LONG-TERM TIME TRANSFER STABILITY OF A FIBER OPTIC LINK

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Abstract

The paper is devoted to the study of the long-term stability of the propagation delay of a fiber-optic timing link under real environmental conditions. The temperature dependence of the light propagation delay on surrounding temperature changes has been found as dominant. An appropriate method has been developed to correct mathematically the thermal delay variations in the fiber. After the correction for this temperature effect, only subnanosecond residual variations have remained.

INTRODUCTION

To ensure subnanosecond time comparisons of the remote clocks over a long period of time (one year and more), an adequate transmission system must be used in addition to stable measurement and distribution systems. A time transfer link based on the optic fiber seems to fulfill the requirements for precise timing over a distance of several tens of kilometers. The electronic part of the optic transfer link can be basically well designed and maintained in closely controlled laboratory conditions. Also, the parameters of the electronics can be regularly checked to obtain good long-term time transfer stability. In contrast, the fiber, which spans the outer distances between the laboratories, is exposed to uncontrollable natural environment even if buried under ground, taking into account the insensitivity of the fiber to the electromagnetic perturbation, all other environmental factors like temperature, humidity, atmospheric pressure, etc. may have influence upon it. All these factors may cause the instability of the propagation delay of the optical signal in the fiber. The spurious fluctuations of the link propagation delay superimposed on true measured phase-time values could be mistakenly interpreted as the instability of the compared clocks unless special care (correction, compensation) is taken with respect to the measured data.

For this reason the investigation of time transfer parameters of fiber-optic links was one of the first tasks which arose just after the realization of the Czech National Time and Frequency Group Standard (CNTFGS) [1] in 1993. The CNTFGS is based on the HP 5071A cesium clocks operating in two remote laboratories in Prague. Fiber-optic links are used to provide the internal traceability of individual clocks. These transfer links (each of them consisting of an identical 1300 nm optical transmitter, approximately 10-km-long single-mode fiber buried underground, and an optical receiver followed by a 5 MHz PLL filter) are used to transfer 5 MHz output signals of the clocks in both directions. The two-way configuration of the CNTFGS time transfer network permits use of the standard data obtained from the routine time scale comparisons for evaluation of the link transfer stability. This paper summarizes the results of nearly four-year study of the instability of the propagation delay of the fiber timing links. It has been found that the temperature of the soil surrounding the optic cable, which causes the thermal dilatation of the fiber, is dominant among all other environmental factors which also might affect the long-term propagation delay fluctuations of the whole link.

THE EXPERIMENT CONFIGURATION AND TIME RELATIONS

The basic configuration of the clocks and timing links is depicted in Figure 1. One cesium clock is located in laboratory A and two clocks in laboratory B. Identical automated measuring systems are used at both laboratories to provide simultaneous phase-time measurements. Two output signals transmitted from B at the time instants T_1 and T_2 using the links 1 and 2 are received at A at the time instants T_1^* and T_2^*, respectively. In the same way, the output signal transmitted from A at the time instant T_0 using the link 0 is received at B at T_0^*. Each transfer link is characterized by its total propagation delay which can be modeled as a sum of a constant and a variable parts. Only these variable components τ_i, $(i = 0,1,2)$ will be of further interest . To make the remote clock comparisons, the differences T_0 -T_1 and T_0 -T_2 should be known. Apparently, they cannot be measured directly, but they can be evaluated from the differences measured at laboratory A:

$$\Delta T_{A1} = T_o - T_1^* \tag{1a}$$
$$\Delta T_{A2} = T_o - T_2^* \tag{1b}$$
$$\Delta T_{A12} = T_1^* - T_2^* \tag{1c}$$

and at laboratory B:

$$\Delta T_{B1} = T_o^* - T_1 \tag{2a}$$
$$\Delta T_{B2} = T_o^* - T_2 \tag{2b}$$
$$\Delta T_{B12} = T_1 - T_2 . \tag{2c}$$

Since $T_i^* = T_i + \tau_i$, the desired phase-time differences

$$T_0 - T_1 = \Delta T_{A1} + \tau_1 = \Delta T_{B1} - \tau_0 \tag{3a}$$
$$T_0 - T_2 = \Delta T_{A2} + \tau_2 = \Delta T_{B2} - \tau_0 \tag{3a}$$

and the following relation can be derived from (1) and (2).

$$\Delta T_{B1} - \Delta T_{A1} = \Delta_1 = \tau_0 + \tau_1 \tag{4a}$$
$$\Delta T_{B2} - \Delta T_{A2} = \Delta_2 = \tau_0 + \tau_2 \tag{4b}$$
$$\Delta T_{B12} - \Delta T_{A12} = \delta = \tau_2 - \tau_1 \tag{4c}$$

$$\Delta T_{A1} + \Delta T_{B1} = 2(T_0 - T_1) + (\tau_0 - \tau_1) \tag{5a}$$
$$\Delta T_{A2} + \Delta T_{B2} = 2(T_0 - T_2) + (\tau_0 - \tau_2). \tag{5b}$$

Δ_1 and Δ_2 denote the summary delay of the loops 1 and 2 made up by the link 0 together with the links 1 and 2 respectively, and δ denotes the differential delay of the links 1 and 2.

ANALYSIS OF OBTAINED DATA

DELAY OF THE LOOPS 1 AND 2 AND ITS CORRECTION

The plots of daily values of Δ_1 and Δ_2 are displayed in Figure 2. One can see that the curves exhibit very similar seasonal variations with the peak-to-peak value being approximately 15 ns. The maximum frequency deviation is about $\pm$ 1.10^{-15}. The third curve displayed in Figure 2 represents mean daily temperature T_{out} taken in Prague . The close correlation of the long-term propagation delay with the outdoor temperature is obvious. The detailed study shows that the correlation coefficient reaches its maximum value ($\rho \cong 0,85$) if the Δ_1 or Δ_2 functions are delayed by about 20 days with respect to T_{out} . Such a delay of the response to the outdoor temperature might be explained only by the slow propagation of heat in the soil. Therefore, it can be assumed that the underground temperature which has an influence on the fiber is the source of this type of fluctuations. To confirm this assumption, the underground temperature along the cable should be known. However, the direct measurement of this temperature is almost impossible. The fact is that the 9-km-long section of the optic cable traces the urban area and is buried in different depths varying from 0,5 m to 3 m (part of the cable is led in a cableduct ; another part is laid in the soil). So the soil temperature was modeled under the following simplifying presumptions:

- the soil was presumed to be homogeneous,
- the mean daily temperature of the soil surface was supposed to be equal to the mean temperature of the air,
- there are no other sources of heat influencing the optic cable.

Under these conditions the soil temperature in different depths 0.25 m to 3 m was evaluated as described in [3] . The correlation of the Δ_1 and Δ_2 with the relative daily values of soil temperature in different depths was analyzed, yielding the results displayed in Figure 3. It is seen that the maximum correlation coefficients ($\rho_{\Delta 1,T(h)} \cong 0.93$ for Δ_1 and $\rho_{\Delta 2,T(h)} \cong 0.9$ for Δ_2) are obtained for the depth $h \cong 1.3$ m.

An attempt has been made to find a correlation of the Δ_1 and Δ_2 with other environmental factors (air pressure, indoor temperature of the laboratories A and B). None of the correlation coefficients have exceeded 0.05. This indicates that the temperature of the soil surrounding the optic cable has the dominating influence on the long-term stability of its propagation delay .

In order to make the optimal correction of the temperature changes of the link delay, the estimation method has been used. The temperature coefficient K_i [ns/ km.°C] minimizing the value A(h) for different values of the depth were chosen for the loop 1 and 2:

$$A(h) = \sum_{n=N1}^{N2} \left[\Delta_i(n) - K_i . d . T_h(n) \right]^2 \tag{6}$$

where Δ (i) - samples of daily values of the loop delay

$T_h(n)$ - samples of daily values of the soil temperature for the depth h

$N_1 = MJD_{min}$

$N_2 = MJD_{max}$.

i = 1, 2 denotes the number of loop
d - length in km of the buried part of the cable (d=9 + 9= 18)

The minimum A(h) ≅ 1 ns was found for h = 1.3 m . That is in a close agreement with the correlation result mentioned above. The values K_1 = 0.046 and K_2 = 0.041 obtained from (6) for this "effective" depth do not differ very much. This result is not surprising if we take into account that the individual fibers placed within one cable should exhibit very similar propagation delay variations under the same environmental conditions. That makes it possible to simplify the above relations by assuming

$$\tau_0 = \tau_1 = \tau_2 = \tau. \tag{7}$$

Under this assumption

$$\Delta = \Delta_1 = \Delta_2 = 2\tau \tag{8}$$

holds and so the temperature-corrected loop delays Δ_{icorr} (i = 1, 2) can be evaluated as

$$\Delta_{icorr} = \Delta_i - K_i . d . T_h . \tag{9}$$

The plots of corrected time functions Δ_{1corr} and Δ_{2corr} are shown in Figure 4 . They have no long-term variations, but they show residual noise fluctuations as the curves Δ_1 an Δ_2 in Figure 3. Note that the records in Figure 3 and 4 consist of two different parts. The left-hand part (MJD 49379 to MJD 50299) has been obtained from the data measured by less accurate time interval counters, which provided uncertainty of σ = 0.52 ns. Since that uncertainty was too large, high resolution counters with σ = 30 ps were used later in the course of experiment (MJD 50300 to MJD 50687).

Among the measures used in the time domain, the time difference

$$TDEV(\tau) = \sqrt{\frac{1}{6}\langle (D^2 \overline{x})^2 \rangle} \tag{10}$$

seems to be optimal to describe the time stability of the uncorrected time transfer and to estimate the effect of temperature correction .TDEV (1 day ≤ τ ≤ 240 days) was evaluated first for Δ_2 within the time interval MJD 49379 to 50299. The corresponding plot denoted as Δ_2 LRC is presented in Figure 5. It is seen that the TDEV(τ) is basically constant for 1 day ≤ τ ≤ 30 days. The value of TDEV (τ=1day) = 0.94 ns . The TDEV(τ) is increasing for τ ≥30 days and it reaches its maximum for τ ≅ 180 days. This is the result of the seasonal fluctuations. Then the TDEV (1≤ t ≤ 90 days) was evaluated for Δ_2 within the time interval MJD 50300 to MJD 50687. In this case the curve Δ_2 HRC representing TDEV(τ) characterizes the instability of the loop much better because of substantially higher resolution of the counters. The plot Δ_2HRC starting from $TDEV_2$ (1 day) = 0.4 ns is monotonously increasing and reaching the Δ_2LRC for τ = 90 days.

The corresponding TDEV(τ) plots (denoted by Δ_{2corr} LRC and Δ_{2corr} HRC) calculated for Δ_{2corr} in the above mentioned intervals of τ and MJD are displayed in Figure 6. We can see that the TDEV(τ) values characterizing the temperature-corrected loop propagation delay well correspond to the ones of uncorrected loop propagation delay within the interval 1 day ≤ τ ≤ 30 days . The correction effect is evident for τ > 30 days.

CORRECTION OF MEASURED PHASE TIME DATA

Knowing the law of temperature dependence of the propagation delay, we can correct for the measured phase-time data in order to remove the long-term fluctuations due to the transmission link. For one-way time transfer the following formula (i=1,2) can be used:

$$T_0 - T_i = \Delta T_{Ai} - K.d.T_h, \tag{11}$$

This correction needs the current soil temperature T_h to be evaluated from the mean daily outdoor temperature, as described in [3]. Let us mention that the outdoor temperature changes will exert an influence upon the fiber of the described system after a delay of 20 days.

Another way to correct the data is to take advantage of the two-way transmission. It is clear (if (7) and (8) are valid) that the desired time differences cleared of transmission link fluctuations can be obtained simply by using (5a, 5b) e.g.

$$T_0 - T_i = \frac{\Delta T_{Ai} + \Delta T_{Bi}}{2} \tag{12}$$

even without the knowledge of the actual values of link propagation delay.

CONCLUSION

The obtained results demonstrate the possibility of stabilizing mathematically the propagation delay of the studied time transfer optic link within 1 ns or less (in the sense of TDEV(τ)) for time intervals $\tau \geq 1$ day by correcting for the influence of the soil temperature variations upon the optic fiber buried underground. This correction reduces the long-term instability for time intervals longer than 30 days and permits us to reach 1 ns timing uncertainty within the group standard. In the course of almost four-year period of experiment, no significant systematic phase drifts (aging, etc.) have been observed.

Even after the temperature correction residual phase fluctuations for shorter time intervals, $\tau \leq 30$ days, remain. Their source is not yet fully known; however, from the data of the two sets of counters with different resolution we can conclude that at least a part of the fluctuations is due to the limited counter resolution.

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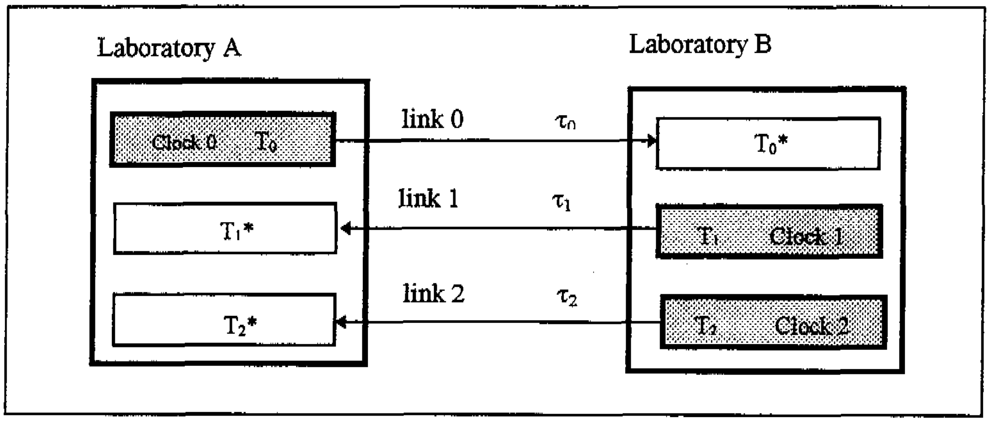


Fig.1 : Basic diagram of the time transfer system. One clock signal is transmitted from the laboratory A to the laboratory B and two clock signals are transmitted in a opposite direction using identical fiber-optic transfer links.

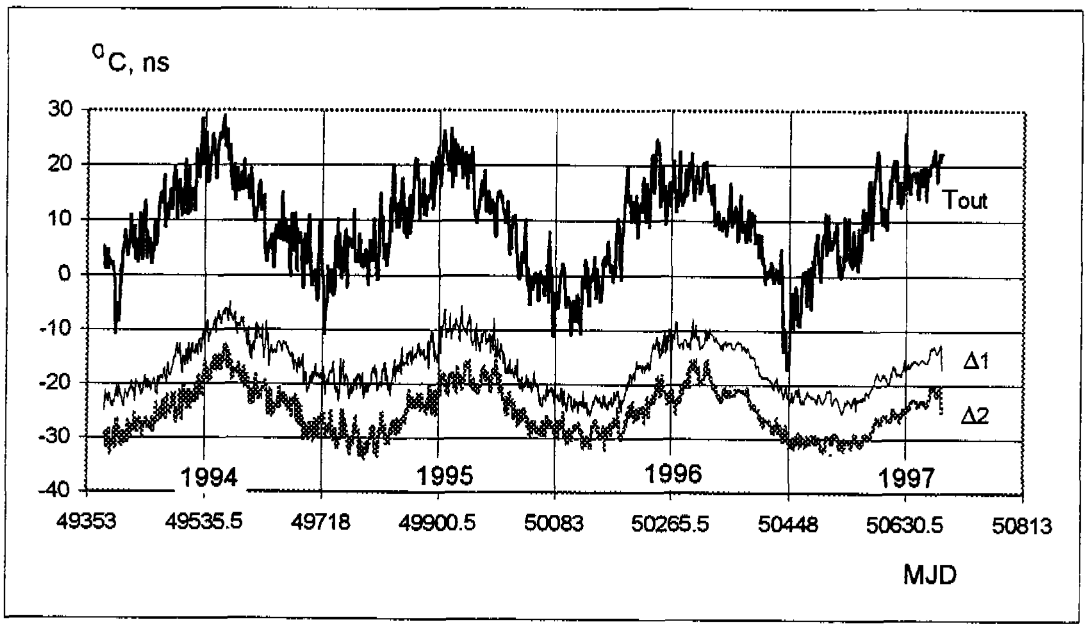


Fig.2 This figure shows the plots of relative summary propagation delay Δ_1 of the loop 1 created by links 0 and 1, and Δ_2 of the loop 2 created by links 0 and 2. The third plot displays the mean daily outdoor temperature T_{out} in Prague.

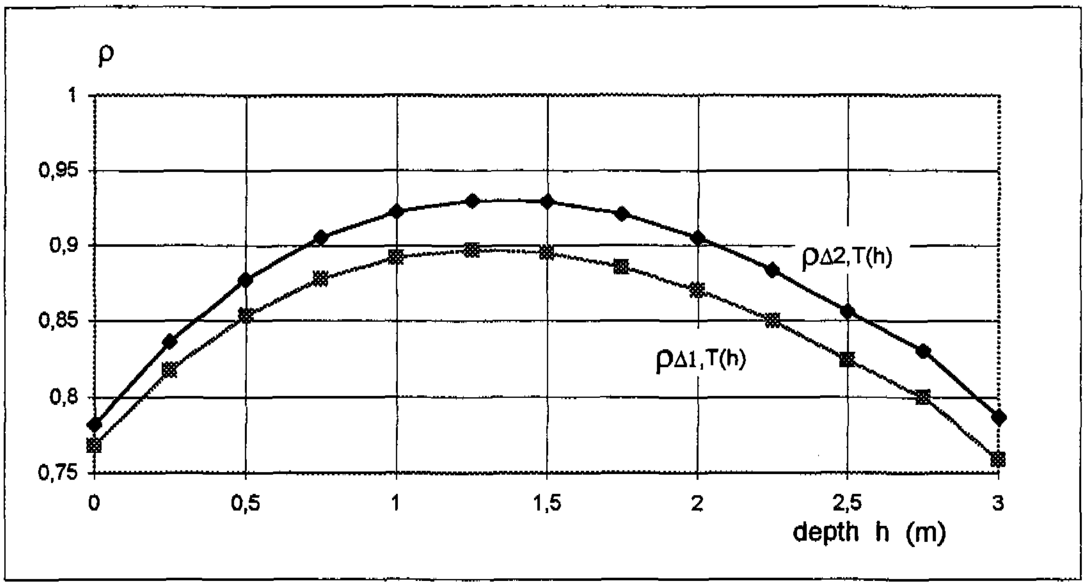


Fig.3 Correlation of loop delays with underground temperature in different depths. The correlation coefficient ρ reaches its maximum value for the depth $h \cong 1.3$ m.

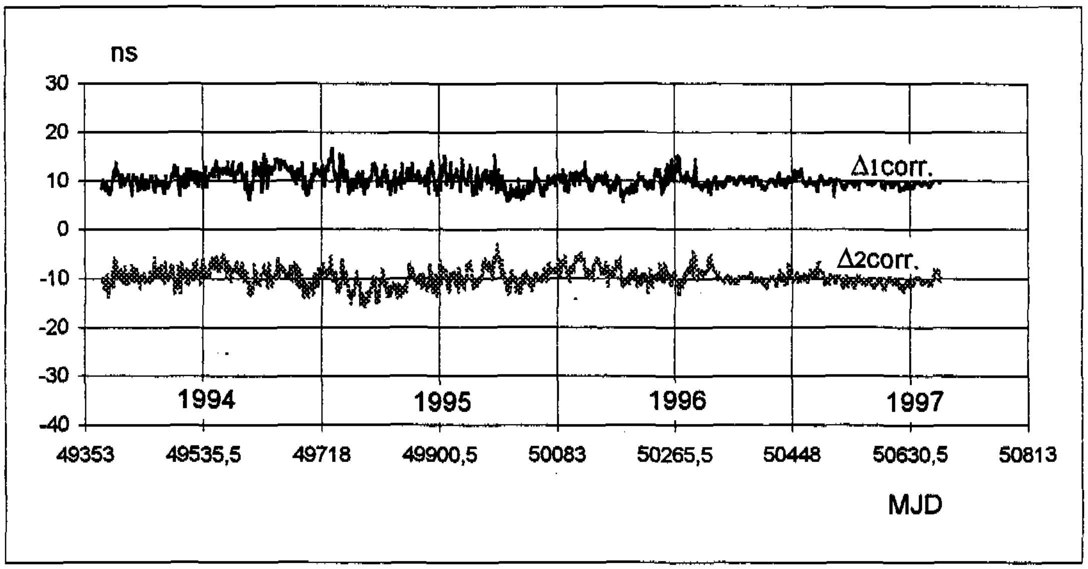
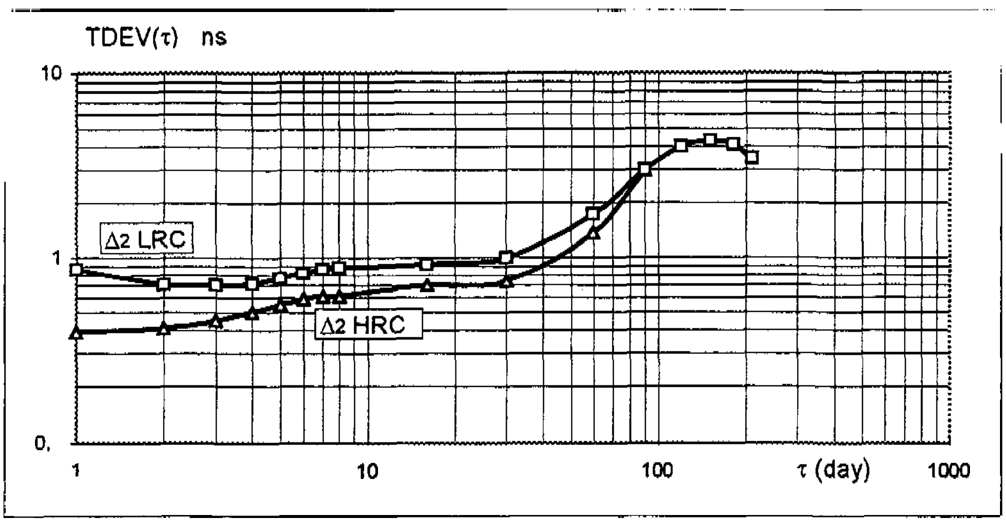


Fig.4 displays the plots of the relative propagation delays of the loops 1 and 2 after correction for the soil temperature in the depth h = 1..3 m



displays the plots TDEV (τ) of uncorrected propagation delay of the loop 2 calculated from the data measured by low resolution counters (Δ_2 LRC) and by high resolution counters (Δ_2 HRC).

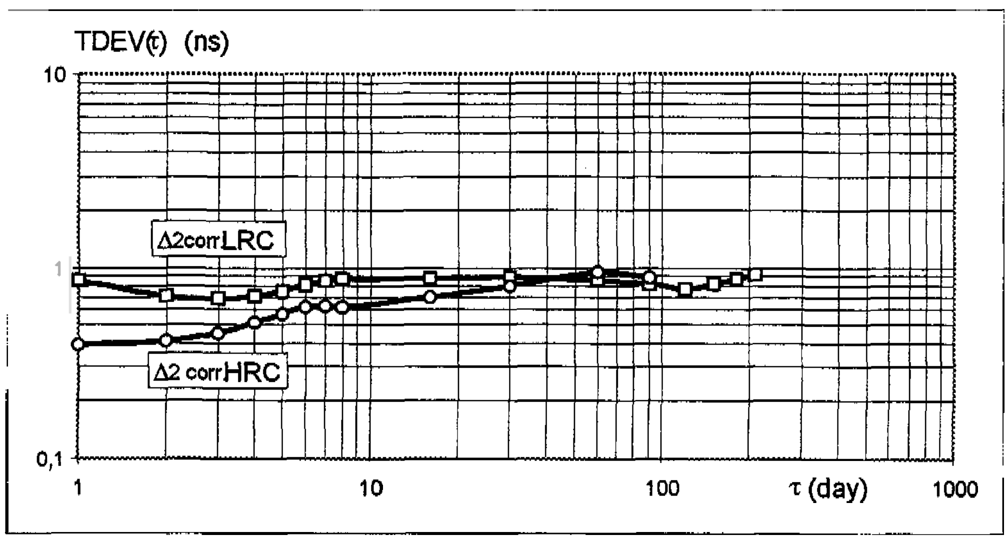


Fig. 6 displays the plots of TDEV (τ) of corrected propagation delay of the loop 2 calculated from the data measured by low resolution counters ($\Delta_{2\ corr.}$ LRC) and by high resolution counters ($\Delta_{2\ corr.}$ HRC).

Questions and Answers

ALBERT KIRK (JPL): You show a seasonal temperature plot and you also mention that the depth of the cable was between .5 (point 5) and three meters. At what depth did you measure the temperature?

OTOKAR BUZEK: The temperature measurement was not down under the ground. We used, as input data, the mean temperature of the air in Prague. It was supposed that this is the ground surface temperature. Then using the standard equations, the temperature underground was calculated. It was only calculated, because the soil is operating as a low-pass filter. Only the long wave of the heat is transported down and time delayed. So it was not measured, it was calculated.

ALBERT KIRK: Was most of the cable at the three-meter depth or between .5 (point 5) and three meters? Can you express that in a certain percentage, the relationship of depth for the 10 kilometers?

MALCOLM CALHOUN (JPL): May I answer that?

ALBERT KIRK: Yes, please.

MALCOLM CALHOUN: Eight hundred meters was at a half-meter depth. The rest of the link was at two to three meters. Unfortunately, the 800-meter at a half-meter depth would account for the biggest part of the cycling that we saw.

BOB WEAVER (UNIVERSITY OF SOUTHERN CALIFORNIA): What was the total extent of the temperature fluctuations in your graph? I could not quite read the graph.

MALCOLM CALHOUN: Minus 10 to plus 35 – yes, minus 10 C to plus 35 C.

OTOKAR BUZEK: These peaks are from approximately minus 18 to plus 30 degrees Celsius.