# A WIDE-BAND FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM EMPLOYING THERMALLY CONTROLLED PHASE COMPENSATION*

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## *Abstract*

***An active wide-band fiber optic frequency distribution system employing a thermally controlled phase compensator to stabilize phase variations induced by environmental temperature changes is described. The distribution system utilizes bidirectional dual-wavelength transmission to provide optical feedback of induced phase variations of 100 MHz signals propagating along the distribution cable. The phase compensation considered here differs from earlier narrow-band phase compensation designs in that it uses a thermally controlled fiber delay coil rather than a VCO or phase modulation to compensate for induced phase variations. Two advantages of the wide-band system over earlier designs are (1) that it provides phase compensation for all transmitted frequencies, and (2) the compensation is applied after the optical interface rather than electronically ahead of it as in earlier schemes. Experimental results on the first prototype shows that the thermal stabilizer reduces phase variations and Allan deviation by a factor of forty over an equivalent uncompensated fiber optic distribution system.***

## INTRODUCTION

The Frequency Standards Laboratory at the Jet Propulsion Laboratory is interested in developing ultrastable fiber optic frequency distribution systems for the Deep Space Network, which would allow for the distribution of high quality microwave local oscillator signals to several antennas from a central distribution point. To meet the requirements of such systems which will transmit over several tens of kms and require parts in $10^{17}$ stability for 1000 s averaging times, fiber optic frequency distribution systems employing active phase compensation techniques are being studied.

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This paper describes an active wide band fiber optic frequency distribution system which employs a thermally controlled phase compensator to stabilize phase variations arising from environmental temperature changes occurring along the distribution cable. The distribution system utilizes bidirectional dual-wavelength optical transmission to provide optical feedback of induced phase variations of 100 MHz signals propagating along the distribution cable. The phase compensation considered here differs from earlier narrow-band phase compensation designs in that it uses a thermally controlled fiber delay coil rather than a VCO or phase modulation to compensate for induced phase variations. Two advantages of the wide band system over earlier designs are (1) that it provides phase compensation for all transmitted frequencies, and (2) the compensation is applied after the optical interface rather than electronically ahead of it as in earlier designs. In the next section, the design issues of passive and active frequency distribution schemes are discussed. Following this, the design of a thermal stabilizer and corresponding linear transfer function describing the dynamics of a thermally controlled frequency distribution system are presented. Finally, experimental results obtained from a thermally stabilized 3.8 km distribution system are given.

## PASSIVE VERSES ACTIVE DESIGNS

The preferred transmission medium for distributing RF frequency standards at JPL's Goldstone Deep Space Network Antenna Complex is optical fiber cable. Fig. 1(a) describes a typical optical fiber frequency distribution system installation. A Hydrogen maser located at a signal processing center (SPC) is used to impress a highly stable 100 MHz RF reference signal on an optical carrier by intensity modulation of a semiconductor laser. This signal is subsequently transmitted and distributed to a remote antenna via a buried optical fiber. However, because of environmental temperature variations the optical path length between the SPC and antenna is unstable. This effect is observed at the antenna in the form of a induced, time varying disturbance phase angle on the distributed RF standard.

For transmission systems employing superior optical isolation at the laser transmitter output as well as an adequate signal to noise ratio, the frequency stability of the distributed standard is predominately dependent upon the amplitude and time characteristics of the thermal disturbance effects [1]. For passive transmission distribution designs, thermal environmental effects can be reduced by burying the optical fiber underground and employing fibers having small thermal coefficients of delays. Two way transmission tests (those that are independent of the stability of the frequency reference) performed by Calhoun [2] on ultrastable field installed distribution links employing these methods have shown to be capable of achieving parts in $10^{16}$ stabilities for 1000 second averaging times.

Two way tests performed on distribution systems employing state of the art fiber optic transmitters and receivers under ideal, thermally stable laboratory conditions at JPL have shown the capability of achieving parts in $10^{17}$ stabilities over 1000 seconds. To maintain these levels of stabilities in a field installation where the environment is thermally unstable and transmission distances may span several tens of kilometers, distribution system designs employing active phase compensation techniques have been a subject of research and development. Fig. 1(b) illustrates the principle of operation employed by a distribution system utilizing active phase stabilization. In this scheme, optical feedback is employed to sense the thermal disturbance along the distribution cable through the use of a backward travelling optical carrier supporting the distributed RF standard at the antenna. The resulting feedback signal then drives special stabilizer circuitry at the SPC which in turn adjusts the RF phase at the transmission end to actively compensate for the disturbance angle induced along the forward direction of distribution. Narrow-band stabilization schemes employing a VCO or phase modulation to generate the necessary compensating phase angle have been designed in the past at JPL by Lutes [3], Primas [4], and others with varying amounts of success. In each of these schemes, the compensation was performed on the narrow-band RF distribution signal ahead of the optical interface. An alternative wide band scheme shall now be presented which provides compensation for wide band RF signals and involves manipulating only the optical signal itself.

## THERMAL STABILIZER DESIGN

While the optical fiber used to transport the RF standard between the SPC and antenna has proven to be sensitive to environmental temperature changes (and thus susceptible to thermally induced phase disturbances), one might consider employing the thermal sensitivity of the fiber also to provide the necessary compensation to nullify outside disturbances. A stabilization system based upon this premise is illustrated in Fig. 2. Shown in series with the distribution cable is an additional length of fiber located inside a thermal electric cooler (TEC). The purpose of this special section of thermally controlled fiber is to compensate for length changes induced in the distribution cable by heating (or cooling) the small fiber coil so as to keep the optical path length between the SPC and antenna constant. The control loop is manifested by providing a secondary transmission link between the antenna and the SPC. In this case the primary transmission system transmits the frequency reference through the TEC and distribution cable to the antenna receiver, while the secondary transmission system returns the distorted antenna signal back to the reference end through the same optical fiber path. To isolate the forward and backward transmissions, the primary and secondary links are supported by two different optical wavelengths and signals generated by each system are routed to appropriate receivers by use of wavelength division multiplexers (WDMs) at each end of the common transmission path. Phase detection of the feed back RF signal from the secondary transmission system provides an error signal used to drive the TEC.

RF signal flow through the active distribution system is illustrated in Fig. 3. Ignoring phase differences arising from average transit delays, it is observed from this diagram that the phase of the RF signal received at the antenna along the primary transmission path (path 1) is $\theta_{1R} = \theta_{Ref} + \phi_{1C} + \phi_{1D}$. The phase observed at the second receiver at the front end resulting from the feed back transmission path (path 2) is $\theta_{2R} = \theta_{Ref} + \phi_{1C} + \phi_{1D} + \phi_{2C} + \phi_{2D}$. Under conditions where the compensation and disturbance phase angles are approximately equal for the two wavelength carriers, a closed loop transfer function describing the output phase angle of the active distribution system may be written as

$$\Phi_{out} = \frac{\Phi_D}{1 + 2K_{PD}H(s)} + \Phi_{ref} \tag{1}$$

where $K_{PD}$ is the phase detector gain and $H(s)$ describes the transfer function of the thermal phase compensator. Note that in the active configuration, the effect of disturbance angle is reduced by a factor $1 + 2K_{PD}H(s)$ over an equivalent passive distribution system.

A simple linear model describing $H(s)$ may be constructed by assuming that the TEC cold plate behaves as a leaky integrator (heat storage plus heat loss) and that the thermal interface between the cold plate and the fiber behaves as a simple first order thermal lag network. The front end of the TEC consists of a current driver which is controlled by an input voltage. Thus the thermal phase compensator transfer function (Volts in to phase out) may be modeled as

$$H(s) = \frac{K_{TEC}ab}{(s + a)(s + b)} \tag{2}$$

where $K_{TEC}$ is the TEC current driver gain, $1/a$ is the cold plate temperature time constant resulting from a step current input and $1/b$ is the time constant of the RF phase induced by the TEC fiber resulting from a step temperature cold plate change. This model is undoubtedly overly simple, but it provides a starting point for the analysis to follow. Employing Eq. (2) for $H(s)$ into the overall transfer function of Eq. (1) for the active frequency distribution system yields a second order system having an underdamped natural frequency described by

$$\omega_n^2 = 2K_{PD}K_{TEC}ab + ab - \frac{(a+b)^2}{4} \approx K_{ab} \tag{3}$$

where $K = 1 + 2K_{PD}K_{TEC}$ is the disturbance phase compensation factor corresponding to the DC gain of Eq. (1). The natural frequency and phase compensation factors are parameters which may be easily measured and employed to characterize the system as will be seen in the next section.

If the disturbance phase angles induced along the two transmission paths are significantly different because of differential dispersion effects between the two optical carriers, then the compensation will be degraded. In this case $\phi_{2D} \neq \phi_{1D}$ and in lieu of any other advantage, it can be seen that it is only possible to compensate for the average of the forward and backward induced disturbance phase angles. However, the ideal compensation of Eq. (1) may be recovered if the dispersion effect behaves approximately linear such that $\phi_{2D} \approx \alpha\phi_{1D}$ and $\phi_{2C} \approx \alpha\phi_{1C}$ for some constant $\alpha$ over the compensation temperature ranges. The reciprocal linear compensating effect supposed here requires that the thermal stabilizer employ the same fiber as utilized in the distribution cable.

## EXPERIMENTAL RESULTS

A frequency distribution system incorporating thermally controlled phase compensation was constructed and tested in the test chambers of the Frequency Standards Laboratory at JPL. The distribution cable was 3.8 kms in length and utilized an optical fiber having a thermal coefficient of delay of 7 ppm/°C. The distribution cable was located in a temperature controlled test chamber which could be programmed to maintain a constant temperature or thermally cycle 1°C sinusoidally over a 24 hour period. The rest of the distribution system was located outside the test chamber. This included an AT&T 1300 nm laser and in-house receiver for the primary transmission path and a Fujitsu 1550 nm laser and BTD receiver for the secondary feedback path. The 1300 nm laser was installed with 55 dB of optical isolation, while the 1550 nm laser possessed 35 dB isolation. The frequency stability of this system under constant temperature conditions was estimated to be $1 \times 10^{-16}$ at 1000 s averaging times. The supplied RF reference frequency was 100 MHz, obtained from a Hydrogen maser.

The thermal phase compensator consisted of 200 m of 7 ppm/°C Corning fiber wrapped in a 6 inch loop pressed down on the cold plate of a TEC. To improve the thermal coupling between the cold plate and the fiber, thermal paste was applied between the winds of the fiber and the cold plate. The thermal compensation unit was located in series with the 3.8 km fiber to produce a total mean optical path length between transmitters and receivers of approximately 4 km. The laser transmitters and receivers were interfaced to the 4 km common transmission path through the use of two WDMs manufactured by JDS. By disturbing the electrical drive to the TEC the underdamped response of the distribution system could be observed. These experiments revealed natural oscillations having a period of approximately 50 s. Employing this result with a phase compensation factor of K = 40 (see later) in Eq. (3) yields $1/(ab) = 2533\ s^2$ which gives a measure of the product of the internal time constants of the thermal stabilizer (TEC and delay fiber coil).

Figs. 4 and 5. show the theoretical and experimental Allan deviation curves resulting from cycling the 3.8 km distribution cable 1 °C. Time residual measurements revealed a 115 ps oscillation corresponding to a 4.14° peak to peak diurnal phase shift at 100 MHz. The resulting theoretical Allan deviation equation for this diurnal variation is, from Greenhall [5], $\sigma(\tau) = 2X_0/\tau \sin^2(\pi \nu \tau)$ where $2X_0 = 115$ ps and $\nu = 1/86400$ Hz. This expression is plotted in Fig. 4. The experimental curve of Fig. 5. shows evidence of the thermal disturbance starting about $\tau = 1000$ s, where it emerges from the baseline phase noise characteristic, finally peaking near $\tau = 43200$ s.

Fig 6. shows the experimentally derived Allan deviation curve arising from the thermally cycling 3.8 km distribution system after the 200 m stabilizing fiber coil was activated. Peak to peak RF phase variations at the distribution system output were observed to be 0.104° which correspond to a 40 fold reduction over the uncompensated case. This compensation factor may also be inferred by comparing Figs. 5 and 6, although there are no data points at the theoretical peak at $\tau = 43200$ s in Fig. 6 where this observation should be made directly. Note that the stability of the system for $\tau = 1000$ s is 1 part in $10^{16}$. Comparing these same curves for small $\tau$s also reveals that the stabilizer added no amount of significant phase noise beyond that produced by the uncompensated system.

As the distribution cable was cycled 1°C, the TEC was observed to vary just under 20°C which is consistent with the 19 to one ratio of optical fiber lengths employed in the distribution cable and thermal stabilizer. However for experiments lasting 24 hours or more, the temperature characteristic of the thermal stabilizer was observed to drift upward in temperature and resulted in somewhat higher values of Allan deviation. We believe that this thermal drift could be corrected with some additional work. The present data shown in Fig. 6 is a record of the best data that was observed.

## CONCLUSIONS

A 3.8 km active fiber optic frequency distribution system employing thermally controlled phase compensation has been built and tested. The prototype system demonstrated a 40 to one improvement in frequency stability over an equivalent uncompensated frequency distribution system when subjected to a diurnal thermal disturbance. One advantage of this design over earlier compensation schemes is that it provides compensation over a wide band of transmitted RF frequencies since the compensation afforded by this system purposes to maintain a constant optical path length between the frequency reference and the distribution point. Also the compensation is applied after the optical interface rather than in the electronics (before the optical interface), as provided by earlier narrow-band stabilization schemes. Another advantage of the thermal phase compensator is its simple and low cost design, employing only a coil of fiber in a TEC. The thermal stabilizer also possesses very little intrinsic phase noise of its own. Unfortunately, the compensation provided by the thermal stabilizer design is relatively slow, and thus disturbances varying less than several tens of seconds cannot be properly compensated. However, for most applications in the Deep Space Network, the largest source of frequency distribution instabilities arise from diurnal environmental temperature variations. In this case, the thermal controlled stabilizer provides a simple, low noise, and low cost mechanism for actively maintaining ultrastable frequency reference distribution in thermally unstable environments.

## ACKNOWLEDGEMENTS

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# REFERENCES

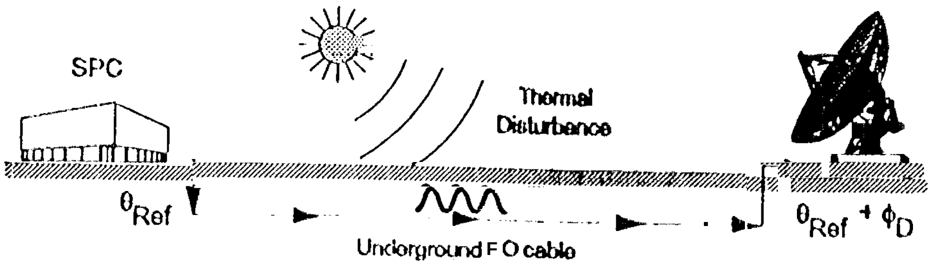
[1] G. Lutes, *"High Stability Frequency and Timing Distribution Using Semiconductor Lasers and Fiber Optic Links,"* SPIE Proc. Laser Diode Technology and Applications, vol. 1043, pp. 263-271, 1989.

[2] M. Calhoun and P. Kuhnle, *"Ultrastable Reference Frequency Distribution Utilizing a Fiber Optic Link,"* Proc. 24th Ann. Precise Time and Time Interval Applications and Planning Meeting, December, 1992.

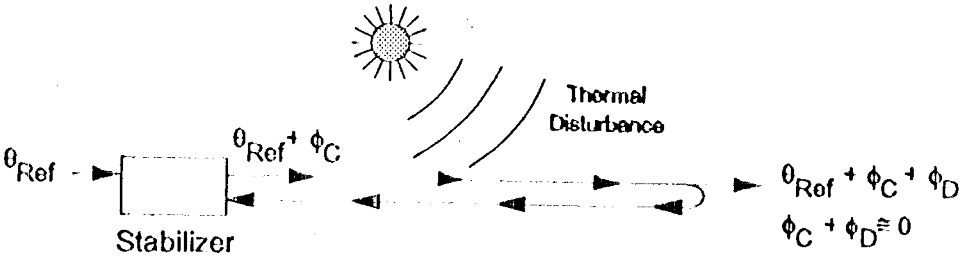
[3] G. Lutes, *"Optical Fibers for the Distribution of Frequency and Timing References,"* Proc. 12th Ann. Precise Time and Time Interval Applications and Planning Meeting, pp. 663-680, NASA Conference Publication 2175, Goddard Space Flight Center, December 1980.

[4] L. Primas, R. Logan, G. Lutes, *"Applications of Ultra-Stable Fiber Optic Distribution Systems,"* IEEE 43rd Annual Symposium on Frequency Control - 1989, pp. 202-210, June, 1989.

[5] C. Greenhall, *"Frequency Stability Review,"* The Telecommunications and Data Acquisition Progress Report 42-88, pp. 200-212, October-December, 1986.



(a) Passive distribution



(b) Frequency distribution with active phase compensation

Figure 1. Fiber optic frequency distribution systems.

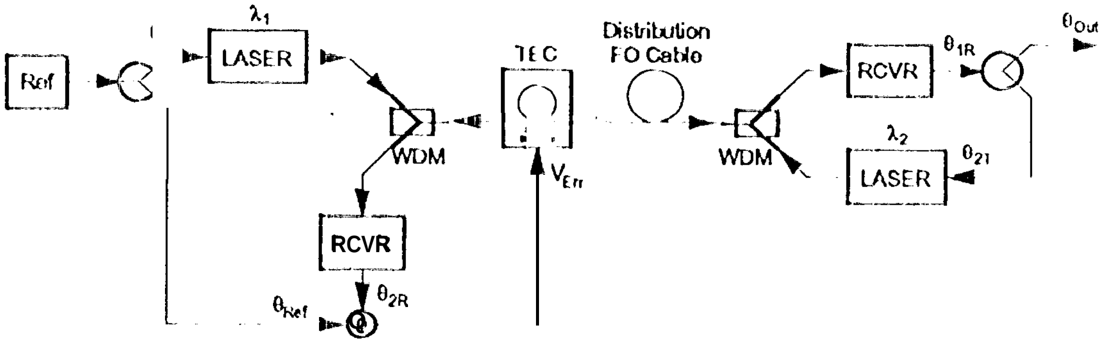


Figure 2. Block diagram of a fiber optic frequency distribution system employing thermally controlled phase compensation.

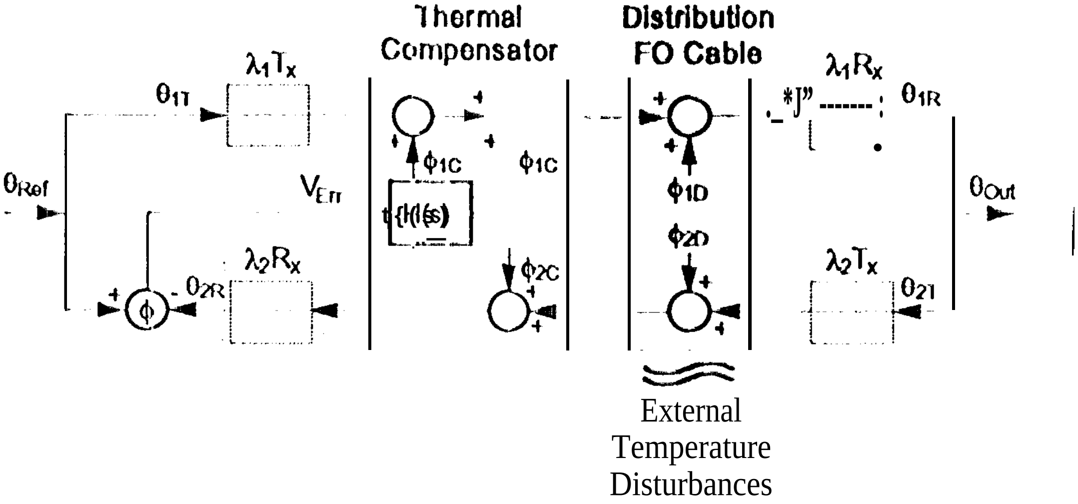


Figure 3. Signal flow diagram of thermally stabilized fiber optic frequency distribution system,

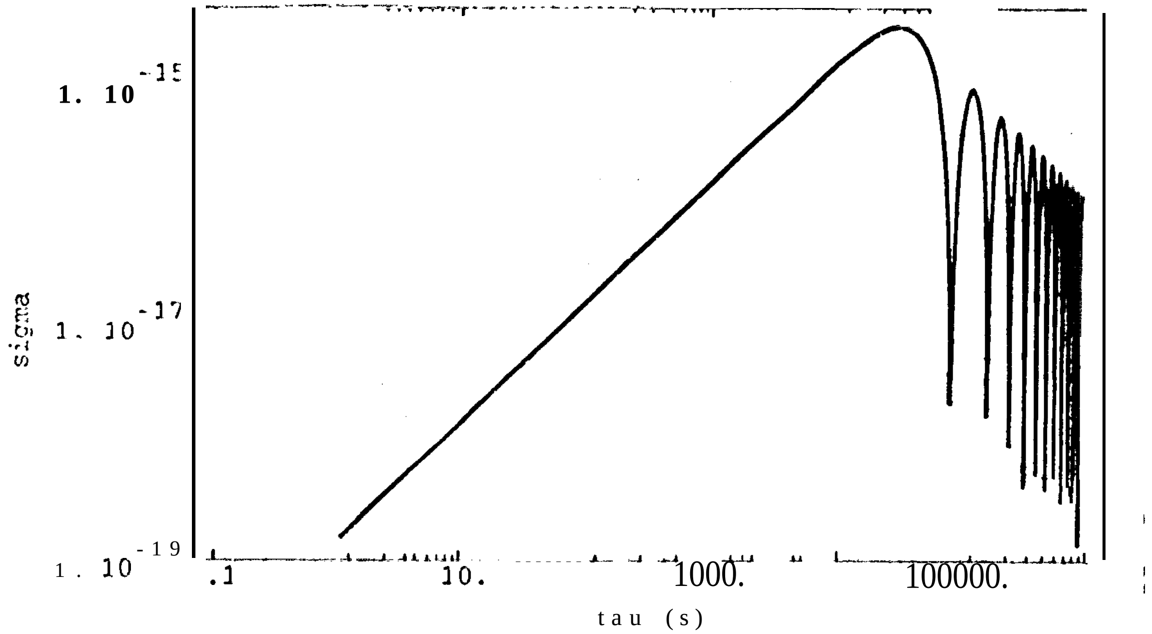


Figure 4. Theoretical Allan deviation curve arising from a diurnal phase variation having a peak to peak time residual of 115 ps (4.14° at 100 MHz).

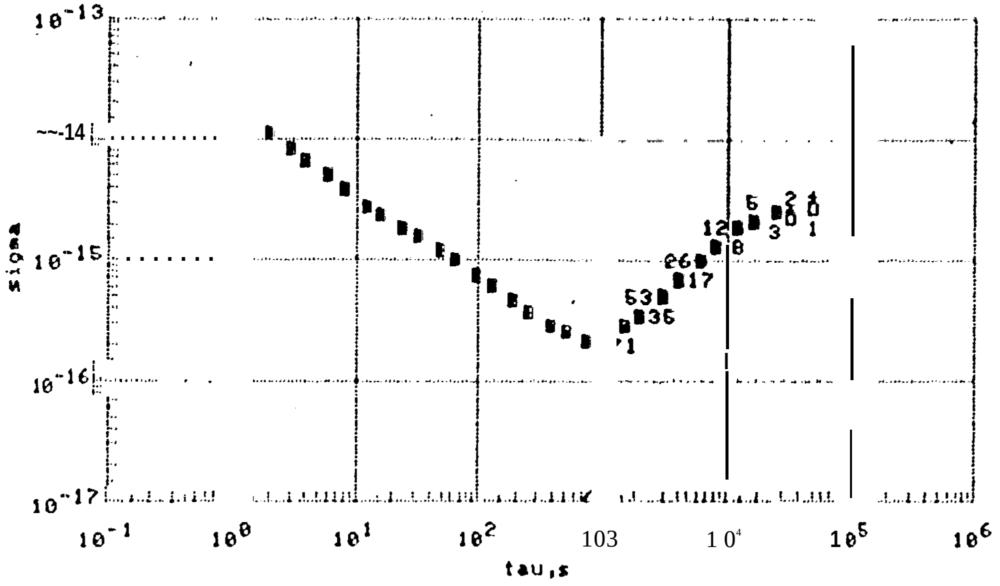


Figure 5. Experimental Allan deviation curve arising from a 3.8 km, 100 MHz passive frequency distribution system cycling 1 °C over a 24 hour period.

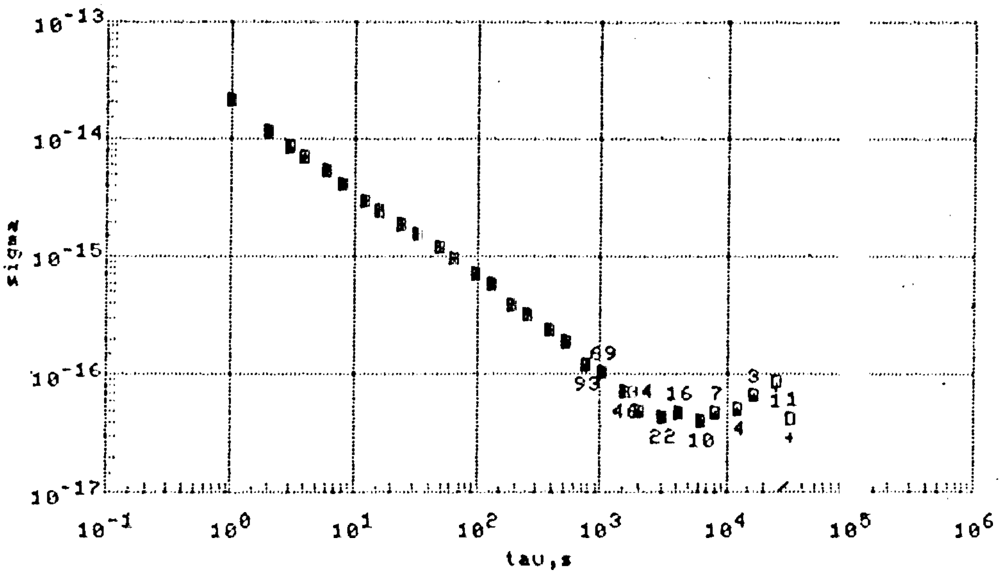


Figure 6. Experimental Allan deviation curve arising from a 3.8 km, 100 MHz actively compensating frequency distribution system consisting of a 3.8 km distribution cable (cycling 1 'C over 2.4 hours) stabilized by a 200 m coil under thermal electric control.