DSN Frequency and Timing System Mark III-81

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The DSN Frequency and Timing System configuration and functions are described. The text is historical in nature, ending with the current system design and performance.

I. Introduction

Frequency and timing requirements in the DSN have, in the past 20 years, approached state-of-the-art technology. In the frequency domain, we have evolved from high-quality crystal oscillators, having accuracies of parts in 10^6, to today's technology of hydrogen masers having stabilities to parts in 10^{15}. Intermediate technology provided rubidium vapor standards and cesium beam standards which are still very much a part of the DSN.

The time domain capabilities have followed the advances of frequency standards along the evolutionary path. Timing accuracies have advanced from milliseconds to nanoseconds, in support of spacecraft navigation requirements. The Frequency and Timing Subsystems are now the hub of DSN requirements, providing all subsystems with fast, accurate and reliable frequency and timing references.

The following is a discussion of the current timing system in the DSN, with some background on how it evolved to be the most accurate and reliable global system in the world.

II. Background

As early as 1965, it became evident that deep space probes would require very accurate time and frequency synchronization between Deep Space Stations in order to achieve the required navigational performance. Until this time, time ticks broadcast by the National Bureau of Standards (NBS) radio stations WWV and WWVH were adequate. Time could be synchronized to within one millisecond of NBS time in the United States and about five milliseconds at the overseas Deep Space Stations. Several very low frequency (VLF) stations began broadcasting about the same period, making it possible to establish and track frequency offsets for the then used rubidium vapor standards. This method allowed detection of a few parts in 10^{10} and later parts in 10^{11} frequency offset or change. The result of this double-spoked process allowed time synchronization to within one millisecond and determined offset in time from that initial point forward. A few microseconds per day change, plus or minus, was not abnormal.

The digital timing equipment consisted of very early transistorized decade dividers, which provided the various pulse rates for the user subsystems. A commercial time code generator was used for serial and binary-coded decimal codes for recoding purposes as well as displays. Commercially available frequency distribution amplifiers were used to distribute 100 kHz, 1 MHz and 5 MHz to users. Phase coherency and pulse to phase relationships were poor by today's standards, but very adequate for that period in the Deep Space Network.

Redundancy in this equipment was not available. However, a battery backup mode was provided to power oscillators and divider circuits in case of firm power outages. Frequency counters, oscilloscopes, and amplifiers were excluded from power backup due to high alternating current requirements.

In the late 1960's, a new digital Frequency & Timing Subsystem was designed with a special highly reliable collection of circuit boards and components. The equipment, known as FTS-II, is the equipment now used in the Deep Space Stations. It was installed in all Deep Space Stations in 1969-1971. The subsystem design featured a triple redundant clock with majority voting, allowing measurement of the output of all three clocks to 1 microsecond. If the outputs did not agree to within 1 microsecond, the erroneous clock was flagged as bad, still leaving two clocks available. The bad clock was negated from providing user outputs if selected.

Another feature provided by the present system is an uninterruptable power system, which provides alternating current to the subsystem in case of firm power outages. This reduced hardware and special circuit design for selected modules that had to be powered to preserve frequency stability and time synchronization. Figure 1 depicts the current Frequency and Timing Subsystems at the Deep Space Stations.

In the early 1970's a system was introduced into the Deep Space Network which successfully and accurately accomplished network time synchronization. Commonly known as "Moon Bounce," the system consisted of an X-band transmitter at Goldstone (DSS 13), the moon as a reflector body, and a receiver at the Deep Space Stations. A psuedorandom code was transmitted to the moon and reflected to the stations with a mutual view. The receiving station had a receiver with a similar code generator, and a correlator for aligning the codes. This technique provided time synchronization and transfer in the 10-microsecond range throughout the network. The system provided time synchronization for the network for nearly a decade before being abandoned in 1980 for more sophisticated reliable methods, such as very long baseline interferometry.

By the mid-1970's, hydrogen masers had come to the forefront as the frequency reference of the future. Units were built and purchased to supply 64-meter stations with oscillator stabilities to 1 part in 10^{15}. Reliability of the units was uncertain, although while operating, the performance was superb. Further design analysis and modification provided units with much higher reliability, and today's units now function very well up to three years before major maintenance is required.

With this background and history, we have set the stage for a truly accurate and reliable network-wide system to meet the sophisticated and rigorous requirements of deep space flight projects. We have reliable and redundant timing subsystems, very accurate and reliable frequency standards driving the clocks and the technology to provide microsecond timing accuracies with frequency accuracies to parts in 10^{14}.

Through the span of 20 years the DSN has progressed in the frequency and timing disciplines 5 orders of magnitude in an operational environment. That is progress!

III. DSN Frequency and Timing System Description – Mark III-81

The "System" consists of several major components as depicted in the block diagram (Fig. 2). The National Timing Standard block (upper center of Fig. 2) is the reference for the DSN. Through agreements and cooperation with several international agencies, time and frequency are provided to the three Deep Space Communications Complexes.

The United States Naval Observatory (USNO) and the National Bureau of Standards (NBS) are the references for the Deep Space Network (DSN). Although they are independent agencies, they coöperate totally in establishing this country's Time and Frequency Standards. They are aware of their differences and publish notes to any user identifying the differences by the day. This portion of the block diagram is not a controlled part of the Frequency and Timing System, only a reference, and is discussed to describe continuity of the DSN as the reference.

A close examination of the National Timing Standard (Fig. 3) shows the relationship between all the complexes and the signal source (or traceability) of time and frequency. As can be seen, a traveling clock is the correspondent between the USNO and NBS, and is the key to maintaining their relationship. Comparisons are made both in frequency and time at regular intervals.

To service Australia, portable clock trips are made to the Australian National Mapping Services at least twice per year by the USNO. The Mapping Service then serves as the Australian distributor of time to users. Occasionally, clock trips are made to the Canberra Complex for comparison with clock performance measured by Australian TV synchronization pulse techniques.

The Spanish Complex is serviced by the Long Range Navigation system (LORAN) network, which provides timing signals via radio waves. On occasions the USNO travels to Europe, and when convenient pays a visit to the Madrid Complex for comparison. With the LORAN network and occasional clock trips, the Spanish Complex is synchronized to USNO, and therefore synchronized to a known offset to the Australian Complex (Fig. 4).

The Goldstone Complex is serviced similarly to the other complexes by traveling clock, but at more frequent intervals. The Goldstone Reference Standards Laboratory (RSL) maintains an ensemble of cesium oscillator clocks which, as discussed later, are the Network Master Clocks. Historically, the master clock has maintained time to within 50 nanoseconds of the NBS/USNO, and is often referred to as the best clock ensemble on the U.S. West Coast.

As described, the three complexes are serviced by the NBS/USNO entity, tying the complexes to one reference. The subsystems at the complexes assume the role of local standards for the generation and distribution of time and frequency to the users. A typical subsystem is described below (Refer to Fig. 5).

In Fig. 5, which depicts the Australian Complex, there are three major functions: The Frequency and Timing Subsystem and its users in the 64-m and 34-m configuration; the stand alone 34-m Frequency & Timing Subsystem; and the Communication Facility.

The 64-m/34-m conjoint station is considered the Complex Master Clock. The clock consists of one hydrogen maser as the primary oscillator, two cesium oscillators as backup, a coherent frequency distribution assembly and a triple redundant clock. Typically, the hydrogen maser maintains its stability to several parts in 10^{14} and is specified to support 3×10^{13} for 10 days. Translated into time, this relates to approximately 26 nanoseconds, which is considered very stable. The cesium oscillators are specified about 1 order of magnitude less than the masers.

Referring again to Fig. 5, frequencies are generated and distributed to the various users. Sinusoidal waves of 0.1 MHz to 100 MHz are derived, synthesized and distributed by the coherent reference generator. Constant amplitude and phase relationships are maintained. A 1-p/s pulse train is also supplied to the outlying stations via a microwave link. The delay time between the two clocks is measured to the submicrosecond level so that the clock at the outlying station can be accurately synchronized.

Again, note that although the complex is remote from other complexes, constant vigilance of the NBS/USNO and complex frequency and timing relationship is maintained. Television time synchronization is observed, calculated and used at the complex as well as the remote station. Weekly reports are made to JPL by teletype message, identifying relationships of all the oscillators and clocks. It is not uncommon for a complex to know its time relationship to NBS/USNO to within ±5 microseconds at any given time.

Figure 6 describes the Goldstone Complex, which can be seen as somewhat more diversified. The major difference is, of course, the Reference Standards Laboratory, which is the home of the DSN Master Clock. The Deep Space Network Master Clock is an ensemble of several cesium oscillators and a hydrogen maser. Although the hydrogen maser is currently remote from the bank of cesiums, its frequency is used, along with the cesium, to establish the Deep Space Network Standard. Similarly, Goldstone distributes time synchronization to the outlying Deep Space Stations by microwave and, again, the Deep Space Stations are typically within ±3 microseconds of the NBS/USNO reference. Each Deep Space Station generates and distributes frequencies and time to its particular users.

As a system check, independent from the NBS/USNO, a very long baseline interferometer technique has been utilized. By this technique, all three 64-m Deep Space Stations are scheduled to observe the same radio star source within 24 hours twice per week. The data are sent to JPL for reduction and establishment of the Deep Space Station offset to the Deep Space Network Master clock. This method is a near-real-time technique, and with historical data can very precisely determine each complex's frequency and time offset. It can be seen that with hydrogen-maser-driven clocks, continuous checks by TV and LORAN, and the VLBI, the Deep Space Network very precisely keeps track of itself.

Figure 2 describes the total global systems, pointing out time and frequency distribution, both on a global and local level. One can readily see the NBS/USNO relationship, the reporting process and how the complexes are tied together.

IV. Frequency and Timing Subsystem Description

The Frequency and Timing Subsystem generates and distributes sinusoidal reference frequencies, timing pulses, and epoch time codes for other subsystems within each Deep Space Communications Complex (DSCC). The primary frequency standard and epoch time are maintained within prescribed tolerance throughout the entire DSN and relative to the selected National Standards Agency.

The foundation of the DSCC Frequency and Timing Subsystems is the oscillator selected for use. The 64-m network (Deep Space Stations 14, 43, and 63) is equipped with hydrogen masers. The 64-m network requires hydrogen masers because of intricate navigation of the deep space probes. These are the stations that are ultimately used to gather VLBI data and radio metric data for orbit determination and navigation. The smaller aperture Deep Space Stations are equipped with cesium oscillators, which are nearly as stable as the hydrogen masers.

The masers are kept in an environmentally controlled area, away from vibration and fluctuating magnetic fields. The area is designed for temperatures of 21 to 26°C, at 50% humidity. At these specifications, the maser stability is specified as follows, in terms of Allan Variance (see Appendix A):

1×10^{-12} for 1 second	1×10^{-14} for 12 hours
1×10^{-14} for 10^4 seconds	1×10^{-13} for 10 days

As seen in Fig. 7, the outputs of the three oscillators are connected to a switching network that selects the frequency standard desired. Three inputs are necessary, i.e., 0.1, 1 and 5 MHz, which are input to the coherent reference generator. The switch is semiautomatic in that it will switch to another oscillator if the primary standard fails. This switching takes place in less than 1 microsecond.

Due to the complexity of the Deep Space Stations supported by the Frequency and Timing Subsystem, the coherent reference generator must synthesize and distribute several frequencies. The coherent reference generator provides sinusoidal signals at frequencies of 0.1, 1, 5, 10, 10.1, 45, 50, and 55 MHz at 11.5 ±1.5 dBm. All frequencies maintain a constant phase relationship.

The triple redundant clock receives 1 MHz from the coherent reference generator for pulse shaping, pulse train generators and time code generators. The three clocks are identical and act upon the 1-MHz reference in the same manner, providing pulses and time codes. Controls are available on the front panel of the equipment to allow adjustment of the three clocks. The majority vote circuitry determines, at the microsecond level, if the three clocks are in synchronization, and permits timing signals to be distributed if at least two clocks are synchronized to within 1 microsecond.

The rationale for triple redundant majority voted clocks is to ensure that at least two clocks are operating correctly to obtain outputs. If all three clocks are not synchronized, no output is available. The assumption here is that it is better to have no time output than to have an output that may be erroneous. The majority vote circuitry cannot switch clock outputs, only detect if an output is incorrect. A manual switch is provided for clock selection.

Pulse trains are generated in the clocks in decade steps from 1 million pulses per second to 1 pulse per minute. Except for selected pulses that are treated independently, all pulse trains have 10 percent duty cycles. Rise and fall times are typically 250 nanoseconds from the 10 to 90 percent amplitude levels. Parallel and serial time codes are generated and distributed in 30-bit parallel binary-coded decimal, 30-bit parallel binary and 36-bit serial (NASA time code). Provision is also made for time displays throughout the control rooms, displaying day of year, hour, minutes and seconds of day adjusted to Greenwich Mean Time (GMT). (All clocks at all complexes are adjusted to GMT.)

An auxiliary reference divider is utilized to generate an independent 1 pulse per second derived from the secondary oscillator. Provided one knows the offset of the primary oscillator, by comparing the 1-pulse-per-second signals from the clocks and the auxiliary divider, an offset of the secondary or backup oscillator can be determined. In fact, this process is routinely recorded and long-term frequency offsets are determined for any and all backup oscillators at all Deep Space Stations.

To determine the offset of the primary oscillator, a portable clock measurement is made. Measurements are made on a weekly basis by determining the time difference between portable clock and the station clock on a nanosecond resolution counter (Goldstone only). As described earlier, the portable clock is referenced similarly to NBS/USNO. Therefore, the offset and rate of offset of the station clocks and oscillators can be accurately determined, traceable to the NBS/USNO references. In the case of overseas Deep Space Stations, as implied in Figs. 3 and 4, offsets are determined by LORAN or television signals. The tie is again via portable clock to NBS/USNO, periodically.

A reporting scheme from all Deep Space Stations, on a weekly basis, provides data to the Deep Space Network Operations Analysis Group, which determines how well the DSN is synchronized and what the precise offsets are. This data is provided all users, such as projects and experimenters.

To negate the possibility of a power failure rendering the equipment useless, endangering the record analysis credibility, a backup power system is utilized. Basically, it is a large converter system that is powered by a bank of batteries, converting the direct current to 115 volts alternating current. The unit is on line continuously, able to switch from firm power to its batteries for a power source. This scheme has proven satisfactory in the past several years, having had only one minor and inconsequential failure.

V. DSN Frequency and Timing System Performance

Performance of the frequency and timing equipment is measured in availability, accuracy and stability. Although accuracy and stability are represented by minute numbers, availability is represented by a large number, displaying the engineering that was applied to the subsystem design, with redundancy designed into the clock, oscillators and power. The subsystem boasts of availability of better than 99.8%. In terms of hours per year this implies the equipment was available for support all but 17.5 hours. Unlike most subsystems, Frequency and Timing is operating 24 hours per day supporting missions, testing and experiments.

Accuracy in this discipline is measured both in time and frequency. In regard to time, during the period of Voyager 1 encounter of Saturn to this writing, clock accuracies between complexes, i.e., Madrid, Canberra and Goldstone, were kept to within 20 microseconds and the accuracy between USNO and any complex was within 20 microseconds. During the 130-day encounter phase, accuracies were within 10 microseconds.

In the frequency domain, the masers have performed at better than 3 parts in 10^{13} for the same period, or less than 26 nanoseconds clock change per day. The stability of the masers, hence the clocks, performed at better than 2×10^{13} long term, i.e., up to 10 days, in terms of Allan Variance.

The above performance was measured by the "System" over a period of one year. Portable clocks, LORAN, TV time synchronization, VLBI and the data analysts contributed to the impressive results.

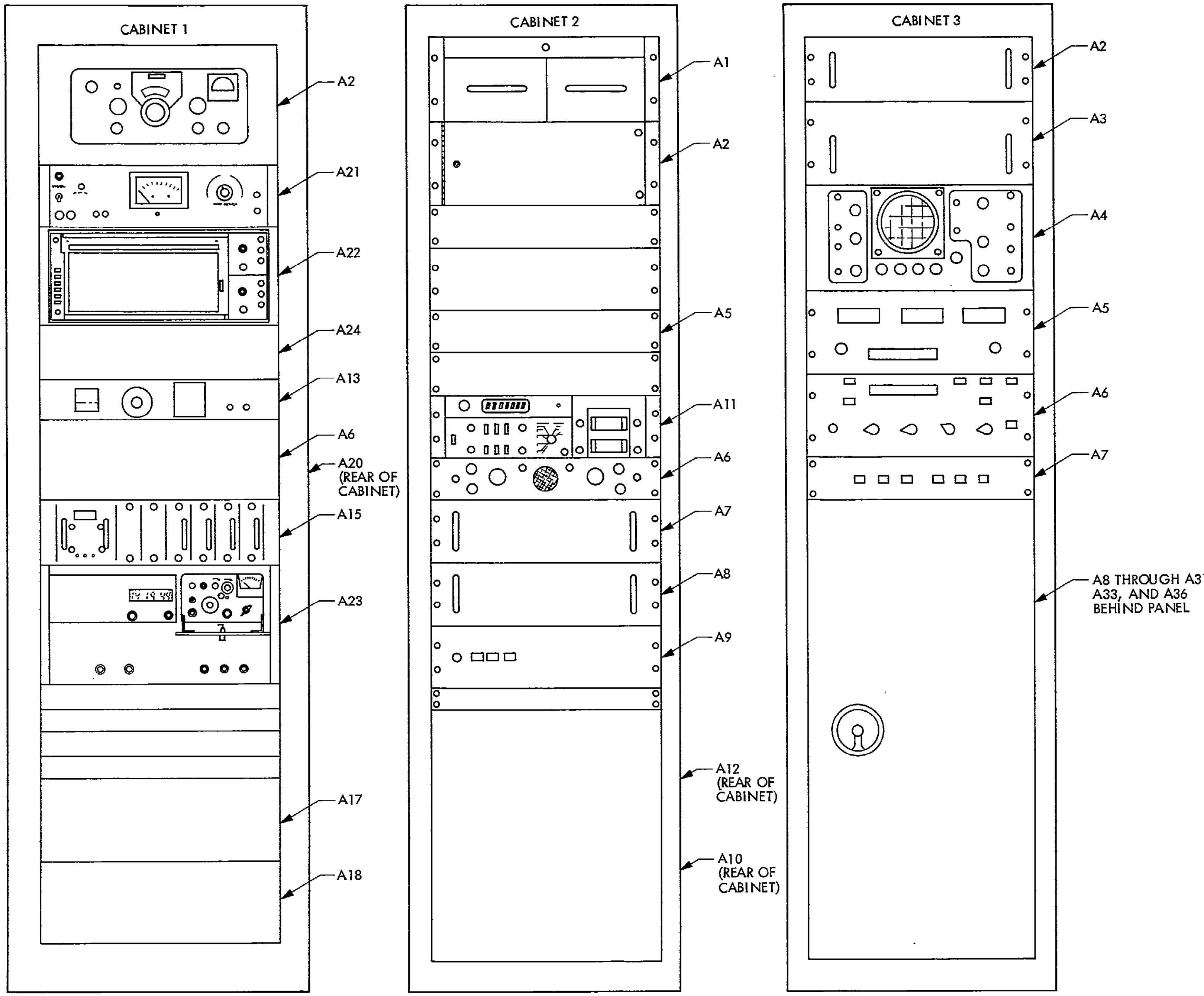

Fig. 1. DSN Frequency and Timing Subsystem—major cabinet assemblies components

COMPONENT REFERENCE DESIGNATION	NOMENCLATURE	COMMON NAME
1-2 1986/FTS-1	CABINET ASSEMBLY NO. 1	CABINET 1
A2	COMMUNICATION RECEIVER	WWV-WWVH RECEIVER
A3	PHASE COMPARATOR AND RECORDER ASSEMBLY	PHASE COMPARATOR AND RECORDER
A3A1, A3A2	SECONDARY FREQUENCY STANDARD ASSEMBLY	SECONDARY FREQUENCY STANDARD (CRYSTAL)
A4	VLF TRACKING RECEIVER SERIES 599	VLF RECEIVER
A6	FREQUENCY SOURCE SELECTOR ASSEMBLY	SOURCE SELECTOR
A8	RUBIDIUM FREQUENCY STANDARD R20	RUBIDIUM NO. 2
A9	RUBIDIUM VAPOR FREQUENCY STANDARD HP 5065A	RUBIDIUM NO. 1
A10	RUBIDIUM RUNNING TIME PANEL	TIME PANEL
A11	RUBIDIUM V-4760 POWER SUPPLY	RUBIDIUM POWER SUPPLY
A13	FREQUENCY DISTRIBUTION AMPLIFIER	5 MHz DISTRIBUTION AMPLIFIER
A14	FREQUENCY DISTRIBUTION AMPLIFIER	1 MHz DISTRIBUTION AMPLIFIER
A15	WIDE BAND FREQUENCY DISTRIBUTION AMPLIFIER	WIDE BAND DISTRIBUTION AMPLIFIER
A17	ISOLATION AMPLIFIER POWER SUPPLY ASSEMBLY	PULSE AMPLIFIER POWER SUPPLY
A18	PULSE ISOLATION AMPLIFIER	PULSE AMPLIFIER
A20	BCD TIME PANEL	BCD DISTRIBUTION PANEL
A21	PHASE COMPARATOR	PHASE COMPARATOR
A22	CHART RECORDER ASSEMBLY	CHART RECORDER
A23	CESIUM FREQUENCY STANDARD	CESIUM STANDARD
A24	CESIUM SWITCH PANEL ASSEMBLY	CESIUM SWITCH PANEL
1-3 1987/FTS-2	CABINET ASSEMBLY NO. 2	CABINET 2
A1	ISOLATION AMPLIFIER POWER SUPPLY ASSEMBLY	PULSE AMPLIFIER POWER SUPPLY
A2	PULSE ISOLATION AMPLIFIER	PULSE AMPLIFIER
A5	DECIMAL LAMP DRIVERS ASSEMBLY	LAMP DRIVER
A6	COMMUNICATION PANEL	COMMUNICATION PANEL
A7	TRANSFORMER PANEL ASSEMBLY	TRANSFORMER PANEL
A8	POWER SUPPLY ASSEMBLY	POWER SUPPLY
A9	AUXILIARY REFERENCE DIVIDER CONTROL ASSEMBLY	DIVIDER CONTROL
A10	JUNCTION MODULE ASSEMBLY	JUNCTION MODULE
A11	COUNTER	COUNTER
A12	AUXILIARY LOGIC DRAWER ASSEMBLY	AUXILIARY LOGIC DRAWER
1-4 1988/FTS-3	CABINET ASSEMBLY NO. 3	CABINET 3
A2	POWER SUPPLY ASSEMBLY	POSITIVE POWER SUPPLY
A3	POWER SUPPLY ASSEMBLY	POSITIVE-NEGATIVE POWER SUPPLY

COMPONENT REFERENCE DESIGNATION	NOMENCLATURE	COMMON NAME
A4	OSCILLOSCOPE	OSCILLOSCOPE
A5	STATION CLOCK MONITOR CONTROL ASSEMBLY	CONTROL NO. 2
A6	SUBSYSTEM MONITOR CONTROL ASSEMBLY	CONTROL NO. 1
A7	MISCELLANEOUS DECODER CARD FILE ASSEMBLY	ERROR DETECTOR
A8	REFERENCE TIMING PULSE GENERATOR CARD FILE ASSEMBLY	REFERENCE DIVIDER
A9	TIME CODE GENERATOR CARD FILE ASSEMBLY	NASA 36-BIT GENERATOR
A10	TIME CODE GENERATOR CARD FILE ASSEMBLY	NASA 28-BIT GENERATOR
A11	TIME CODE GENERATOR CARD FILE ASSEMBLY	NASA 20-BIT GENERATOR
A12	FILTER MODULATION CARD FILE ASSEMBLY	FILTER MODULATOR
A13	JUNCTION BOX CARD FILE ASSEMBLY	JUNCTION BOX NO. 3
A14	BCD TO DEC CONVERTER CARD FILE ASSEMBLY	BCD TO DEC
A15	JUNCTION BOX CARD FILE ASSEMBLY	JUNCTION BOX NO. 2
A16	BCD TO DEC CONVERTER CARD FILE ASSEMBLY	BCD TO DEC CONVERTER
A17	JUNCTION BOX CARD FILE ASSEMBLY	JUNCTION BOX NO. 1
A18	AUXILIARY REFERENCE TIMING PULSE GENERATOR	AUXILIARY TIMING PULSE GENERATOR
A19	AUXILIARY PULSE AMPLIFIER CARD FILE ASSEMBLY	PULSE AMPLIFIER
A20	BCD TIME SELECTOR CARD FILE ASSEMBLY	30-GATE FILE A
A21	BCD TIME SELECTOR CARD FILE ASSEMBLY	SIMULATOR 30-GATE FILE
A22	BCD TIME SELECTOR CARD FILE ASSEMBLY	30-GATE FILE B
A23	JUNCTION BOX CARD FILE FILE ASSEMBLY	JUNCTION BOX NO. 4
A24	BCD TIME SELECTOR CARD FILE ASSEMBLY	30-GATE FILE C
A25	TIMING PULSE GENERATOR CARD FILE ASSEMBLY	DATA DIVIDER A
A26	CLOCK CARD FILE ASSEMBLY	CLOCK A
A27	TIMING PULSE GENERATOR CARD FILE ASSEMBLY	DATA DIVIDER B
A28	CLOCK CARD FILE ASSEMBLY	CLOCK B
A29	TIME PULSE GENERATOR CARD FILE ASSEMBLY	DATA DIVIDER C
A30	CLOCK CARD FILE ASSEMBLY	CLOCK C
A31	POWER DISTRIBUTION AND MONITOR ASSEMBLY	POWER DISTRIBUTION AND MONITOR
A33	INTERCONNECT BOX	INTERCONNECT BOX
A36	INTERCONNECT BOX	INTERCONNECT BOX

Fig. 1 (contd)

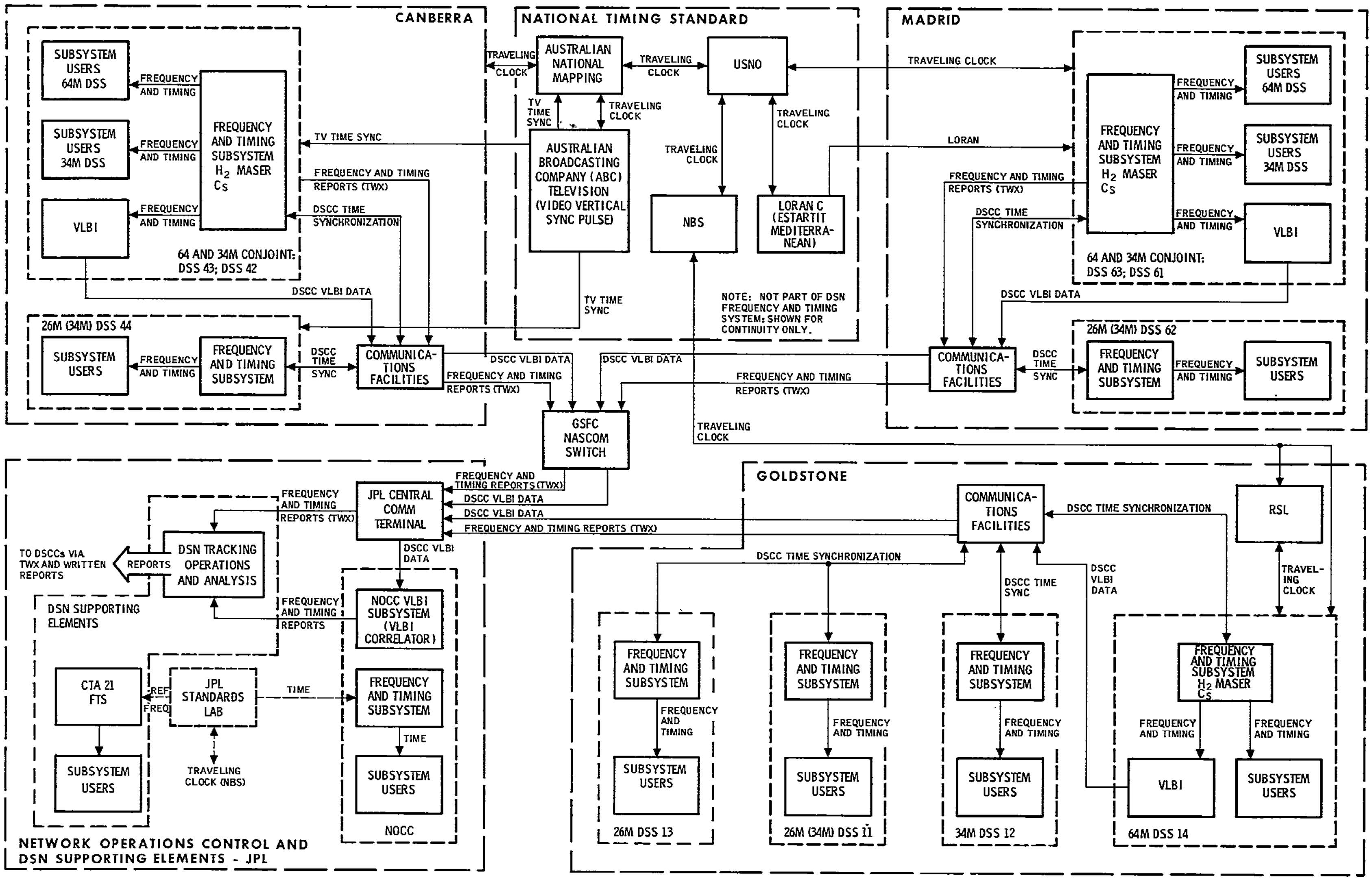

Fig. 2. DSN Frequency and Timing System block diagram

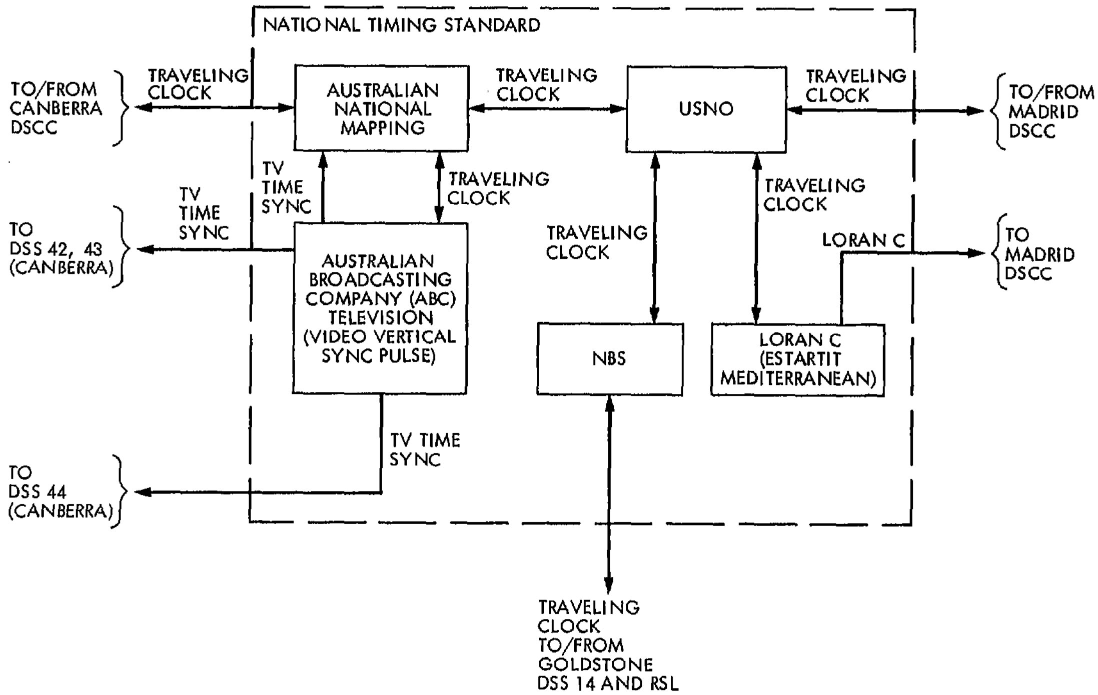

Fig. 3. National Timing Standard data flow

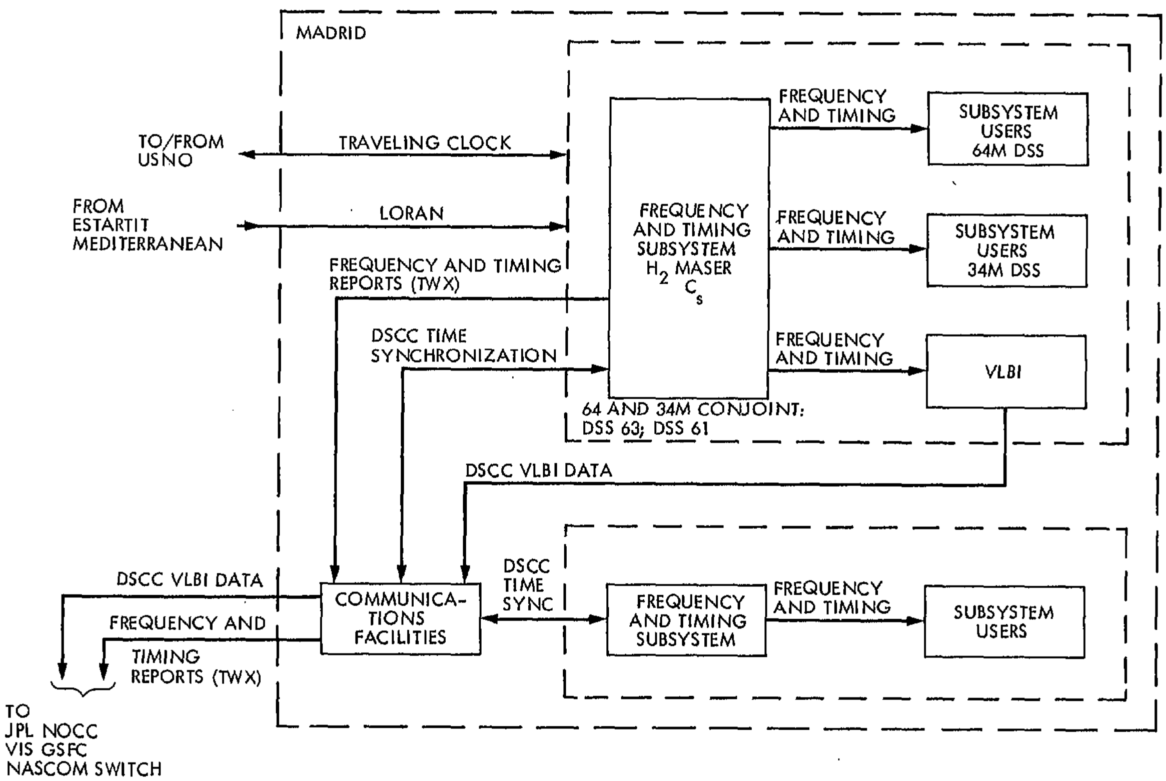

Fig. 4. Frequency and Timing Subsystem (Madrid, Spain)

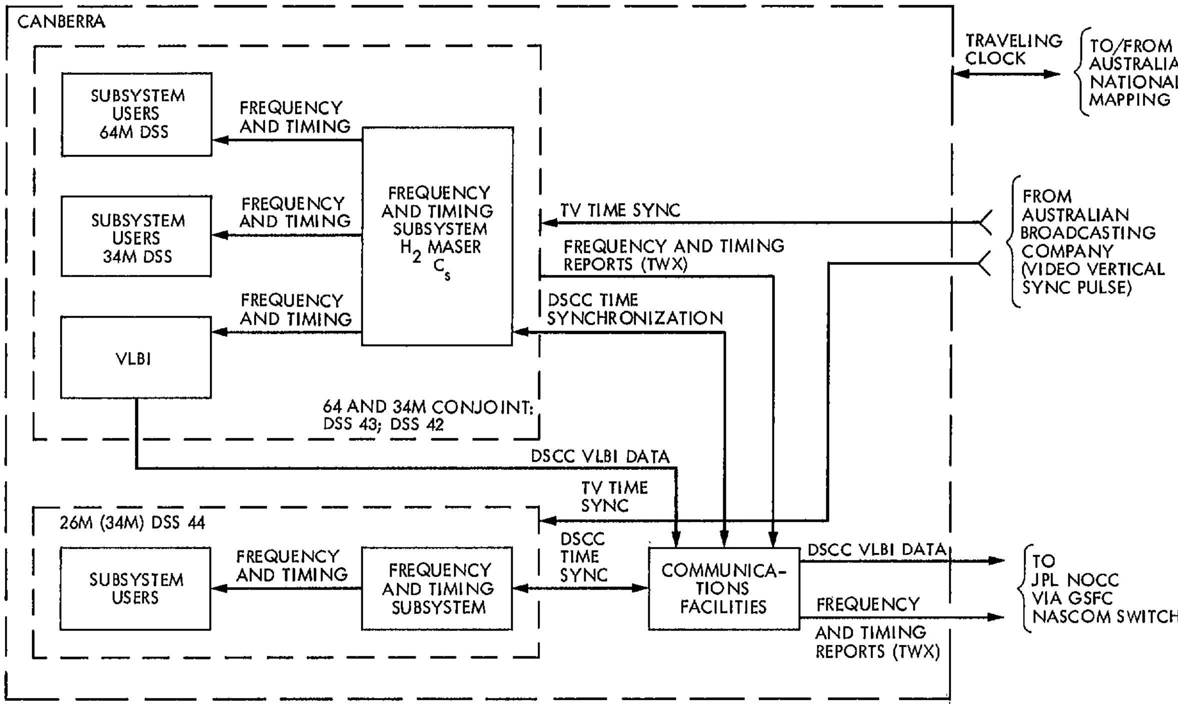

Fig. 5. Frequency and Timing Subsystem (Canberra, Australia)

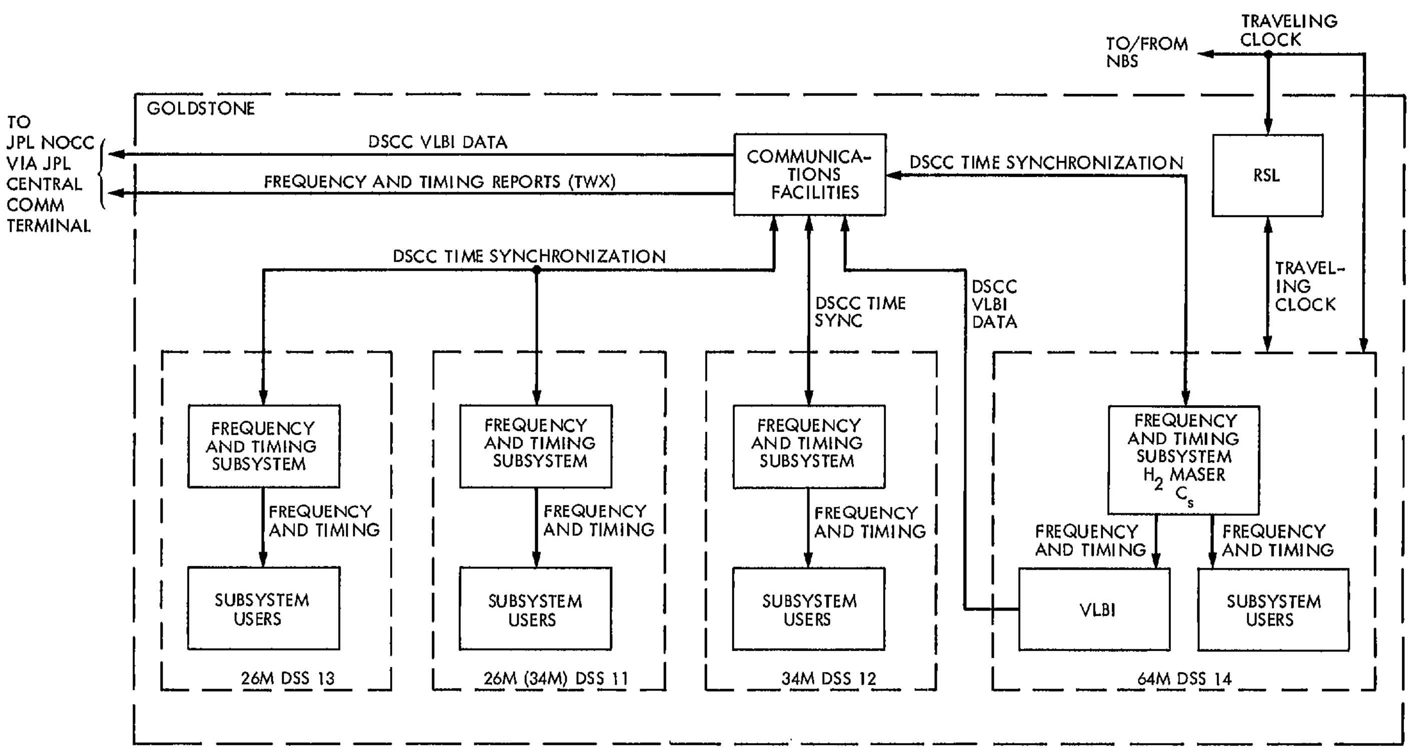

Fig. 6. Frequency and Timing Subsystem (Goldstone, California)

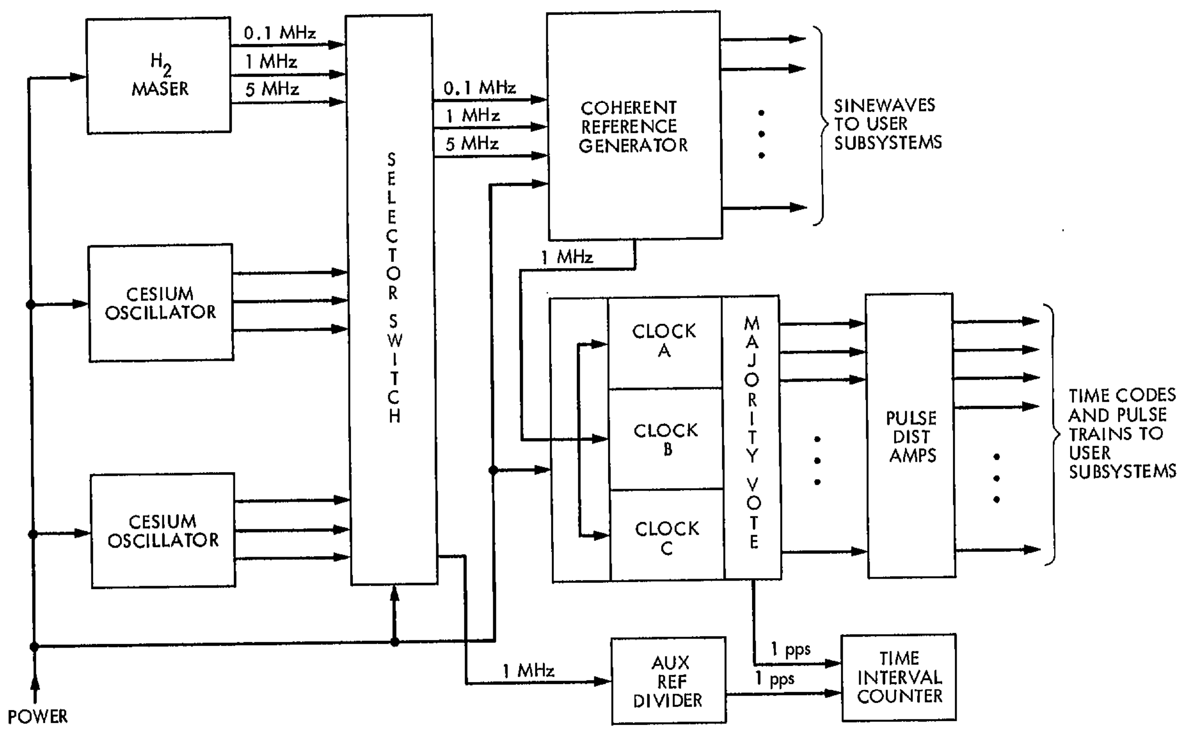

Fig. 7. Frequency and Timing Subsystem block diagram

Appendix A
Allen Variance Definition

A measure of the average fractional frequency deviation of a frequency source is defined as follows: Let the instantaneous phase of the source be $2\pi\nu_0 t + \phi(t)$, where ν_0 is the nominal frequency, and O(t) is the instantaneous phase deviation. The instantaneous fractional frequency deviation y(t) is

$$y(t) = \frac{1}{2\pi\nu_0} \frac{d\phi(t)}{dt} .$$

Fix an averaging time τ, and consider successive time intervals $(k\tau, (k + 1)\tau)$, $k = 0, 1, 2, \ldots$. The average of y(t) over the k^{th} interval is

$$\overline{y}_k = \frac{1}{\tau} \int_{k\tau}^{(k+1)\tau} y(t)\, dt = \frac{\phi((k+1)\tau) - \phi(k\tau)}{2\pi\nu_0\tau} .$$

By definition, the Allan variance is the quantity

$$\sigma_y^2(\tau) = \frac{1}{2} < (\overline{y}_{k+1} - \overline{y}_k)^2 >,$$

where $< >$ means infinite time average over k.

In practice, where only a finite number m of differences $\overline{y}_{k+1} - \overline{y}_k$ are available, the Allan variance is estimated by

$$\hat{\sigma}_y^2(\tau) = \frac{1}{m} \sum_{k=0}^{m-1} \frac{1}{2} (\overline{y}_{k+1} - \overline{y}_k)^2 .$$

Since $\sigma_y^2(\tau)$ does vary with τ, each specification of deviation ($\sqrt{\text{variance}}$) should include the averaging time, which gives the time scale over which the deviation specification applies. The specification should also mention the number of samples and the noise bandwidth of the measuring system.