II is not under user's control. The transit satellite report series 17 published by U.S. Navy Astronautics Group, Point Mugu, C.A. gives the offset of each satellite clock with respect to UTC, can be obtained on request and one can apply the correction. The consistency the Cesium Beam Atomic clock was synchronised using NNSS Timing Receiver. For this purpose a good satellite pass was selected and at the time of closest approach the FTM was detected and used to set 1PPS of receiver clock. Using the satellite orbital data the delay was computed and then the 1PPS of Cesium Beam Clock was synchronised. In the actual set up the 1 PPS of the Cesium Beam Clock was given to the start input of the Time Interval Counter and 1PPS from Timing Receiver was given to the stop input. For each satellite pass two sets of data were recorded near the closest approach. The corresponding time interval between 1PPS of cesium beam clock and 1PPS of Timing Receiver were noted down.

Just before starting the experiment the Timing Receiver clock was set to the nearest second of UTC. With the help of a satellite alert programme the rise time, the time of closest approach and time of setting for all the 5 satellites were predicted.

RESULTS.

(i) For studying the internal consistency of NNSS, the receiver was operated from 21st to 27th January 1981. Satellite passes occured during office hours were used for time transfer purpose. Low elevation passes (elevation less than 30^{o}) were rejected manually and the data points for which the time difference between 1PPS of Cesium Beam clock and 1PPS of NNSS timing receiver after applying propagation delay correction, was more than 100 microsecond were rejected. The RMS for rest of the data points was computed. The internal consistency of all the 5 propagation delay error contributed by ionosphere and troposphere at 400 MHz is less than a microsecond and is negligible. The major error is contributed by the receiver delay which varies with signal strength as shown in Fig. 4. The correction can be applied using the relation given by

$$d = \pm ms + D_o$$

where
d = Delay in microsecond
s = Signal strength
Do = Receiver mean delay at a give signal strength
m = Slope of delay curve

APPLICATIONS.

Time is one of the basic standards in science and its measurement related with the happening of an event (epoch) in the infinite flow of time is one of the most important problems of users. For all the experiments where time accuracy (epoch) requirement is of the order of 100 microsecond or better the TRANSIT system provides a unique facility. Tracking of satellites using Laser Ranging is one of the fields where this finds application. The optical satellite tracking stations (at least in India) are located at remote places and it is just not possible to take flying clocks due to the obvious limitations of transportation, the TRANSIT technique is found to be quite handy.

While analysing the data an arbitrary error was made in the antenna position by as much as 10 km and it was found that such error in the position does not affect much the accuracy of time transfer. A table giving position error and time error is given below. This technique also provides facility for experiments located at unsurveyed places.

Position error	RMS Time error
10 km in Latitude	± 11 microsecond
10 km in Longitude	± 10 microsecond
10 km in Radial	± 7 microsecond
1 km in Radial	± 1 microsecond

For a country like India which is not hooked up by TV network as is the case in Europe and U.S. it is not possible to transfer time using either TV active or passive technique, the **TRANSIT** system finds a lot of potentiality.

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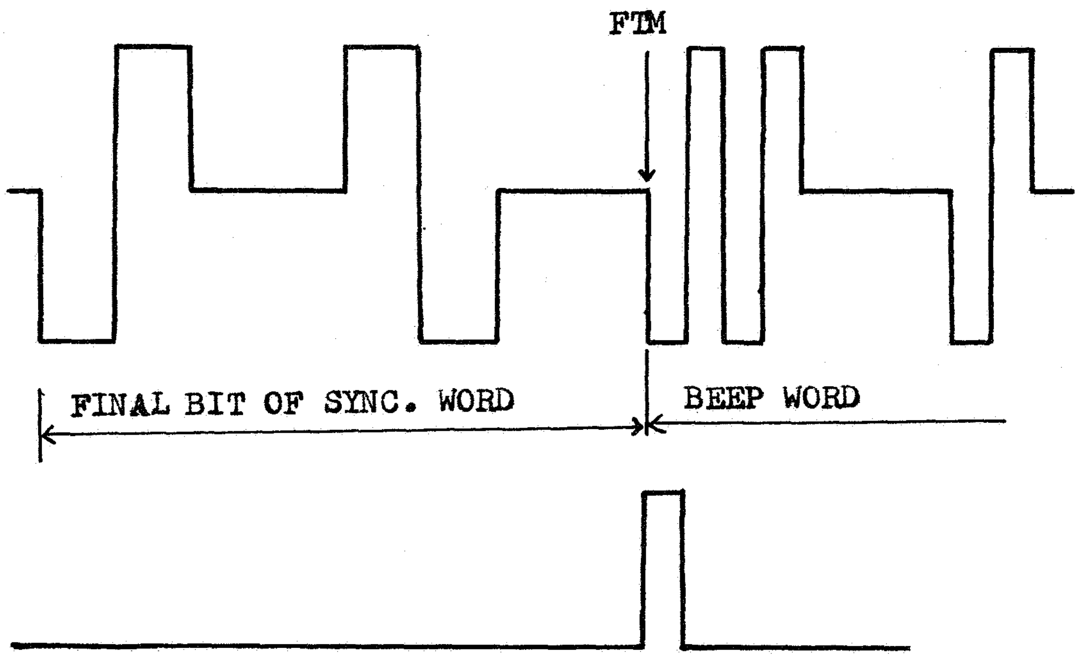
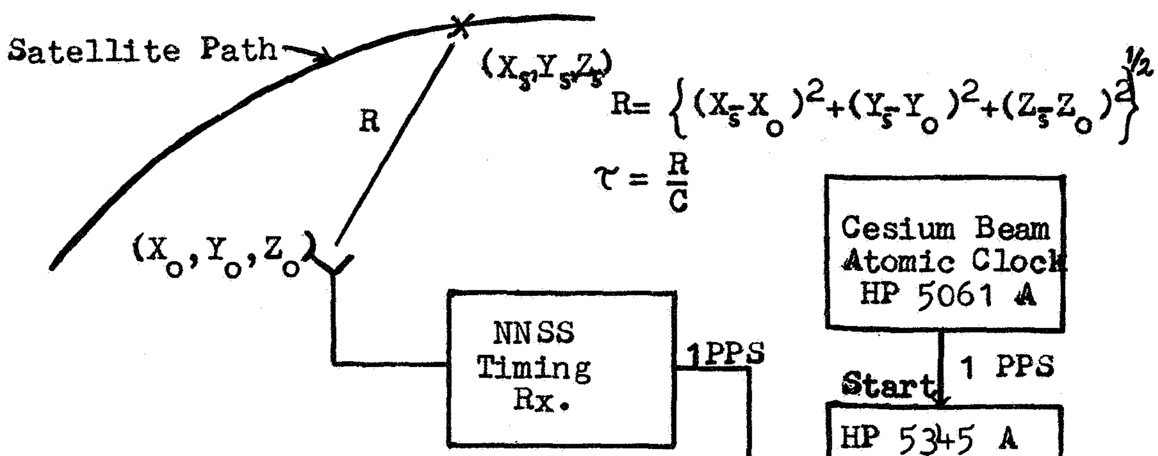


FIG. 1 - FTM DERIVATION



τ_o = 1 PPS of Cesium-1 PPS of NNSS
= τ +Ionospheric Delay ± FTM Jitter
+ Receiver Delay ± Receiver Delay Variation
± Time Difference Between UTC and Satellite Clock

FIG. 2 - EXPERIMENTAL SET UP

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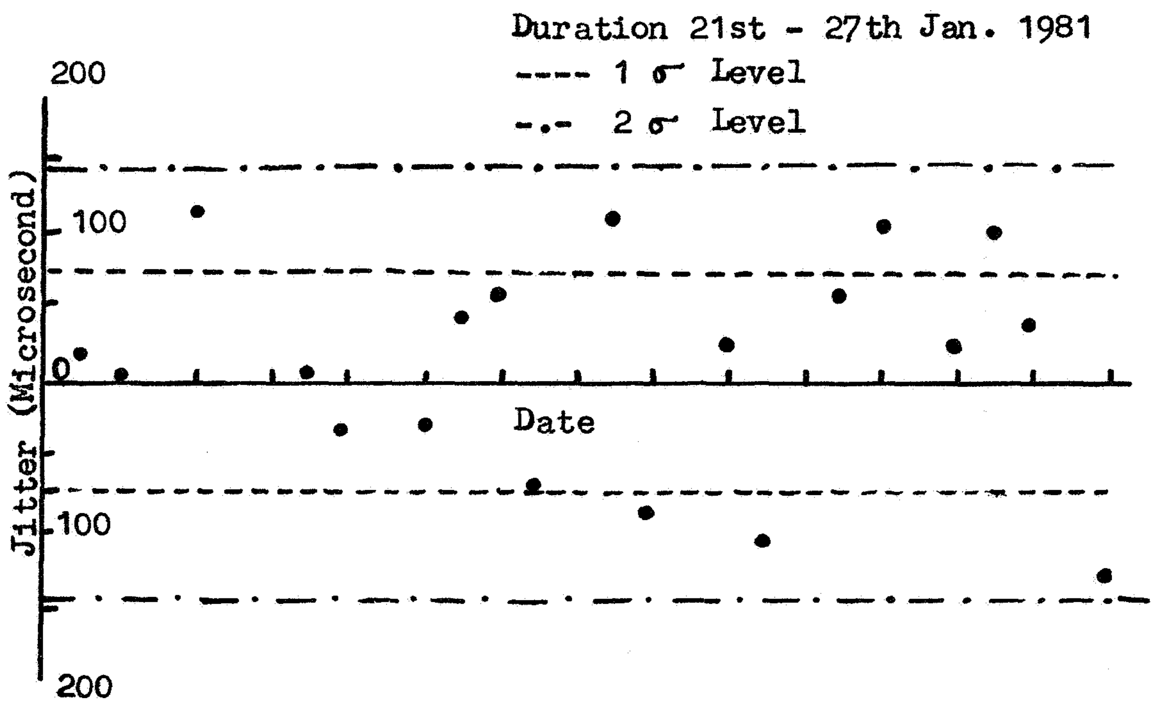

FIG. 3A - INTERNAL CONSISTENCY OF NNSS

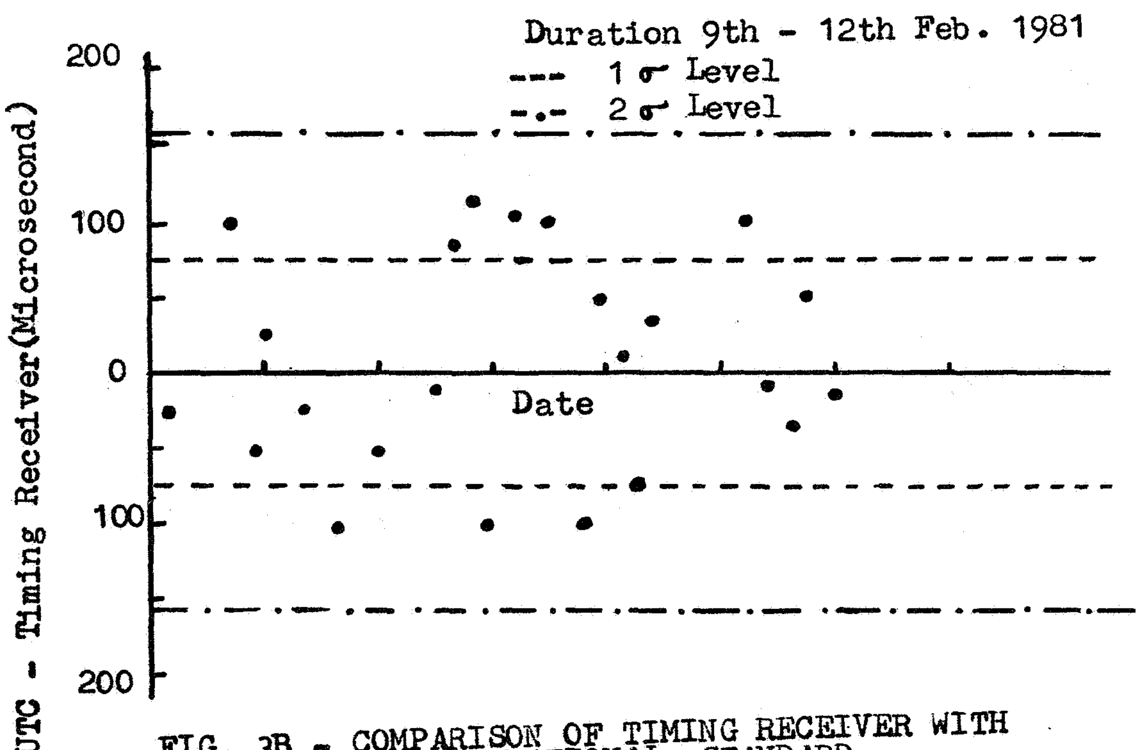

FIG. 3B - COMPARISON OF TIMING RECEIVER WITH NATIONAL STANDARD

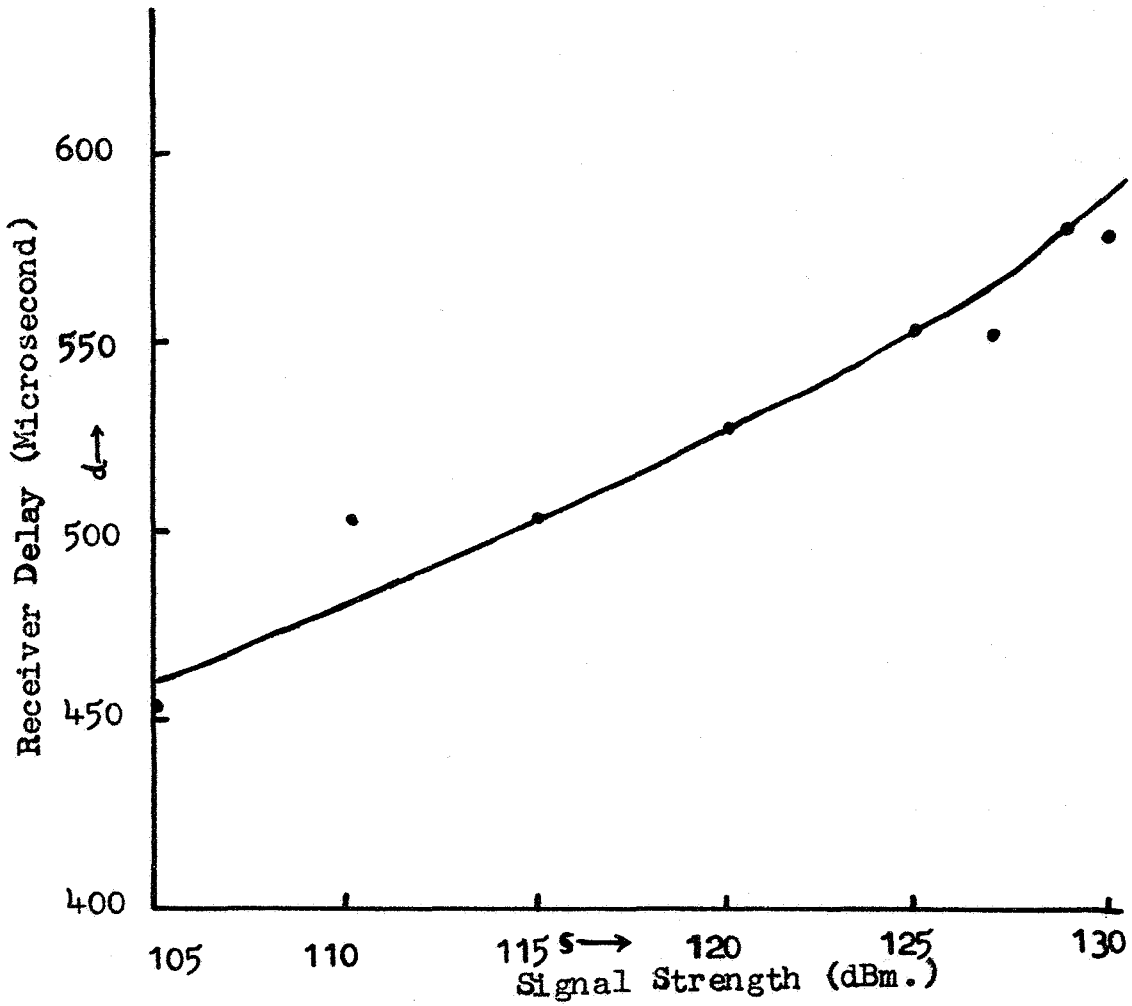

FIG. 4 - SIGNAL STRENGTH V/S RECEIVER DELAY