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The Abnormal Influence of the Partial Solar Eclipse on December 24th, 1992, on the Time Comparisons between Atomic Clocks (*).

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Summary. — During the partial solar eclipse on Dec. 24th, 1992, time comparisons beetween atomic clocks were made: direct comparisons between different clocks at one and the same station, clock transport comparisons, GPS comparisons and LOC comparisons. And it is concluded from the observations that solar eclipse exerts an influence on the rate of atomic clocks.

PACS 04.80 – Experimental tests of general relativity and observations of gravitational radiation.
PACS 95.55.Wk – Other instrumentation and techniques (including clocks, frequency standards, etc.).
PACS 96.90 – Other topics on the solar system.

1. – Introduction.

During solar eclipse, some physical phenomena appeared to be abnormal, which cannot be interpreted in the frame of present gravitational theories. Hence they were called abnormal gravitational phenomena [1-4].

During the partial solar eclipse on Dec. 24th, 1992, atomic clocks in relevant stations and institutes were arranged to make the direct comparison between different clocks at one and the same station and the clock transport comparison. GPS and LOC comparison data were collected. And it is concluded from the data obtained that solar eclipse exerts an abnormal influence on the rate of atomic clocks.

2. – Relevant astronomical data of the partial solar eclipse.

The partial solar eclipse on Dec. 24th, 1992, had a rather strong effect in Northeast Asia and the Northern Pacific. The astronomical data on the solar eclipse

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TABLE I. – *Relevant data about the solar eclipse at the stations for the clock transport comparisons.*

Station	Latitude	Longitude	Sunrise		
			time	azimuth	
				P (a)	V (b)
Harbin	45° 80 N	126° 60 E	23d 23h 11m	292° 0′	332° 3′
Beijing	39° 95 N	116° 32 E	23d 23h 33m	306° 0′	352° 30′
Wuhan	30° 60 N	114° 30 E	23d 23h 16m	325° 0′	22° 25′

Station	Eclipse maximum		Eclipse end		
	time	magnitue	time	azimuth	
				P (a)	V (b)
Harbin	23d 23h 36m	0.61	24d 0h 53m	67° 00′	94° 26′
Beijing	—	0.40 (c)	24d 0h 25m	57° 00′	97° 42′
Wuhan	—	0.20 (c)	23d 23h 57m	40° 00′	93° 24′

(a) Parallels of altitude.
(b) Vertical semidiametre.
(c) Eclipse maximun occurred when the Sun was below the horizon. The magnitude is that at sunrise.

at the stations chosen inside China for the clock transport comparison are presented in table I and fig. 1; it can be seen from table I that the effect of the solar eclipse at the stations is very weak.

3. – Observation scheme.

3·1. *Atomic clocks for the clock transport comparisons.* – Two fixed clocks $C(1)$ and $C(2)$ provided by Wuhan Time Station, two fixed clocks $C(3)$ and $C(4)$ provided by Beijing Institute of Radio Metrology and Measurements; a fixed clock $C(5)$ at Harbin Station provided by Xi'an Institute of Radio Metrology and Measurements; and the transporting clock $C(F)$ provided by Wuhan Time Station.

The main performance indices of each caesium atomic clock are shown in table II.

3·2. *Comparison mode.* – The following comparisons were made before, after, and during the solar eclipse.

a) Direct comparisons were made between different clocks at one and the same station in Harbin, Changchun and Wuhan.

b) Clock transport comparisons were made between the transporting clock $C(F)$ and $C(1)$ in Wuhan and between $C(F)$ and $C(3)$ in Beijing.

c) The GPS and LOC comparison data were collected from relevant stations and institutes.

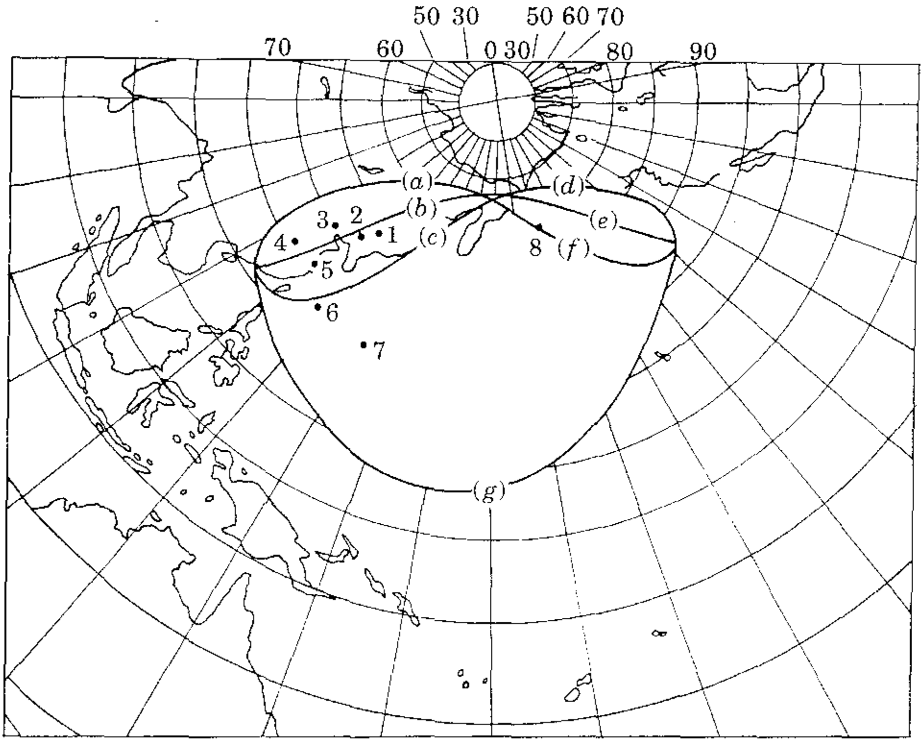

Fig. 1. – Approximate locations of the stations for clock comparisons. 1) Harbin, 2) Changchun, 3) Beijing, 4) Wuhan, 5) Shanghai, 6) Gesashi Japan (LC9970$_y$), 7) IWO Jima Japan (LC9970$_M$), 8) St. Paul AK (LC9990$_M$). *a*) End of penumbral phase occurs at sunrise. *b*) Maximum phase occurs at sunrise. *c*) Beginning of penumbral phase occurs at sunrise. *d*) Beginning of penumbral phase occurs at sunset. *e*) Maximum phase occurs at sunset. *f*) End of penumbral phase occurs at sunset. *g*) South boundary of the eclipse.

4. – Observation results.

4·1. *Direct comparisons between different clocks at one and the same station.*

i) In Harbin.

In Harbin, clocks $C(F)$ and $C(5)$ were placed in one and the same laboratory at a room temperature of 19.5 ± 0.5 °C.

Direct comparisons were made from 00:30 Dec. 23rd to 7:00 Dec. 24th; the data were taken in a time interval of 30 minutes in general, and the interval became 10 minutes from 22:30 23rd to 1:00 24th.

The comparison results are presented in fig. 2 and table III. It can be seen from fig. 2 that the slopes of segment AB (before 23d 17h) and CD (after 24d 01h) remain unchanged and the slope of CD is smaller than that of AB. This means that the rate difference between the two clocks remains unchanged before and after the solar eclipse, as is exactly what two stable clocks are expected to perform. The slope of segment BC (from 23d 17h to 24d 01h) varies gradually with the influence of the solar eclipse, which means that the rate difference between the two clocks varies

TABLE II. – *Main performance indices of the caesium atomic clocks for the clock transpo comparisons.*

Clock number	Type	Accuracy	Stability (10^4 s)	Environmental influence		Working site
				temperature	magnetic field	
$C(1)$	Hp 5061A U.S.	$\pm 1 \cdot 10^{-11}$	$8 \cdot 10^{-13}$	0–50 °C maintained	2G: $\pm 2 \cdot 10^{-12}$	Wuhan
$C(2)$ (^{a})	Hp 5061A U.S.	$\pm 7 \cdot 10^{-12}$	$8.5 \cdot 10^{-14}$	0–50 °C maintained	2G: $\pm 2 \cdot 10^{-12}$	Wuhan
$C(3)$	Hp 5061A U.S.	$\pm 7 \cdot 10^{-12}$	$8.5 \cdot 10^{-14}$	0–50 °C $< 5 \cdot 10^{-12}$	2G: $< 2 \cdot 10^{-12}$	Beijing
$C(4)$	XSC Germany	$\pm 1 \cdot 10^{-11}$	$5 \cdot 10^{-13}$	0–50 °C $< 5 \cdot 10^{-12}$	2G: $< 2 \cdot 10^{-12}$	Beijing
$C(5)$	B-3200 SA	$\pm 1 \cdot 10^{-11}$	$3 \cdot 10^{-13}$	0–50 °C $< 2 \cdot 10^{-12}$	2G: $< 2 \cdot 10^{-12}$	Harbin
$C(F)$	FTS4010A U.S.	$\pm 7 \cdot 10^{-11}$	$\pm 5 \cdot 10^{-13}$	over 0–50 °C $< 5 \cdot 10^{-12}$	2G: $< 5 \cdot 10^{-12}$	transpor

(a) Caesium clock $C(2)$ has been ageing.

TABLE III. – *Direct-comparison data for different clocks at one and the same station. S is the standard deviation from the least-squares fit line; ΔT is the time difference variation due to the solar eclipse; $\Delta T/T$ is the relative time difference variation due to the solar eclipse, and T is the duration of the eclipse physical effect.*

Station	Clock number	Segment AB	
		slope (ns/h)	$3S$ (ns)
Harbin	$C(F)$ $C(5)$	-34.3	15.1
Changchun	$Rb(1)$ $Rb(2)$	257.0	$1.5 \cdot 10^3$
Wuhan	$C(1)$ $C(2)$	-62.2	53.1

Station	Segment CD		ΔT (ns)	$\Delta T/T$	$\Delta T/3S$
	slope (ns/h)	$3S$ (ns)			
Harbin	-32.3	11.7	76.8	$2.4 \cdot 10^{-12}$	5.1
Changchun	250.0	$1.0 \cdot 10^3$	$65.0 \cdot 10^3$	$3.6 \cdot 10^{-8}$	43
Wuhan	-59.9	55.8	-468.2	$1.7 \cdot 10^{-12}$	8.8

gradually. And ΔT, the difference between the actual measured value at t (point C) and the ordinate value at t (point C) of the extended line of the least-squares-fit line AB, is 76.8 ns, which is the time difference between clocks with different structures and in different states at one and the same station due to the solar-eclipse effect. In fig. 2, the perpendicular dot-dashed line represents the time of the eclipse maximum.

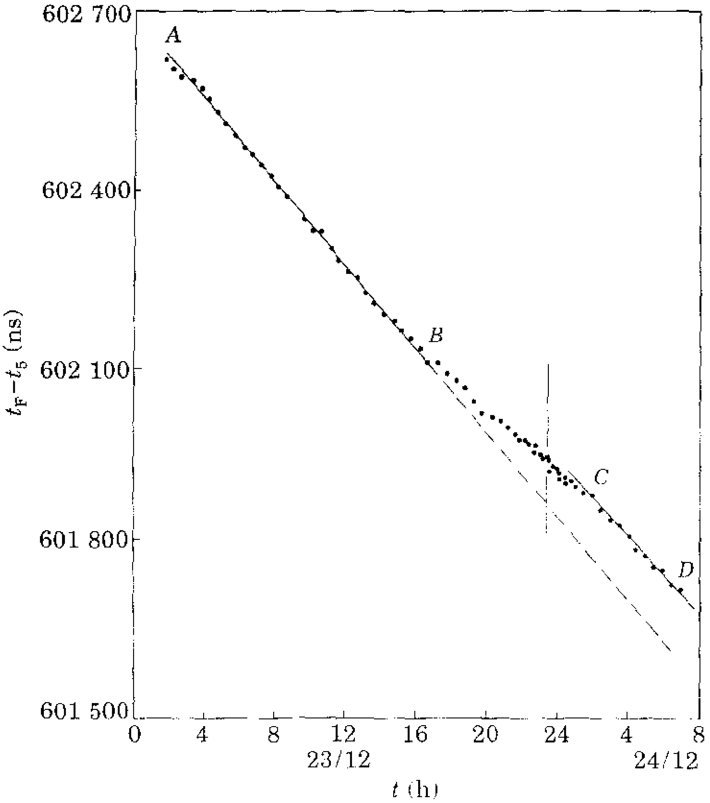

Fig. 2. – Time difference curve of direct comparisons between $C(F)$ and $C(5)$ in Harbin.

It should be pointed out that the duration of the physical effects of the solar eclipse is not exactly the same as that of its optical effects. It is known from table III that the relative variation due to the solar eclipse is small. However, $\Delta T/3$ s is 5.1, *i.e.* the variation of the time difference is believable.

ii) In Wuhan.

In Wuhan, $C(1)$ and $C(2)$ were placed in one and the same laboratory at an indoor temperature of 20 °C. Direct comparisons were made during the period of Dec. 19th, 1992 to Jan. 3rd, 1993, with the data automatically taken by a computer. The comparison results are shown in fig. 3 and table III.

iii) In Changchun.

The results of the direct comparisons between the main clock ($Rb(1)$) and $Rb(2)$ in Changchun are shown in fig. 4 and table III.

4˙2. *The clock transport comparisons.* – The following controlled tests had been carried out for the transporting clock $C(F)$ before the clock transport comparisons were formally made: temperature controlling test, bump test and flying test ($C(F)$ was flown from Wuhan to Bejing and back to Wuhan in fifteen hours). No abnormalities were found in the above controlled tests.

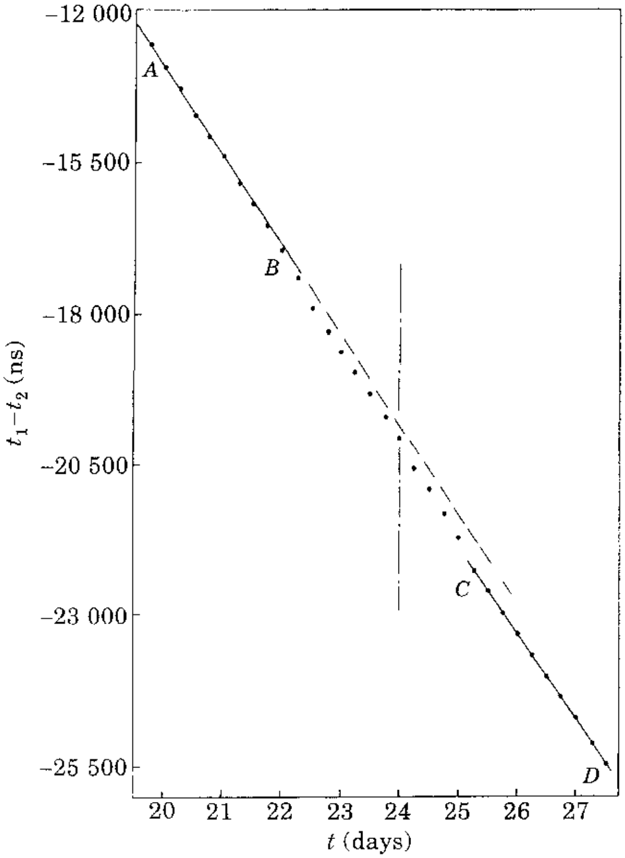

Fig. 3. – Time difference curve of direct comparisons between $C(1)$ and $C(2)$ in Wuhan.

The formal clock transport comparisons began on Dec. 18th. The clocks $C(1)$, $C(3)$, and $C(5)$ were fixed, respectively, in Wuhan, Beijing and Harbin all the time, and *experienced the effect of the solar eclipse from 23rd to 24th therein.* The transporting clock $C(F)$ was compared with $C(1)$ in Wuhan before Dec. 18th; on Dec. 18th it was flown from Wuhan to Beijing, and was compared with $C(3)$; on Dec. 22nd it was flown from Beijing to Harbin to compare with $C(5)$ and *underwent the effect of the solar eclipse from 23rd to 24th therein*; on Dec. 25th it was flown from Harbin to Beijing, and was compared again with $C(3)$; on Dec. 28th it was flown from Beijing to Wuhan to compare again with $C(1)$; these comparisons lasted until Jan. 3rd, 1993.

i) Between Beijing and Harbin.

The comparison results are presented in fig. 5 and table IV. It can be seen from fig. 5 and table IV that the slopes of the comparison curve AB (before solar eclipse) and the comparison curve CD (after solar eclipse) remain unchanged, respectively, with the slope of the latter smaller than that of the former. And ΔT, the difference between the actual measured value at t (point C) and the ordinate value at t (point C) of the extended line of the least-squares-fit line AB, is -124.8 ns. It will be found from a further analysis that this difference

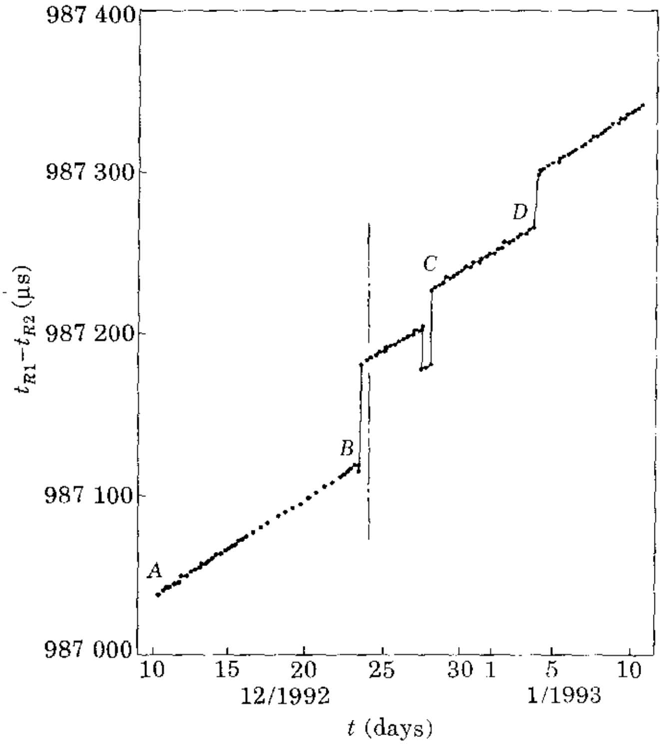

Fig. 4. – Time difference curve of direct comparisons between $Rb(1)$ and $Rb(2)$ in Changchun.

ΔT is mainly due to the effect difference of the solar eclipse between Harbin and Beijing.

ii) Between Wuhan and Harbin.

The comparison results are presented in fig. 6 and table IV.

4'3. GPS *comparisons and* LOC *comparisons*. – The GPS comparisons data were collected from Beijing Institute of Radio Metrology and Measurements, Shanghai Observatory and USNO[5]. It is clear that variation before, after, and during the solar eclipse was appreciable only in some of the stations and observatories. It is seen from fig. 7 that there was a deviation from the mean value during the period of Dec. 20th, 1992, to Jan. 9th, 1993, and a peak value on 24th, which qualitatively illustrates the influence of the solar eclipse on GPS comparisons.

The LOC comparison data were collected from Wuhan Time Station, Shanghai Observatory, Beijing Observatory, Shaanxi Observatory, Changchun Station and USNO[5]. It is shown in these data that an obvious variation before, after, and during the solar eclipse existed only in some of the observatories and stations (see fig. 8 and 9 and table V). These observatories and stations are mainly located in the districts where solar-eclipse effect is strong or in those corresponding penetrated districts on the other side of the Earth. It should be pointed out that the duration of the obvious variation overlaps and greatlly exceeds that of optical effects.

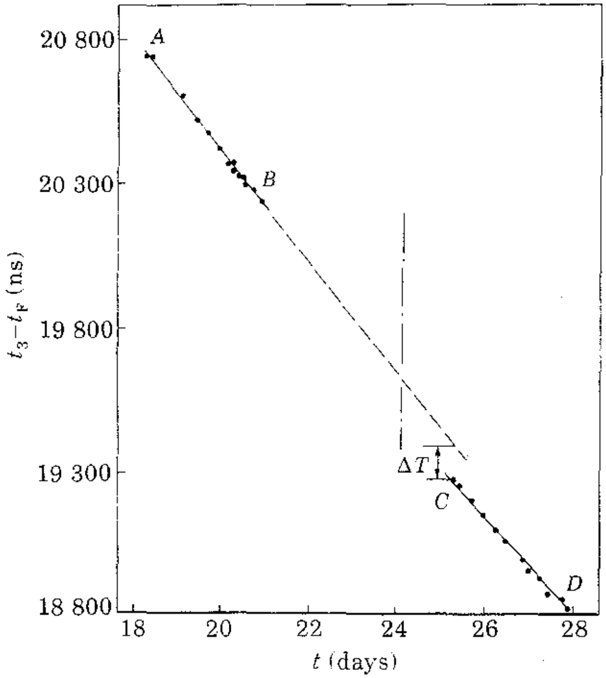

Fig. 5. – The clock transport comparisons between Beijing and Harbin during the solar eclipse.

TABLE IV. – *Data of the clock transport comparisons. S is the standard deviation from the least-squares fit line; ΔT_r is the relativity corrected values; $\Delta T'$ is the time difference variation due to the solar eclipse; $\Delta T = \Delta T_r + \Delta T'$; $\Delta T'/T$ is the relative time difference variation due to the solar eclipse, and T is roughly considered to be* 9 *hours, which is the duration of the eclipse physical effect in Harbin.*

Station	Clock number	Segment AB		Segment CD		ΔT (ns)	$\Delta T/3S$	ΔT_r (ns)	$\Delta T'$ (ns)	$\Delta T'/T$
		slope (ns/h)	$3S$ (ns)	slope (ns/h)	$3S$ (ns)					
Beijing ⇄ ⇄ Harbin	$C(3)$, $C(F)$	− 8.1	25.7	− 7.4	39.9	− 124.8	4.9	39.8	85.0	$2.6 \cdot 10^{-12}$
Wuhan ⇄ ⇄ Harbin	$C(1)$, $C(F)$	− 2.7	120.8	− 0.6	39.8	− 453.6	3.8	208.2	245.4	$7.6 \cdot 10^{-12}$

It is clear that LOC and GPS comparisons are different from the direct comparisons of different clocks at one and the same station or from clock transport comparisons. The latter are not related to the propagation effect, while the former are related and are complicated.

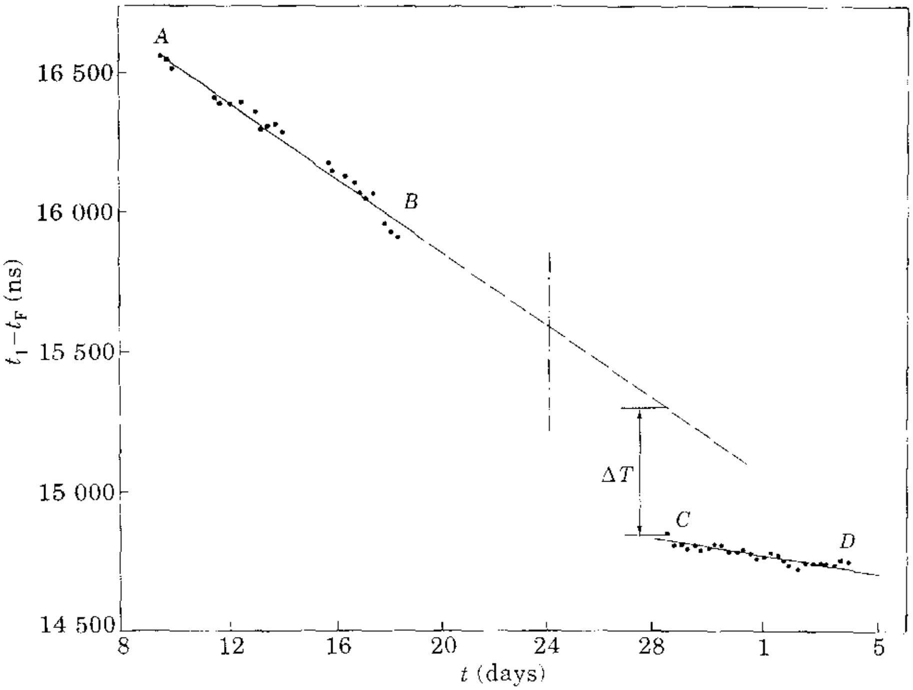

Fig. 6. – The clock transport comparisons between Wuhan and Harbin during the solar eclipse.

5. – Analysis.

5·1. *The stability of the clocks.* – It is most important for the observation of the influence of solar eclipse on the time comparisons of atomic clocks that the rate of the clocks used for clock transport comparisons should be stable. That is to say, the frequency difference of the two clocks remains constant within the range of permissible errors. Therefore the comparison time difference has a linear relation with time, *i.e.* its slope remains constant.

It can be concluded from the two straight line segments *AB* and *CD* in fig. 2, 3, 5 and 6 that the rate of the clocks *C*(1), *C*(3) and *C*(*F*) is stable all through the comparisons except during the solar-eclipse effect. It is clear that after the solar-eclipse effect, the rate of the clock did not reverse immediately to its original rate before the eclipse. The slope of the latter segment *CD* of the comparison line is smaller than that of the former segment *AB*.

5·2. *The effect of the temperature.* – In the whole course of the clock transport comparisons, *C*(1) and *C*(3) were working in laboratories at a constant room temperature. Therefore, no temperature effect is to be considered. *C*(*F*) is a transporting clock, on which the temperature effect is to be ignored when it is carried into the laboratories for comparisons. But the temperature effects during transport should be taken into account and the analysis is as follows:

i) It is known from table II that for *C*(*F*), the temperature effect within the range of 0–50 °C can be neglected.

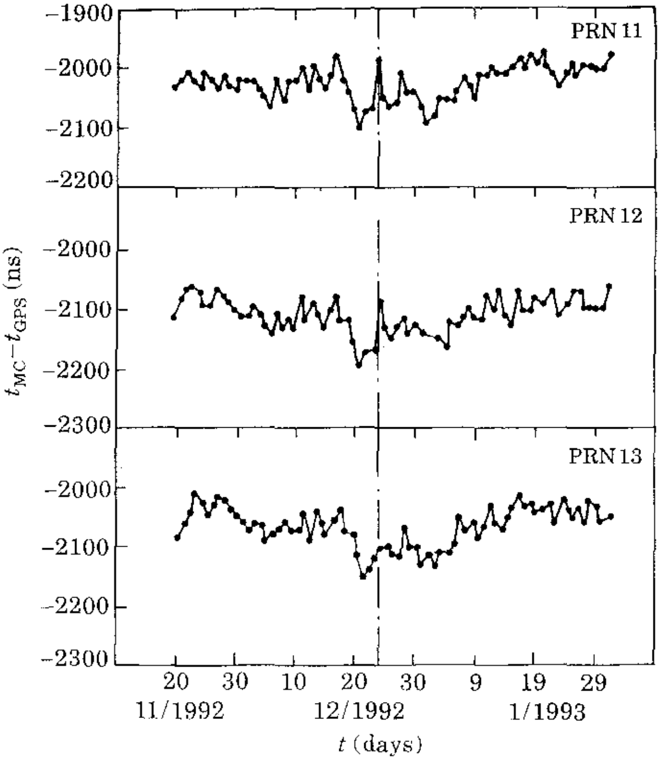

Fig. 7. – GPS comparisons in Shanghai Observatory.

ii) In the course of transport, the temperature is about 10 °C inside a car, about 20 °C on board a plane, and about 20 °C in a waiting room. So the temperature effect in these places can all be ignored. The outdoor temperature in the airport of Harbin is −30 °C, but it takes only 10 minutes to take the $C(F)$ from the plane to the waiting room; furthermore $C(F)$ was wrapped in a heat-insulated cover, therefore the temperature effect can also be ignored because heat conduction needs some relaxation time.

5·3. *The relativistic effects.*

i) Velocity effects due to the latitude difference.

The velocities of clocks fixed in different latitudes are different in the Earth centre coordinate system which does not rotate with the Earth. Therefore, the time difference between two clocks in places of different latitudes should be corrected by means of relativity as follows:

$$\tau_1 - \tau_2 \cong \left\{ -\frac{R^2 \Omega^2}{2C^2} (\cos^2 \lambda_1 - \cos^2 \lambda_2) \right\} \tau_2 , \tag{1}$$

where λ_i, τ_i stand for the latitude and the reading of the clock in station i,

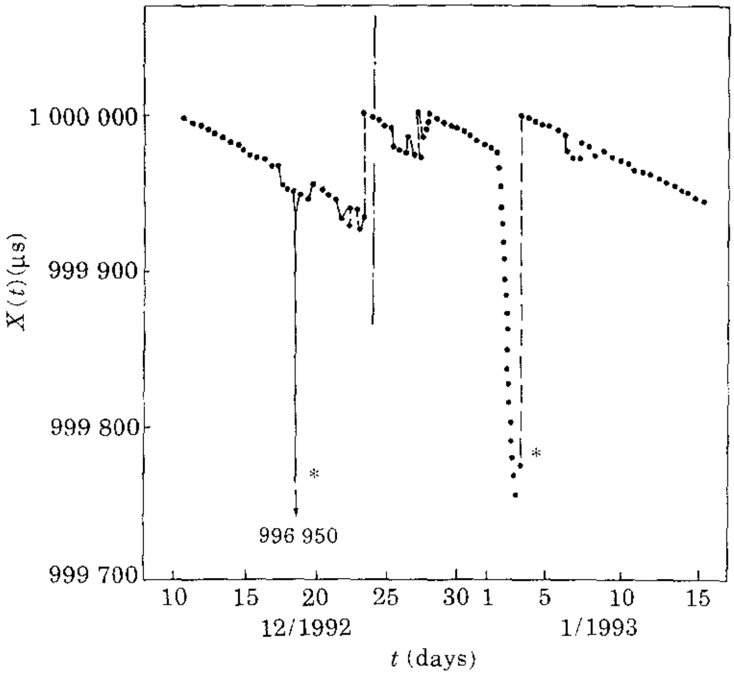

Fig. 8. – LOC comparisons in Changchun. $X(t) = t(\mathrm{MC}) - t(9970_y)$. * : the operator considers that this is an interruption of tracking, and the tracking is reproduced again.

respectively, R, Ω represent the radius of the Earth and its rotation angular velocity, respectively.

For the clock transport compairsons between Beijing and Harbin, when the relevant parameters are substituted into the formula, we have:

$$\tau(\text{Harbin}) - \tau(\text{Beijing}) = 28.3\ \text{ns}\,.$$

For the clock transport comparisons between Wuhan and Harbin, when the relevant parameters are substituted, we have

$$\tau(\text{Harbin}) - \tau(\text{Wuhan}) = 182.5\ \text{ns}\,.$$

ii) The flight effect.

In the course of clock transport compairsons, $C(F)$ suffered both the altitude effect and velocity effect during the flight. Hence the result should be corrected by the following formula:

$$(2)\quad \begin{cases} \tau_{\mathrm{F}} - \tau_{\mathrm{G}} = \oint\left\{\dfrac{gh}{C^2} - \dfrac{1}{2C^2}\left[2R\Omega U\cos\theta\cos\lambda_{\mathrm{F}} + U^2 + R^2\Omega^2(\cos^2\lambda_{\mathrm{F}} - \cos^2\lambda_{\mathrm{G}})\right]\right\}\mathrm{d}t\,, \\ \tau_{\mathrm{F}} - \tau_{\mathrm{G}} \cong \left\{\dfrac{g\overline{h}}{C^2} - \dfrac{1}{2C^2}\left[2R\Omega\,\overline{U\cos\theta\cos\lambda_{\mathrm{F}}} + R^2\Omega^2(\overline{\cos^2\lambda_{\mathrm{F}}} - \cos^2\lambda_{\mathrm{G}}) + \overline{U^2}\right]\right\}t_{\mathrm{go}} + \\ \quad + \left\{\dfrac{g\overline{h'}}{C^2} - \dfrac{1}{2C^2}\left[2R\Omega\,\overline{U'\cos\theta'\cos\lambda'_{\mathrm{F}}} + R^2\Omega^2(\overline{\cos^2\lambda'_{\mathrm{F}}} - \cos^2\lambda_{\mathrm{G}}) + \overline{U'^2}\right]\right\}t_{\mathrm{back}}\,, \end{cases}$$

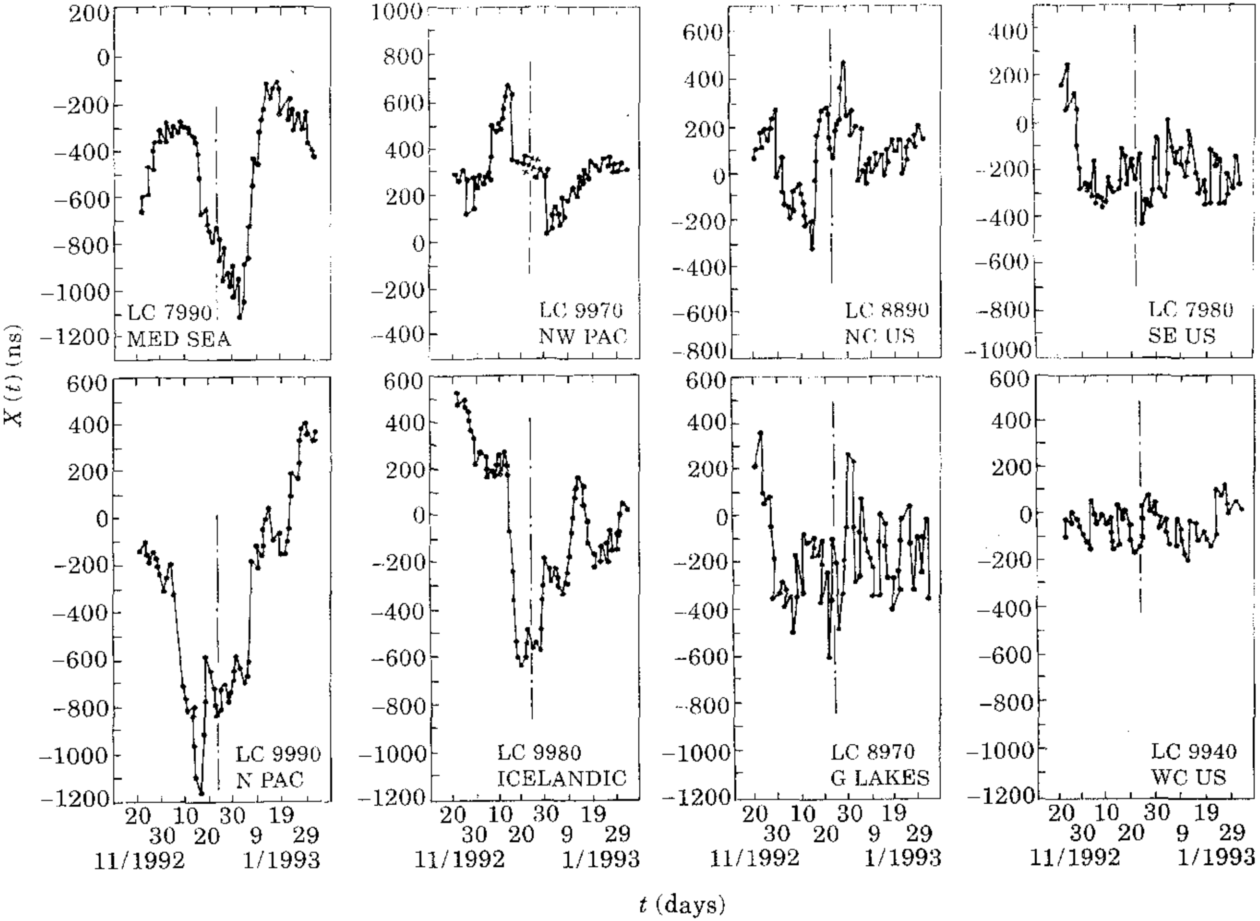

Fig. 9. – LOC comparisons in USNO. $X(t)$ = UTC(USNO MC) – transmitting station. ×: data not available[5].

TABLE V. – *The comparison data on* GPS *and* LOC *in some stations.*

Quantities	GPS	LOC				
	Shanghai	USNO -9980	USNO -9990	USNO -7990	USNO -9970	Changchun -9970$_v$
absolute variation	– 100 ns	– 780 ns	– 960 ns	– 770 ns	– 300 ns	65.0 μs
relative variation	$3.9\cdot10^{-13}$	$1.5\cdot10^{-12}$	$8.5\cdot10^{-13}$	$4.7\cdot10^{-13}$	$3.9\cdot10^{-13}$	$3.6\cdot10^{-8}$

TABLE VI. – *Relativity-corrected values.*

Comparison route	Velocity effects due to latitude difference	Flying effects	General effects
Beijing ⇄ Harbin	+ 28.3 ns	+ 11.5 ns	– 39.8 ns
Wuhan ⇄ Harbin	+ 182.5 ns	+ 25.7 ns	+ 208.2 ns

where subscripts F and G represent the clock in flight and the clock on the ground; h, U, θ, λ_F represent the flying altitude of $C(F)$, its rate, the included angle between the flying direction of $C(F)$ and the due east direction and its latitude, respectively. The symbol —— means average, λ_G represents the latitude of the clock on the ground, t_{go} represents the time taken from place A to place B, and t_{back} the time taken from place B to place A; $(\tau_G - \tau_F)$ is the time difference between the clock fixed in place A and $C(F)$ after it was transported from place A to place B and back to place A.

For the clock transport comparisons between Beijing and Harbin, by substituting the relevant parameters into formula (2), we have

$$\tau_F - \tau_G = 11.5\ \text{ns}\,.$$

For the clock transport comparisons between Wuhan and Harbin, it should be noted that the flight course is Wuhan ⇄ Beijing ⇄ Harbin. By substituting the relevant parameters into formula (2), we obtain:

$$\tau_F - \tau_G = 25.7\ \text{ns}\,.$$

The relativity-corrected values are presented in table VI.

6. – Conclusions.

It is concluded from the observation results and relevant analysis that:

1) The influence of the solar eclipse on the rate of atomic clocks has been observed although the effect of this solar eclipse was very weak.

2) The influences of the solar eclipse on atomic clocks with different structures and states in one and the same laboratory are different.

3) The influences of the solar eclipse on atomic clocks in stations with different solar-eclipse effects are different.

4) The duration of the solar eclipse's physical effect on the rate of the atomic clocks overlaps and exceeds that of the solar eclipse's optical effect as can be seen from the observation results of direct comparisons between different clocks at one and the same station.

5) The solar eclipse exerts an influence on GPS and LOC comparisons, but the behaviour of the comparison curves is complicated because the solar eclipse has an influence on both the rate of the clock and the propagation effect.

6) This is only a report on the observation results. Its theoretical explanation will be given elsewhere.

* * *

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