行政院及所屬各機關出國報告
（出國類別：實習）

赴日本通訊總合研究所進行時間協調模式研究出國報告

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出國地點：日本
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赴日本通訊總合研究所進行時間協調模式研究

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關鍵詞: 日本,通訊總合,時間協調模式

內容摘要: 日本通信總合研究所（CRL）擁有亞洲最佳之時頻研究部門，已有自製之實驗室型銫束原子鐘，亦正進行光頻標準及離子陷阱式原子鐘之研究。在BIPM傳時比對網絡中，更是亞太區之參考節點。時間評量研究上，CRL已進行20餘年，爲亞洲國家鐘最早產生原子時之時頻實驗室。此次由CRL主動邀請赴日進行時間協調模式相關研究，除可促進亞太地區時頻實驗室間之交流外，並對本實驗室建立國家母鐘系統有所助益。本文包括目的、過程、CRL時頻實驗室現況及心得等部份，並包括CRL clock ensemble研究分析報告。

本文電子檔已上傳至出國報告資訊網

摘 要

日本通信總合研究所（CRL）擁有亞洲最佳之時頻研究部門，已有自製之實驗室型銫束原子鐘，亦正進行光頻標準及離子陷阱式原子鐘之研究。在 BIPM 傳時比對網絡中，更是亞太區之參考節點。時間評量研究上，CRL 已進行 20 餘年，為亞洲國家鐘最早產生原子時之時頻實驗室。此次由 CRL 主動邀請赴日進行時間協調模式相關研究，除可促進亞太地區時頻實驗室間之交流外，並對本實驗室建立國家母鐘系統有所助益。本文包括目的、過程、CRL 時頻實驗室現況及心得等部份，並包括 CRL clock ensemble 研究分析報告。

目錄

壹、目的

利用多部原子鐘協調產生一穩定且精確之時標(Time Scale)作為標準時，為國際先進時頻實驗室如 NIST, USNO, OP, BIPM, CRL 行之有年之方法，其中以 CRL 之條件、狀況與 TL 類似，皆擁有十部左右之銫原子鐘，其演繹法相當值得 TL 參考。本實驗室由民國 90 年開始進行國家母鐘計畫，目前已產生一 Paper Clock 每日與 UTC(TL)比對，預計民國 92 年可製作實體鐘，產生較穩定及精確之 UTC(TL)。此次研習可與 CRL 共同交換經驗，為建立新系統及技術時之參考，並洽談進一步合作比對事宜。

貳、過程

本案係依據標準檢驗局委託本所「建立及維持我國時間與頻率國家標準」九十二年度計畫辦理。並奉經濟部標準檢驗局(經標四字)字第 09200005020 號函同意准予參加。此次實習自民國 92 年 2 月 5 日至民國 92 年 3 月 28 日止共 52 天。

行程如下：

92 年 2 月 5 日

啟程搭乘日亞航班機 EG-278 由中正機場➔東京成田機場

92 年 2 月 6 日～92 年 3 月 27 日

開始進行時間協調模式研究

92 年 3 月 28 日

東京成田機場搭乘日亞航 EG-279➔中正機場返國

參、CRL 時頻研究現況

日本通信總合研究所（CRL）成立於明治 29 年（1896 年），開始是從事無線電傳播研究，其後逐漸擴充研究範圍，現今擁有情報通信、無線通信、電磁波計測、基礎先端等四個主要研究領域（表一）。

Oct, 1896	Radio Telegraph Research Division was established as a part of Electrotechnical Laboratory, Ministry of Communications
Jan. 1915	Hiraiso Branch was opened
May. 1935	Type Approval System for Radio Equipment was started
Jan. 1940	Frequency Standard Radio Service (JJY) was started
Apr. 1942	Radio Physics Laboratory was opened
Jun. 1948	Radio Physics Laboratory was placed under the auspices of the Ministry of Education
Aug. 1952	Radio Research Laboratory was established
May. 1964	Kashima Antenna Facility was opened
Apr. 1988	Reorganization from Radio Research Laboratory to Communications Research Laboratory
May. 1989	Kansai Advanced Research Center(KARC) was opened Kanto Branch was formed by combining Kashima Space Research Center with Hiraiso Solar Terrestorial Research Center
Jan. 1994	Designated a Center of Excellence by the Science and Technology Agency of Japan
Nov. 1996	Introduction of the external review.
July. 1997	Yokosuka Radio Communications Research Center established.
May. 1998	"CRL Vision 21" was established for the 21 century.
July. 2000	Keihanna Info-Communication Research Center established.
Jan. 2001	Ministry of Posts and Telecommunications became Ministry of Public Management, Home Affairs, Posts and Telecommunications.
Apr. 2001	Communications Research Laboratory, Independent Administrative Institution established.

表一：CRL 沿革

CRL 時頻研究設於電磁波計測部門之下。電磁波計測部門共有

13 個研究領域，時頻研究方面有原子周波數標準、時間周波數計測及日本標準時三部份。原子周波數標準的研究範圍是實驗室型銫原子鐘（CRL-1）維持、噴泉式銫原子鐘及離子阱（ion trap）鐘和光頻標準研製，（圖 3-1, 2, 3, 4）。目前 CRL-1 每月運作 1~2 次，提供 BIPM 做 TAI 參考；噴泉式銫鐘已接近完成，目前正調整參數，以達最佳性能；光頻標準是購買德國 PTB 實驗室產品，目前也完成安裝。最新研究重點為離子阱鐘，研究以鈣離子為主，重點為激發雷射穩頻。

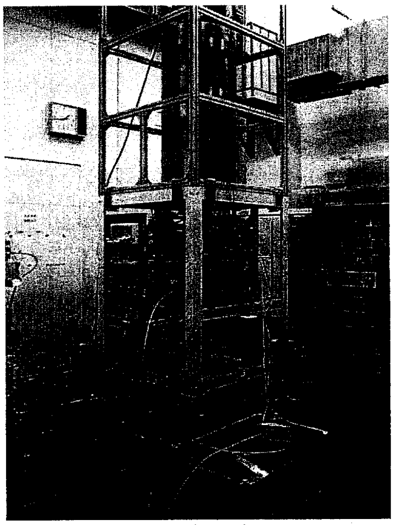

圖 3-1、噴泉式銫鐘

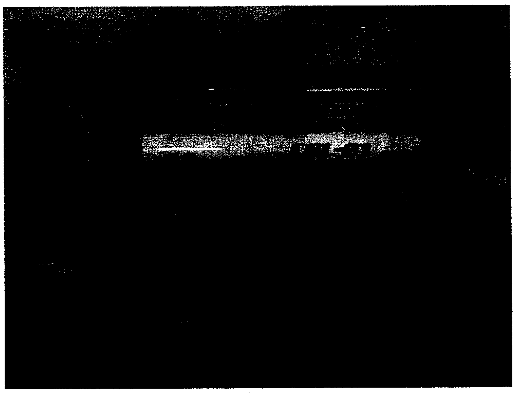

圖 3-2、日本 CRL-1

圖 3-3、ion trap clock

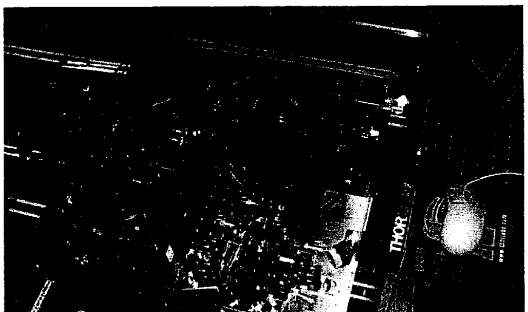

圖 3-4、光頻標準

日本標準時部門的主要工作是發佈日本標準時刻（LF 電台 JJY），及國際比對（TWSTFT, GPSCV, GPSCP, 圖 3-5），標準時

刻由時間週波數計測部門提供，目前研究重點是 CRL-Modem 資料分析。

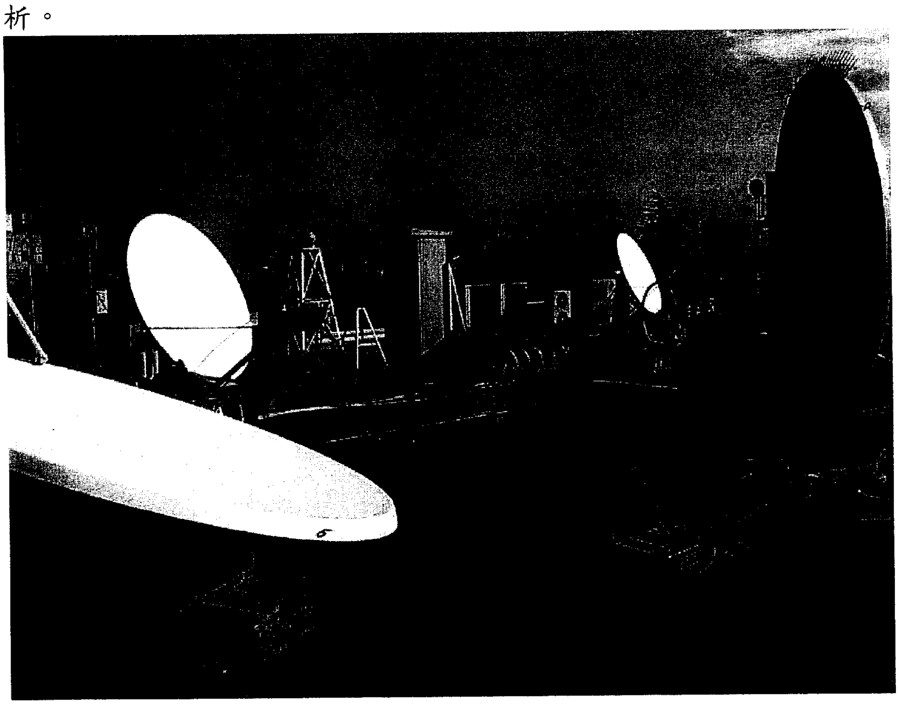

圖 3-5、TWSTFT 天線及 GPS 天線

時間周波數計測主要工作為 TWSTFT, GPSCP 傳時研究及 Time Scales、日本標準時（JST）維持（圖 3-6），主要研究成員及研究領域如下

Leader

Michito IMAE

TWSTFT, Time Scale algorithm, Pulsar timing

- **Senior Researcher**

Masanori AIDA

Yuko HANADO

Pulsar timing, Time scale algorithm, DMTD

Yasuhiro TAKAHASHI

GNSS

- **Researcher**

Tadahiro GOTOH

NTP(TSA), GPS carrier phase, TWSTFT

- **Research Fellow**

Sun Hongwei

Time transfer

目前研究重點為 DMTD(即時多通道頻率比較系統)及 Time scale，另外 CRL-modem 的設計及製作也由此部門負責。

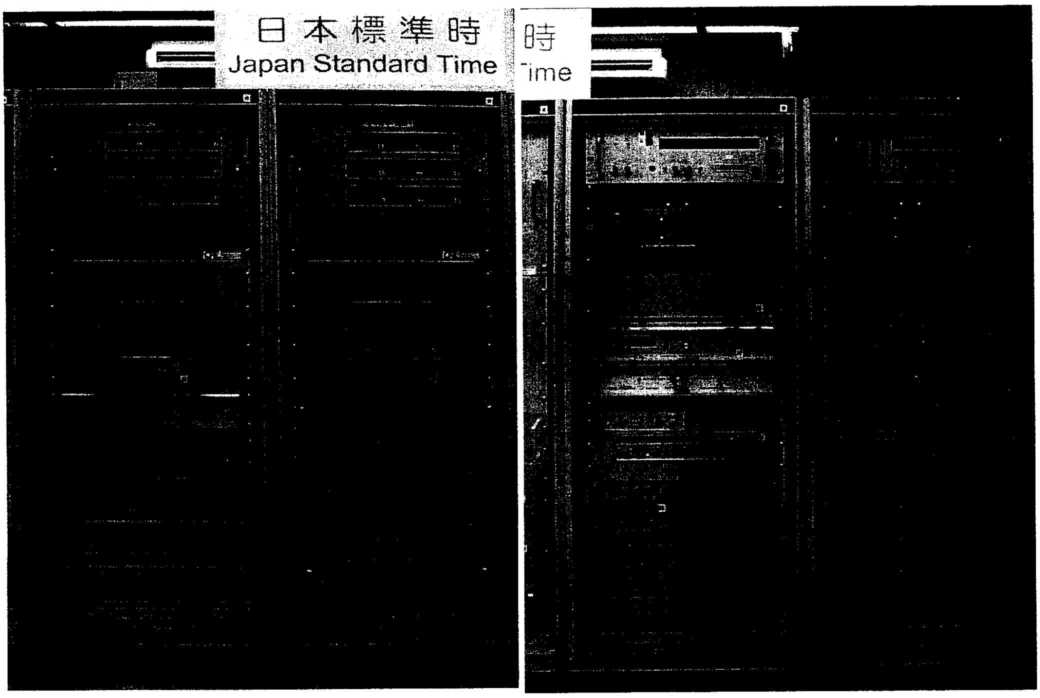

圖 3-6、CRL Time Scale system

此次研習目的即為 Time scale 研究，多數時間在時間周波數計測部門中與 Mr. Imae 及 Dr. Hanado 討論，也針對 CRL 自 1998 年起的資料作分析，分析結果附於本出國報告之第四部分。

肆、Paper Clock Model of CRL Cesium Clock Ensemble

Introduction

A paper clock using an ensemble of 6 cesium clocks was developed. The aim of this work was using a small ensemble of clocks to generate a time scale keeping the best long-term accuracy. The ensemble contains 6 clocks continually operated for more than 2 years. The weight of each clock was set to be proportional to inversely exponential with the index of each clock's standard deviation. The result paper clock can keep in ±20 ns accuracy during 840 days. A phase lock algorithm was also developed, added or reduced the frequency offset with a fixed amount if the phase of reference cesium clock was advanced or retardative with this paper clock. This algorithm can generate more than 2 physical time scales and keep their phase difference under several nano-seconds.

Clock data analyzing

We analyzed more than 8 clocks and found that the clock drift rates were not a constant. That means we cannot use a fixed long-term drift rate to describe the behavior of one clock (figure 4-1). We also found the phase difference between any 5071a clock and UTC is keep in ±15 ns during 30~60 days if drift removed (figure 4-2).

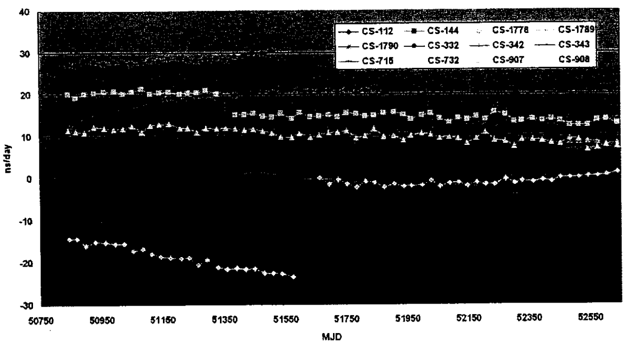

Figure 4-1. Monthly rate of TAI-CRL clocks, the indexes of clocks are the serial number

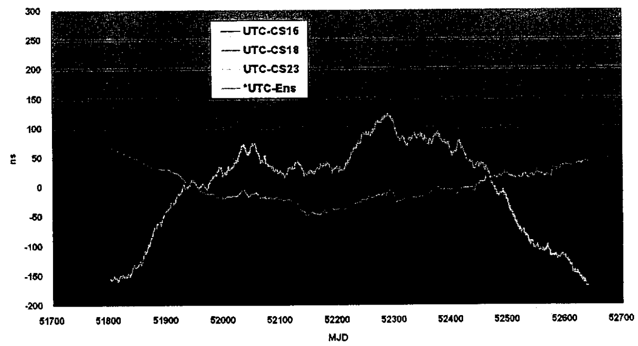

Figure 4-2. UTC-clocks for CS-16, 18, 23 and UTC – 6 clocks ensemble with equal weight

Algorithm and Weighting Process

Base on above analysis, we can assume the 30~60 days drift rate will no change too much during the first and the second 30~60 days, that is, we can use the drift rate 30~60 days ago to predict the drift rate of next 30~60 days. It's reasonable because of the minus value of the Allan deviation of 5071a is 3~5× 10^{-15} when τ = 30~60 days. Another assumption is that: after drift rate removed, the residual fluctuations can be reduced when we summate and average each phase difference of clocks. It's reasonable because of each clock is operated independently.

Our first test is to average the phase difference of UTC-Clocks, ensemble time scale would be

$$ens(t) = crl(t) + \frac{1}{6}\sum_{i=1}^{6} x_i(t) \quad \text{..........} (1)$$

Here we denote $x_i(t)$=*UTC(CRL)-clock$_i$*, the phase difference between UTC(CRL) and each clock, *ens(t)* is the UTC – paper clock at time t, and *crl(t)* =

UTC(t)-UTC(CRL)(t), is the phase difference between UTC and UTC(CRL) at time t.

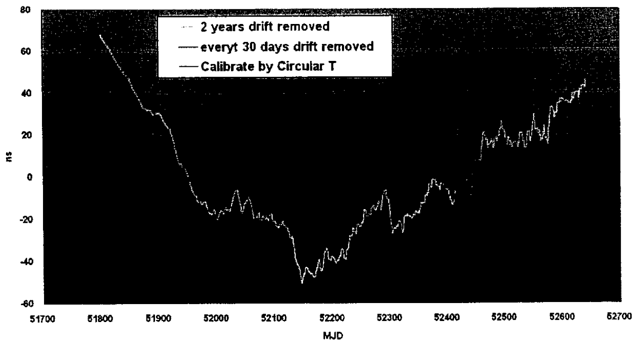

Figure 4-3. Phase difference after removed the ensemble drift rate

The yellow line of figure 4-3 showed that if we just average the phase difference of each clock, the best paper clock could only keep ±50 ns accuracy in 2 years. If we remove each clock's drift rate every 30~60 days then average, modified equation is:

$$ens(t) = crl(t) + \frac{1}{N}\sum_{i=1}^{N}[x_i(t) - (t - t_0)\cdot d_i(t_0 - (t - t_0), t_0)] \quad ....(2)$$

Here the $d_i(t_0-(t-t_0), t_0)$ is the drift rate of clock(i) from time $t_0-(t-t_0)$ to t_0.

The green line of Figure 4-3 is the result of equation (2), it's much better than the result of equation (1) but still have the long-term drift rate about 50ns/840 days. We modified the equation again into:

$$ens(t) = crl(t) + [UTC(t - t_0) - ens(t - t_0)] + \frac{1}{N}\sum_{i=1}^{N}[x_i(t) - (t - t_0)\cdot d_i(t_0 - (t - t_0), t_0)] \quad ......(3)$$

and the result of equation (3) can keep the accuracy in ±20 ns / 840 days.

All time scale algorithm should have weighting process, weighted each clock may filter out the unreasonable data and be helpful for short-term stability. Since this paper clock is designed to optimize the best accuracy, the weight of each clock was set to be proportional to inversely exponential with the index of each clock's standard deviation. That is the more accurate clock would weight more. We didn't set any upper limit of weight because of the inversely exponential has an upper limit itself..

$$ens(t) = crl(t) + [UTC(t - t_0) - ens(t - t_0)] + \frac{1}{N}\sum_{i=1}^{N}w_i(t)\cdot[x_i(t) - (t - t_0)\cdot d_i(t_0 - (t - t_0), t_0)] \quad ......(4)$$

where $w_i(t) = a \cdot e^{-b\sigma^2(t_0-(t-t_0),t_0)}$, $\sigma(t_0-(t-t_0),t_0)$ is the standard deviation of phase during the period t_0-(t-t_0) to t_0

For the result, we found the phase difference between paper and UTC would keep in about ±20 ns, we also test the period t-t_0, for CRL ensemble, t-t_0 = 60 day may get the best fit of Circular T (figure 4-4).

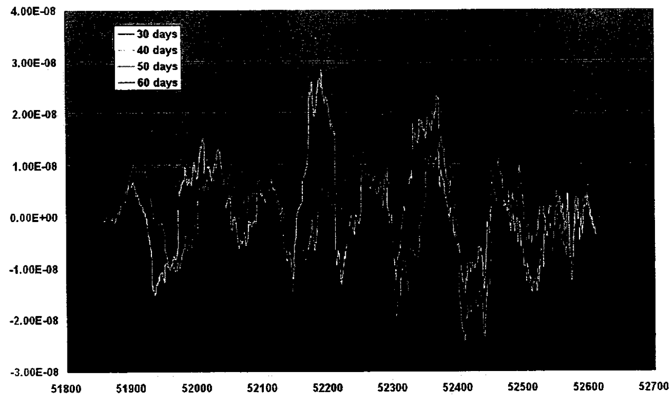

Figure 4-4. The phase difference between UTC and result of paper clock

Phase lock mechanism

A phase lock mechanism also used to sync this paper clock and a single cesium clock via a simulated micro phase stepper. Since the 5071a will not change it drift rate very rapidly in one day, we can lock the phase between 5071a and paper clock by changing the frequency offset of a virtual micro-phase stepper. We compared the phase difference between the paper clock and a cesium, add or reduce the frequency offset with a fixed amount if the phase of 5051a is advanced or retardative with paper clock, the rule is listed below:

if (phase difference > 3 ns) {$drift = $drift + .005 ns/day}
if (phase difference < -3 ns) {$drift = $drift - .005 ns/day}

……(5)

Figure 4-5 showed the phase lock result. Please notice there are only a few phase differences when we use different clock as the reference source (here we use CS24 and CS16).

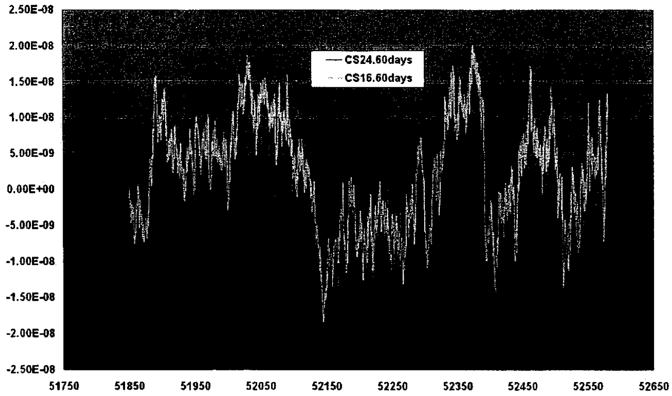

Figure 4-5. Phase lock mechanism result using different clocks

Conclusion and discussion

There are some advantages of this paper clock algorithm; the first one is: this paper clock uses the traditional measurement system (switcher and time interval counter) and simple data processing to generate an accurate time scale. The second advantage is the phase lock mechanism can lock the phase of the result paper clock without any prediction algorithm. The third one is that different clocks can be synchronized in nanosecond by single time scale, which means we can generate more than one backup time scale system and don't need to take care of the phase difference between primary and backup system.

I am sorry that I did not discuss the stability of this paper clock because of there is no long-term clock data of hydrogen maser. Because of I can only stay at CRL less than 2 months, I didn't analyze the influence of the clocks adopt and withdrew, coefficients of equation (4), and the advantage of the exponential weighting process. I hope I can finish them after I go back Taiwan.

Acknowledgement

I greatly appreciate the helps from Mr. Imae, Dr. Hanodo, Dr. Hosokawa and the other colleagues; they gave me many supports for this report. I also have to thank Miss Nenu and Mr. Morisaki; because of them, I could enjoy my daily life in Tokyo.

伍、心得及建議

CRL 位於東京郊區，風景優美。原為政府單位，近年改制為獨立法人，但原有業務及研究方向不變，而事務處理更添彈性。對專業人員尊重向來是日本傳統，一般研究人員也相當認真，工作至晚間九、十點的大有人在。在此間研究氣氛相當不錯。以下是一些心得：

1. 日本自許為亞洲科研龍頭，對基礎科學研究相當重視，CRL 的經費一向充裕，日本政府相信「一個好的研究勝過一百個普通的研究」，研究以朝向世界尖端為導向，儀器採購相當信任研究人員，授權計畫主持人自行處理數千萬日幣以下之儀器採購，可爭取研究時效，並減輕研究人員負擔。
2. CRL 人力優秀且認真，研究人員通常工作至晚上八點，行政人員對研究人員也相當尊重，在背後全力支持。CRL 研究人力與行政人力（時頻計畫內）比約為 3:1，研究人員不須負擔研究以外之雜務，但研究人力似有老化現象，對於新工具如以電腦做程式自動化控制及資料分析的能力有所不足。
3. CRL 時頻部門之研究重點為標準維持、基礎研究、及國際比對，目標明確，經費充裕。在基礎研究方面已設置光頻標準，建立亞洲唯一的實驗室級銫束鐘，將要完成亞洲第一部噴泉式銫原子鐘，接下來的主要目標是離子阱鐘，相當具有企圖心。TL 相較之下無法與 CRL 在基礎研究方面競爭，但在國際比對級標準維持上（時間評量模式）可以努力。
4. CRL 與 TL 同為亞洲國家實驗室。一般國際時頻會議多以法、德、義、英、美等歐盟及北美國家主導，亞洲之日本、韓國、台灣、澳洲等國相對邊陲，即使如日、澳之技術能力相當不錯之實驗室亦然。TL 可與 CRL, NML 做較緊密之合作先在亞洲建立經常性之合作關係，再尋求機會打入國際。CRL 已完成一 TWSTFT Modem，可同時進行八個實驗室之國際比對，預計將建立包括日、台、中、韓、美、澳、星等國家的 TWSTFT Link，在其他實驗室相對缺乏資料分析人力的情況下，TL 可以在此發揮專長，建立對實驗室間

的影響力。

非常感謝公司各級長官的鼓勵及協助，使得本次實習能順利圓滿達成，此後職必將更努力於研發工作，貢獻研習成果。