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Results of Using the Global Positioning System to Maintain the Time and Frequency Sychronization in the Deep Space Network

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There are two hydrogen maser clocks located at each signal processing center (SPC) in the DSN. Close coordination of the time and frequency of the SPC clocks is needed to navigate spacecraft to the outer planets. A recent example was the Voyager spacecraft's encounter with the planet Uranus in January 1986. The clocks were adjusted with the goal of minimizing the time and frequency offsets between the SPCs at encounter. This article describes how the time and frequency at each SPC is estimated using data acquired from Global Positioning System Timing Receivers operating on the NBS–BIH (National Bureau of Standards–Bureau International de l'Heure) tracking schedule. These data are combined with other available timing receiver data to calculate the time offset estimates. The adjustment of the clocks is described. It was determined that the long range hydrogen maser drift is quite predictable and adjustable within limits. This enables one to minimize time and frequency differences between the three SPCs for many months by matching the drift rates of the three standards. The article will describe the data acquisition and processing techniques using a Kalman filter to make estimates of time and frequency offsets between the clocks at the SPCs and UTC (NBS) (Coordinated Universal Time realized at NBS).

I. Introduction

Each SPC (signal processing center) at the Deep Space Communications Complex (three, one at each complex) contains a frequency and timing system which provides the required frequencies and timing pulses for all of the subsystems in that SPC. There are two hydrogen masers located at each SPC; the first acts as the master clock and provides the primary frequency source, and the second acts as a backup. The backup hydrogen maser is kept syntonized (that is, syn-chronized in frequency) to the primary, particularly during critical missions, so that a switch from primary to secondary would have a minimum effect on DSN users.

A requirement exists that timing pulses and frequencies distributed throughout the SPC be coherent. This requirement precludes the use of microsteppers to keep the SPCs clocks synchronized to some uniform time scale. Therefore, the master clock exhibits the characteristic hydrogen maser drift in frequency.

The process of tracking spacecraft involves all three SPCs working in concert to continuously track spacecraft as the earth turns. At Voyager's Uranus encounter the round trip signal transmission time was very long (about five hours). A signal, sent from one SPC to the spacecraft, then transponded and sent back to earth, is received by a second SPC. The Neptune encounter, which is to occur in 1989, will require the transponded signal to be received by the second and third SPC. This procedure requires accurate synchronization and syntonization between SPCs to measure round trip signal transmission time and signal doppler shifts when communicating with the spacecraft. Other requirements such as Very Long Baseline Interferometry (VLBI) and radio science also require accurate synchronization and syntonization among the SPC clocks.

Presently, the DSN Frequency and Timing system (DFT) requirements are to maintain synchronization between SPCs to within ±20 microseconds with a knowledge of ±10 microseconds. Syntonization between SPCs is to be maintained to within 1×10^{-12} df/f with knowledge of $\pm 3 \times 10^{-13}$ df/f. It is possible that navigation at the Voyager Neptune encounter will require knowledge of frequency to less than 1×10^{-13} df/f.

It needs to be emphasized that the DSN is a user of time scales and not a producer. The DSN needs to adjust its clocks from time to time to keep them syntonized and synchronized with each other. It is convenient to use the UTC (NBS) time scale as a reference. First, it is a uniform and continuous time scale. Second, the proximity of the NBS Time and Frequency division to JPL (approx. 1000 km) has historically made NBS the most accessible time scale to the SPC-10 due to the short airplane flight to carry a clock. The use of the Global Positioning System (GPS) time transfer method has made the UTC (NBS) accessible to all SPCs, so we have created an ensemble of clocks using UTC (NBS) as the reference. JPL has a contract with NBS which provides JPL with access to UTC (NBS) and also to the cesium clock associated with WWVH (the NBS time broadcast radio station) in Hawaii, using the data from their GPS timing receiver.

II. The GPS Time and Frequency Coordination System

JPL has installed GPS timing receivers at the three SPCs [1]. These receivers get a timing pulse from the master clock at each SPC which is the "on line" hydrogen maser. The data from these receivers and other data are combined using a Kalman filter to produce estimates of time and frequency offsets of the SPCs with respect to UTC (NBS). JPL uses the tracking schedule published by NBS-BIH. This schedule allows mutual

views with receivers whose tracking data are posted on the GE MK III RC28 Catalog, which is administrated in the United States by the United States Naval Observatory[1]. Figure 1 is a schematic diagram showing the clocks used and the possible mutual views which are available.

The data are gathered by telephone once per week from the receivers in the DSN from the database at NBS and from the GE MK III database using an IBM XT personal computer. This is certainly a change from just a few years ago when we depended on traveling clocks and LORAN. Now we are able to observe the clocks, control them, and provide a guaranteed high accuracy synchronization and syntonization for the users of the DSN.

III. Operation of the Clocks

During the initial installation of a hydrogen maser frequency standard at an SPC, a calibration sequence is performed that includes the following steps:

(1) Verify environmental stability with unit in final position.

(2) Set final operating parameters.

(3) Degauss magnetic shields.

(4) Set internal bias field to required value.

(5) Spin-exchange tune the hydrogen maser cavity.

(6) Calibrate hydrogen maser rate to NBS (synthesizer calibration).

(7) Calibrate rate of backup standards.

(8) Set master and backup clocks.

Figure 2(a) is a quadratic least square fit to the time offsets of the SPCs clocks with respect to UTC (NBS), and Fig. 2(b) is a least square linear fit of the frequency of the clocks with respect to UTC (NBS). The maser frequency drift of approximately 4.5×10^{-15} df/f per day is well behaved and could be matched even closer between the three hydrogen maser clocks. Knowledge of this drift allows us to maximize the time interval between rate adjustments. After the masers are calibrated the cavity is deliberately mistuned so that the average frequency offset with respect to NBS is near zero between rate changes. The average time difference between the three SPCs clocks and NBS is minimized by choosing the appropriate initial time offset. By spin-exchange tuning the hydrogen

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[1] Available from the Catalog Administrator, USNO Time Service Division, Washinton, D.C. 20390, USA.

maser after one to two years and recalibrating the synthesizer, we will be able to determine the long term drift that is due to mechanisms other than the cavity.

The backup standards are monitored on site with respect to the prime standard so that traceability to NBS is maintained. The rate of these units is manually corrected when necessary so that upon switching from prime to backup standard, the frequency shift is minimal. Figure 2(b) shows that this was not accomplished very well. From about day-of-year (DOY) 100 on, backup standards were shifted in and out for various reasons at SPC-60 and SPC-40. The GPS system gives near real time visibility of clock performance at the three SPCs and enables operational control personnel to evaluate and improve overall system performance.

IV. Example of the Voyager Encounter

As the Voyager spacecraft approaches the planet, calculations are made to correct the estimates of the spacecraft's location. The accurate measurements required for these calculations cannot be made until about 10 to 20 days before encounter. With these measurements, adjustments can be made to produce the desired trajectory by the planet. By having the three SPCs' clocks synchronized and syntonized through the encounter period, accurate measurements of the spacecraft's location can be made.

To satisfy encounter requirements it was decided to adjust the rate and offsets at each SPC so that at encounter the frequency and time difference between each station and NBS would be near zero. This was done about two months prior to encounter.

Daily GPS common view time observations were made to monitor the clock performance at each station. Figure 3 shows the time offsets with respect to NBS. The worst case station-to-station and station-to-NBS offset was less than 500 nanoseconds during the encounter period. Note the several prominent time steps at SPC-60 on days 355, 20, 77, and 87. The master clock at each SPC is driven by a 5 MHz "Flywheel" oscillator which is phase locked to the primary standard 5 MHz output. The phases of the backup standards are not maintained at zero with respect to the prime so that upon switching to the backup standard, a time change of up to ±100 nanoseconds may result. This happened on the above mentioned days at SPC-40 when, for various tests and experiments, frequency standards were shifted. On about day 100, SPC-60 was directed to shift to a backup standard without first matching the frequency. A frequency change of about 6×10^{-13} df/f led to the rapid divergence of time from day 100 on.

V. Time and Frequency Offsets Using the Kalman Filter

The difference of the data from the receiver pairs is taken to produce mutual view values for clock pair offsets, one value each day for each spacecraft that is used for a mutual view for a given receiver pair. Using space vehicle i,

$$(c_b - c_a + n_{svi})_i = (gps - c_a + n)_i - (gps - c_b + n)_i$$

where n is the noise, n_{svi} is the total common view noise, c_a, c_b are the ground clocks, and gps is the space vehicle clock.

A mean C_{ba}, of the set of mutual view differences is then calculated along with the mean time T.

$$C_{ba} = \frac{1}{m} \sum_i (c_b - c_a + n_{svi})_i$$

$$T = \frac{1}{m} \sum_i t_i$$

where m is the number of daily observations, and t_i is the time of the observation using space vehicle i.

These mean values are used as inputs to the Kalman filter, which has the effect of giving each space vehicle's common view measurement equal weight. This tends to ignore the bias problem which was described by M. A. Weiss [2]. Also, if a measurement is not made for some spacecraft on a particular day, then the biases of the individual spacecraft measurement tend to offset the estimate for that day, an undesirable side effect.

The Kalman filter is a classical design, written in BASIC, and run on an IBM PC-AT computer. The output of the filter is the time, frequency and frequency drift of each clock with respect to UTC (NBS). An estimate of the time, frequency, and frequency drift for any point between endpoints of the data set can be made by smoothing to that point. The procedure is to smooth to 00 hours UTC each day and use that value of the state vector as the estimate of the time and frequency offset of the clock with respect to UTC (NBS). The data are handled in 30 day batches, with each new batch started off with the state vector and the covariance matrix from the previous batch.

Figure 3 shows the detail of the time offset of each of the clocks through the encounter to about DOY 130. The data were generated by the Kalman filter and each day is a point smoothed to zero hours UTC. Each of the clocks is referenced to UTC (NBS). However, because the estimate is for the

same time, the relation between the clocks at any two SPCs can be obtained by subtracting the value of one SPC from that of the second.

Figures 4, 5, and 6 show the estimated value of frequency of the SPCs clocks before, during, and after encounter. On top of these smoothed values are estimates of frequency obtained from the mutual view data by making a linear least squares estimate of the data over about ten day groups of data. These estimates were done manually with judicious choice of data.

Notice the boxed-in detail on Fig. 4, the frequency offset between SPC-10 and UTC (NBS). This indicates that there was almost 1×10^{-13} df/f change in frequency over a period of 10 to 15 days. Unexplained frequency changes of this magnitude have been noticed in hydrogen masers during tests at JPL. However, the mysterious thing is that the other clocks, SPC-40 and SPC-60, showed similar frequency changes at the same time. The Kalman smoother output agrees with the hand calculations of frequency using the mutual view data which indicates the filter is not causing the appearance of similar frequency changes in the several clocks.

One would conclude that the NBS time scale wiggled. Indeed, the wiggle seems to have been at NBS, but not the time scale. At that time JPL was not accessing the data from the time scale, but from clock nine at NBS. A check with NBS confirmed that clock nine experienced a similar frequency excursion at that time. Two conclusions can be drawn from this: the Kalman smoother produces good estimates of the clock performance and the need to make sure the data is from the UTC (NBS) time scale. This procedure was changed late in 1986; JPL presently accesses the UTC (NBS) time scale.

Figure 7 shows the values of Allan variance of frequency estimates of the three SPCs' clocks produced by the Kalman smoother. Nominal expected drift of the hydrogen masers which are deployed is a slope of 4.5×10^{-15} df/f per day. The SPC-10 line follows the performance of the field hydrogen masers fairly well. At four days or less, the SPC-60 and SPC-60 Allan variance is considerably worse than hydrogen maser performance. The SPC-60 Allan variance settled down to hydrogen maser performance at about eight days. The SPC-40 estimates never seem to settle down.

VI. Conclusions

Daily estimates of frequency with errors of less than 1×10^{-13} df/f are available on a routine basis. It appears that this can be reduced to several parts in 10^{-14} df/f in the next few months. Now it has been shown that DSN can be operated continuously with clocks which are syntonized to within 3×10^{-13} df/f and synchronized to within a microsecond. By matching the drift rates of the clocks it might be possible to routinely match the synchronization and syntonization even more closely.

This year's experience has shown that the development of better methods is needed to assure the secondary hydrogen maser is kept closely syntonized with the primary maser.

References

[1] P. A. Clements, S. E. Borutzki, and A. Kirk, "Maintenance of Time and Frequency in the DSN Using the Global Positioning System" *TDA Progress Report 42-81*, vol Jan.-Mar., 1985, pp. 94-108, Jet Propulsion Laboratory, Pasadena, CA, May 15, 1985.

[2] M.A. Weiss, *Proc. 17th Ann. Precise Time And Time Interval Applications and Planning Meeting*, pp. 261-273, Dec. 3-5, 1985.
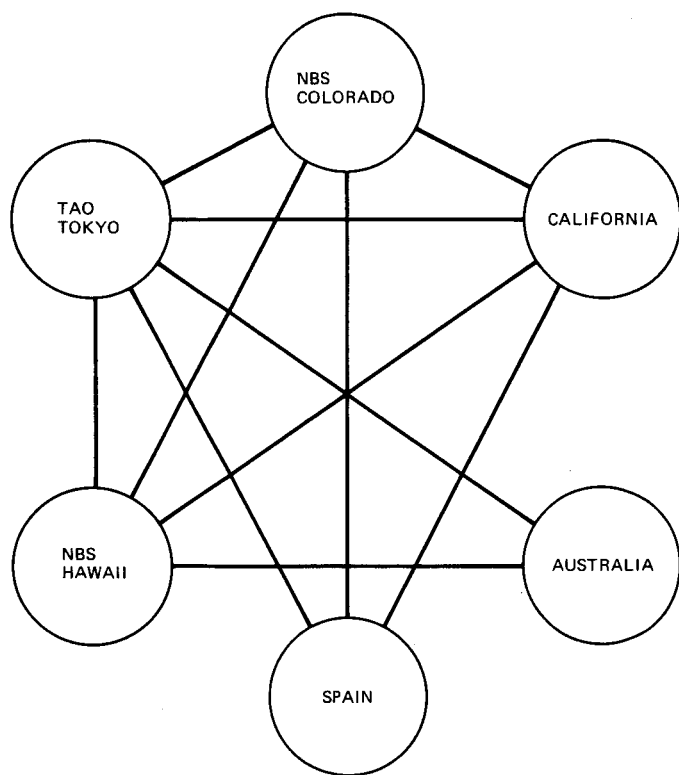
Fig. 1. Possible GPS mutual views available to measure
the DSN clocks
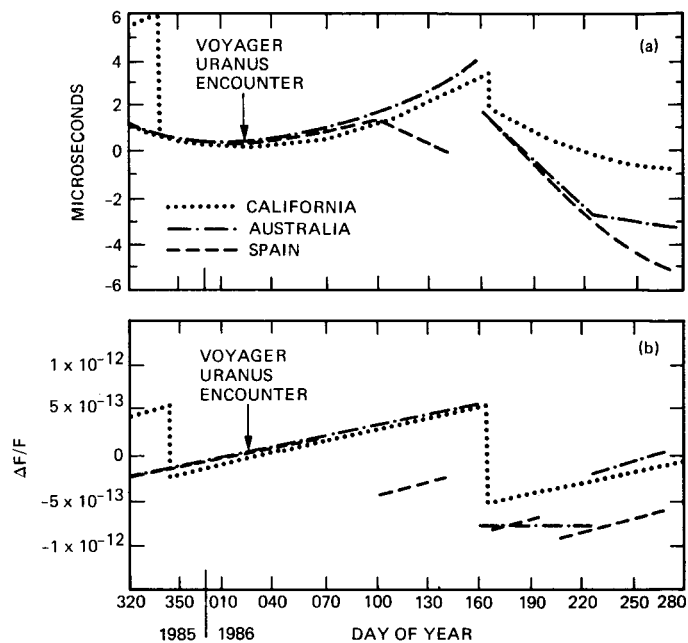
Fig. 2. Time and frequency offset with respect to UTC (NBS)
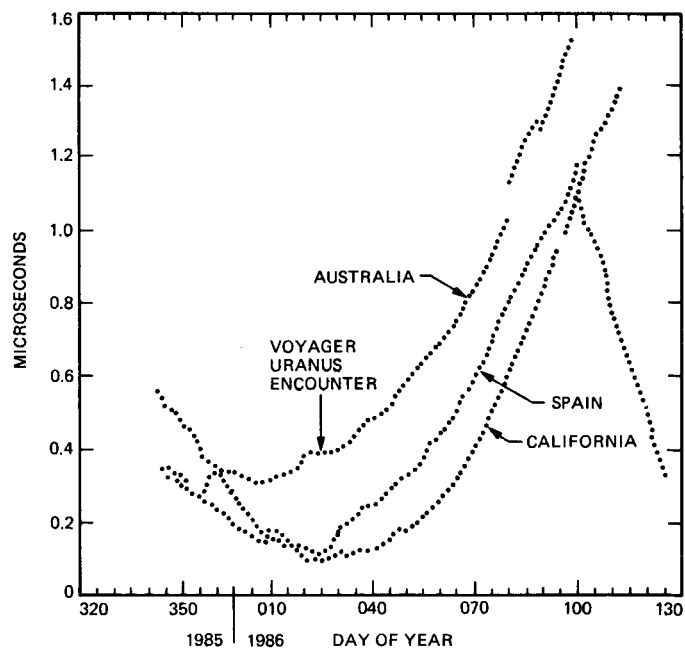
Fig. 3. Time offset with respect to UTC (NBS) (Output of
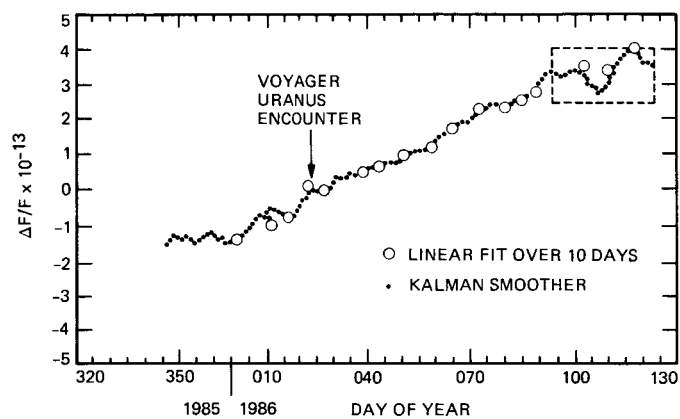Kalman Smoother)

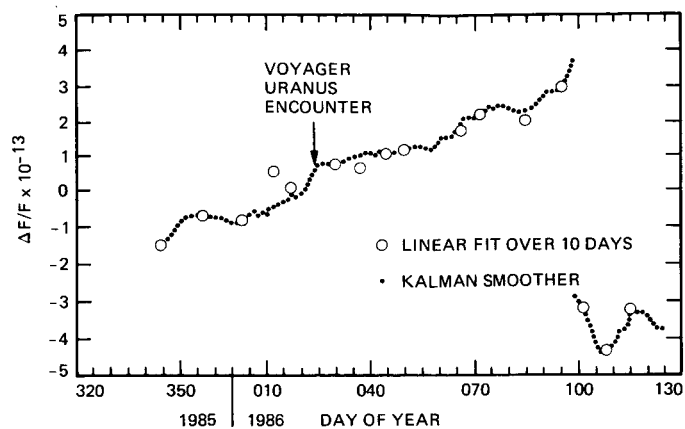Fig. 4. Frequency offset, California–UTC (NBS)

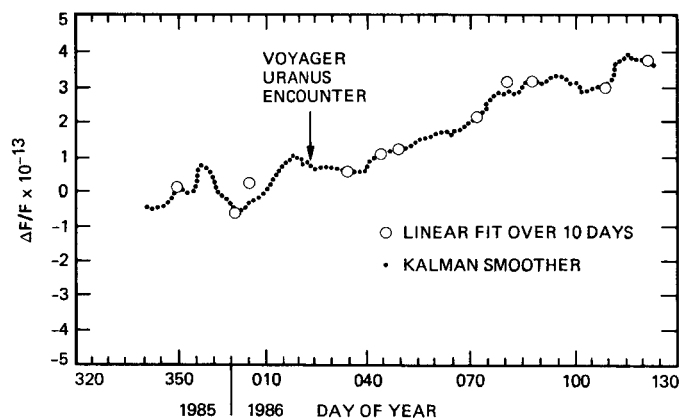Fig. 6. Frequency offset, Spain–UTC (NBS)
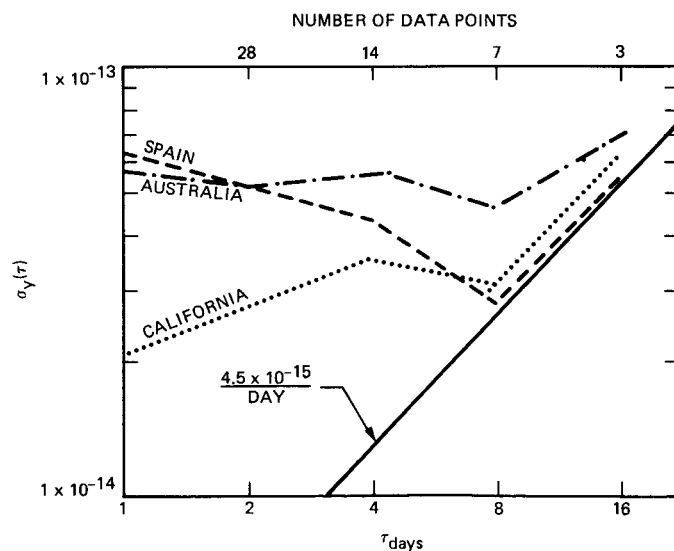

Fig. 5. Frequency offset, Australia–UTC (NBS)

Fig. 7. Allan variance with respect to UTC (NBS)