NASA/JPL DEEP SPACE NETWORK FREQUENCY AND TIMING

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Abstract

The Jet Propulsion Laboratory (JPL) supplies, maintains, and operates the NASA Deep Space Network for ground tracking of outer space probes. There are three major complexes which are located near Los Angeles, California; Canberra, Australia; and Madrid, Spain to provide continuous coverage of the desired spacecraft. This paper will describe the Frequency and Timing equipment utilized at the three complexes, and the methods of time synchronization and frequency syntonization between the three complexes and the National Institute of Standards and Technology (NIST).

Diagrams and specifications of today's system and anticipated future requirements will also be presented.

Introduction

NASA/JPL operates the Deep Space Network which consists of three complexes located around the world. These are located at Goldstone, California; near Robledo, Spain; and Tidbinbilla, Australia. From these three sites, continuous coverage of Deep Space probes (e.g.., Voyager, Pioneer, Magellan and Galileo) is possible. Each site has multiple antennas for simultaneous coverage of several spacecraft or antenna arraying of a single spacecraft. Each complex has one centralized control room which includes one timing subsystem that is distributed to all users. Time synchronization and frequency syntonization between the three complexes and the National Institute of Standards and Technology (NIST) is accomplished today using the GPS constellation.

Configuration

Each complex (e.g.., Goldstone, CA) has a complete Frequency and Timing subsystem. All three complexes have nearly identical equipment and configuration. A typical overall high level block diagram is shown in Figure 1. This is further detailed in several additional block diagrams, each of which is

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one block from Figure 1. These include the Frequency Standards Group (Figure 2), the Reference Frequency Synthesis and Distribution Group (Figure 3), the Master Clock and Timing Group (Figure 4) and the Monitor and Control Group (Figure 5).

Frequency Standards

The Frequency Standard Group (Figure 2) consists of the atomic frequency standards and accessories. The primary and first backup standards are both active Hydrogen Masers manufactured by the Smithsonian Astrophysical Observatory (SAO). The primary unit is a model VL11B and the backup is a model VLG10. The third and fourth units are Hewlett Packard 5061A Cesium Beam Frequency Standards with the "option 004" High Performance tube. All four are battery backed and are, in addition, connected to the Complex Uninterruptible Power Supply (UPS).

Reference Frequency Synthesis and Distribution

The four frequency standards are connected to the Coherent Reference Generator (CRG). The cabinet provides the switch gear to select one of the four frequency standards, synthesis of several additional frequencies and distribution of these to all users within the complex. The frequencies supplied are 0.1, 1, 5, 10, 10.1, 45, 50, 55 & 100 MHz. The total number of outputs is currently 225. To minimize crosstalk and interference the newer distribution amplifier design has a minimum reverse isolation between outputs of 100 dB. The isolation between the four frequency standards is 140 dB minimum to attenuate crosstalk to below the Hydrogen Maser performance specifications. The CRG is a JPL design that has evolved over the past 17 years and occupies two 7 foot high rack cabinets. It is entirely packaged with plug–in field replaceable modules. The entire assembly is equipped with computer based monitor equipment for hard failure detection (no output) and frequency standard selection.

The Phase Calibration Generator (PCG) transmits a reference frequency from the CRG to the antenna. It uses active (feedback) stabilization of the 20 MHz reference frequency to preserve the Hydrogen Maser stability. The device includes a transmitter, receiver and two comb tone generators. The transmitter–receiver pair provides the frequency stability and the comb tone generators the S & X band comb tone spacing and pulse amplitude that is injected into the antenna feedhorn. This provides the method of measuring the receiver delay stability. The principal uses of the PCG are to deliver a Hydrogen Maser stable reference to the antenna for receiver First Local Oscillator use and comb tones to the receiver for Very Long Baseline Interferometry (VLBI) measurements. The PCG is used in two antennas at each complex: 1) the 70M antenna and 2) the 34M High Efficiency Antenna.

Several users require the 100 MHz reference frequency in the antenna cone areas. To provide stabilized 100 MHz, a frequency multiplier (20 to 100 MHz) is connected to the PCG 20 MHz output. This synthesized 100 MHz is distributed to 4 users, using distribution amplifiers with 100 dB minimum reverse isolation. This equipment is mounted in a temperature controlled container, which is installed in the antenna cone area. This 100 MHz meets the present day required Frequency stability performance requirements. This equipment was designed and developed at JPL.

Master Clock and Timing Group

This group contains the complete set of timing equipment. The major assemblies consist of the Phase Locked Oscillator, Triple Redundant Master Clock (MCA), Time Insertion and Distribution Assembly (TID) and multiple Time Code Translators (TCT).

The Phase Locked Oscillator is a 5 MHz Voltage Controlled Crystal Oscillator that is phase locked to the CRG output (and frequency standard). The purpose of this device is to act as a "flywheel" during reference frequency interruptions. This was implemented to maintain clock service during the 10 to 20 milliseconds reference frequency outage when the CRG switches to another frequency standard.

The master clock contains three independent Time Code Generators which are setup to be in synchronization and driven by the complex atomic frequency standard that is currently in use. All three generators are voted by majority vote logic that selects a minimum of two being within limits as the correct time of day and pulse timing.

The TID is a distribution assembly that formulates a modified IRIG-G code for distribution to all the TCT's in the complex (100 maximum). The requirements are that not only UTC be distributed, but a second time code be available which is titled Simulation (SIM) Time. This code may be offset from UTC to anytime within a year to the nearest second. It is programmable to any or all of TCT's in the complex by the centralized Computer Control console. This SIM time programmability is necessary to meet the requirements of simultaneous multiple antenna users, one of which may be performing a training or software exercise for a future planned event.

The TID generated modified IRIG–G code contains UTC in the same format as specified in the IRIG–G specification. The SIM Time code is inserted in the control functions part of each frame. Flags are inserted in each frame that instruct each TCT on the leap year and leap second function. In addition, an address code is inserted in each frame to instruct a discrete TCT on SIM time and required flags (leap year and leap second). In this manner each TCT may be assigned to UTC or SIM time with the necessary flags. Each address is repeated every 100 frames of TID's code (1 second).

The TCT is really a synchronized Time Code Generator. Each TCT accumulates time from the same 5 MHz reference source as the MCA. The TCT is synchronized and controlled by the modified IRIG–G code. The TCT output contains time code and pulses. The current codes available are NASA PB–1 (millisecond of day and day of year) and BCD (millisecond of day and day of year). Timing pulses available are 1 PPS, 10 PPS, 100 PPS and 1000 PPS.

The Timing Jitter and TCT offset relate to TCT performance. The TCT jitter is inherit within the assembly design and exceeds the requirement by a comfortable margin. Each TCT in the complex may be adjusted to decrease the Master Clock to TCT propagation delay to less than 100 nanoseconds. This offset is adjusted and calibrated when the TCT is installed and subsequently verified at regular intervals.

Time Synchronization

GPS is currently the method for measuring the three DSN complexes timing versus UTC at NIST. The "NBS" (NIST) receiver design is currently in use at the three complexes. Data is acquired daily at each receiver (DSN complexes and NIST) versus selected GPS satellites using a predetermined schedule. This data is accumulated weekly at JPL by the DSN Timing analyst and compared with UTC from

(NIST). The result is the "Common View" measurement technique. Weekly time synchronization and frequency syntonization reports are publicized weekly to the DSN.

Monitor and Control

Figure 5 shows the block diagram configuration of the FTS Monitor and Control. Each major assembly has a dedicated microprocessor computer with keyboard for monitor only or monitor and control purposes. Control is limited to the TID, PCG and CRG. Computer control of the Master Clock and Frequency Standards is intentionally omitted, due to the possibility of erroneous messages causing misadjustment of the equipment. The FTS is normally controlled and monitored from the Centralized Monitor and Control (CMC) console. This console is the central area where the entire complex is controlled and monitored for major functions throughout the complex. Local front panel control at each FTS major assembly has also been provided.

Requirements & Performance

There are many detailed requirements imposed on the DSN Frequency and Timing. These are updated to meet requirements for the future planned Deep Space Missions. Only the most important will be addressed in this paper. These involve stability and offset.

Allan Deviation

Allan Deviation requirements and performance are shown in Figure 6. Various missions overrule the general specifications and have more stringent requirements, some of which are difficult to meet with a Hydrogen Maser, which leaves little margin for the transmission to an antenna that is 300 to 700 meters from the frequency standard. Requirements for the recent Voyager Neptune encounter and the future Galileo and Mars Observer missions are also shown. Note that the Voyager Neptune performance met the mission requirements and this was at the antennas using a non– stabilized coaxial cable that is buried one and one half meters below the ground surface. The section on the antenna structure is exposed and subject to the environment which is the most significant contributor to the stability degradation.

The above described non–stabilized coaxial cable method will not be satisfactory for the Galileo or Mars Observer mission stability requirements. While the PCG is feedback stabilized and will marginally meet the Allan Deviation, other parameters limit the assembly performance. Current work, in process, using fiber optic transmission lines should solve this problem.

Power Spectral Density of Phase

The single sideband phase noise requirements and performance are shown in Figure 7. The requirements for Voyager Neptune and subsequently for Mars Observer were better than Frequency and Timing could support. The recent JPL revisions to the Hydrogen Maser electronics have improved the phase noise performance with a reasonable margin. This was accomplished by replacing the VCO with a BVA type crystal voltage controlled oscillator (VCO) and frequency multipliers that did not degrade the VCO. The tracking filter was also replaced with the single sided loop bandwidth set to approximately 0.5 HZ. This equipment was installed prior to the Voyager Neptune encounter to support the Radio Science Occultation and Ring Experiment. These revisions are currently being installed in the balance of the DSN.

Offset and Jitter

Table 1 shows the specifications and nominal performance frequency and time offset, timing jitter and TCT offset versus the Master Clock. The frequency and time offset is the maximum permitted between the three complexes and the National Institute of Standards and Technology (NIST). The knowledge of frequency and time offset is specified somewhat tighter; this is not a problem with the present GPS time synchronization and frequency syntonization techniques used in the DSN. These requirements are easily exceeded with a comfortable margin.

Future Requirements and Improvements

Future missions in the planning stage will possibly require tighter specifications than possible with the equipment implemented or in process, at this time. It is estimated these would be required about year 1995 to 2000. Some of these specifications could be:

- Allan Deviation of 1×10^{-16} at sampling times between 1000 and 10,000 seconds. The driver could be Gravitational Wave Experiments.
- Improved Phase Noise of 10 to 20 dB better than the specifications in Figure 7. This will probably be especially true for close to the carrier responses.
- Reduce the knowledge of timing offset to 1 nanosecond between NIST and the three complexes.
- Reduce the maximum permitted time offset between NIST and the three complexes to 1 microsecond.

The near term improvement is to utilize fiberoptic links to distribute the 100 MHz reference to the DSN antennas from the control room. The Allan Deviation and Phase Noise requirements for Galileo and Mars Observer cannot be met with the present configuration using the PCG. A combination of new state of the art fiberoptic transmitters, receivers and near zero temperature coefficient cable appear to meet the requirements from an ongoing test series. It is planned to complete the evaluation, the design in 1991 and to start installation in the antennas during 1992.

Other possible future improvements that are currently being developed or considered by NASA/JPL are:

- Feedback stabilized fiberoptic reference frequency links at 100 MHz to obtain Allan Deviation performance below 1×10^{-15} at 10^4 seconds.
- Fiberoptic reference frequency links at 1GHz to reduce the phase noise contributed by the links.

- Hydrogen Masers with Adiabatic Fast Passage to obtain Allan Deviation performance of 1×10^{-16} at 10^4 seconds.
- Superconducting Cavity Maser Oscillator that is phase locked to a Hydrogen Maser providing a distinct improvement in Phase Noise and short term Allan Deviation performance.
- Mercury Trapped Ion Frequency Standards as a standalone device or as the long term low aging reference to steer a Hydrogen Maser.
- Sapphire Dielectric Resonator Oscillator
- Two–way time transfer to replace or augment GPS, as a method of time synchronization to the one nanosecond level.

These will be considered in the future as project requirements determine the need for DSN implementation.

Summary

Requirements for Frequency and Timing performance have been tightened in the last few years and will undoubtedly continue to in future years. The recent phase noise performance improvements and near future fiberoptic transmission links will meet Galileo and Mars Observer mission Radio Science experiment requirements. Future, yet to be determined, requirements should be met by equipment currently being researched and developed at JPL.

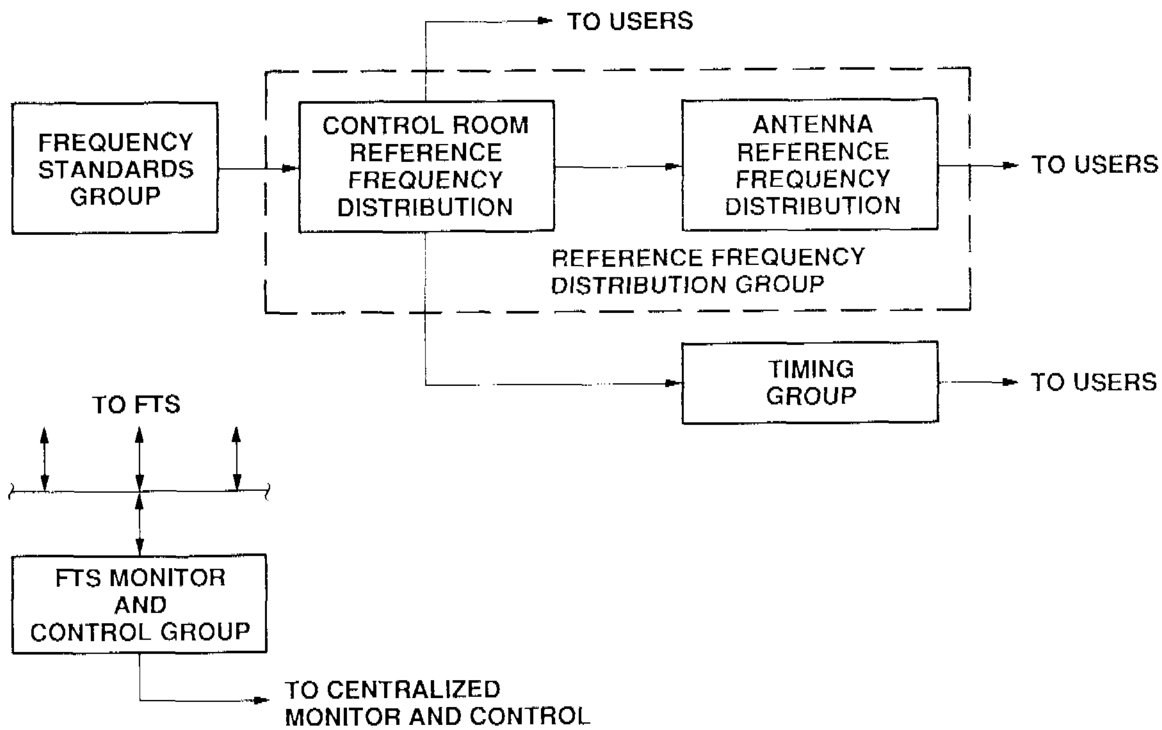

Figure 1. DSN Frequency and Timing Configuration

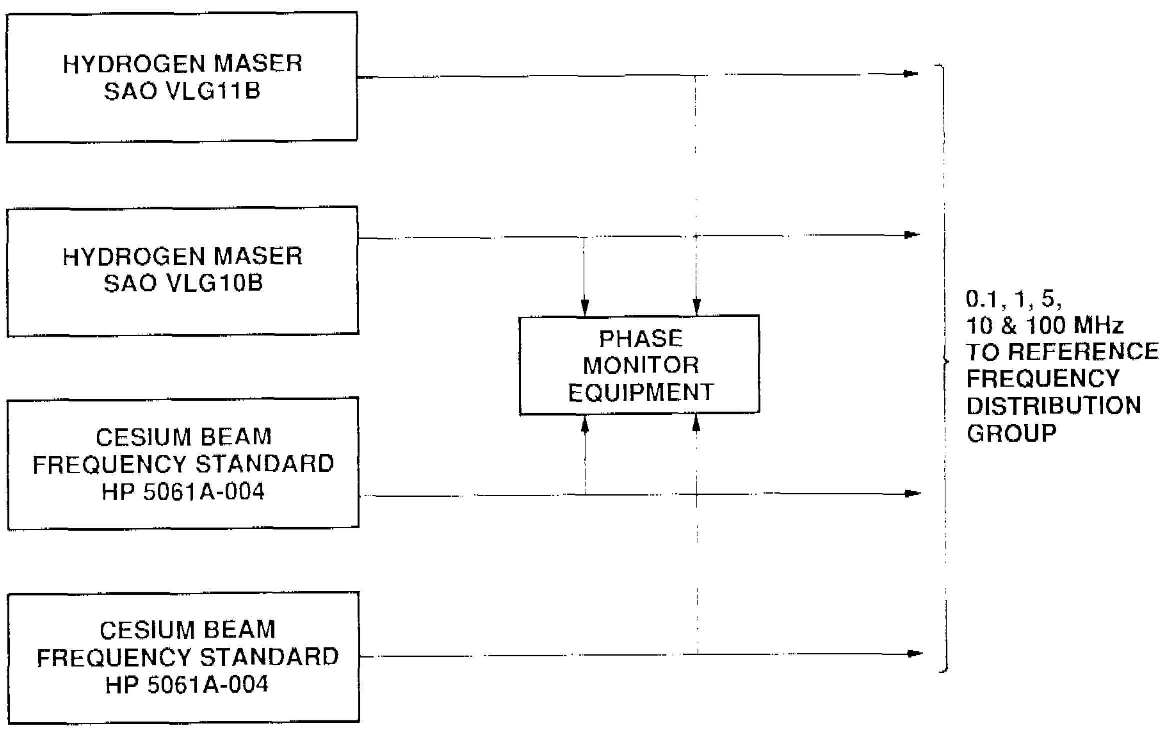

Figure 2. Frequency Standards Group

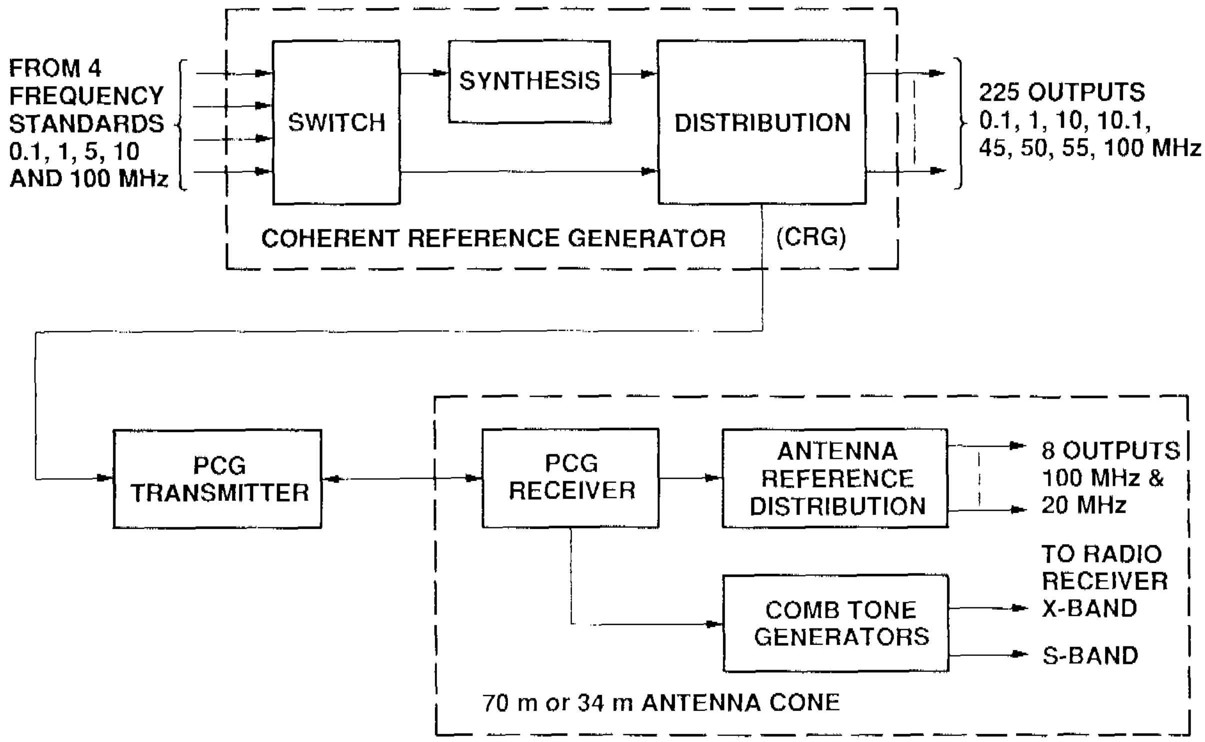

Figure 3. Reference Frequency Synthesis and Distribution Group

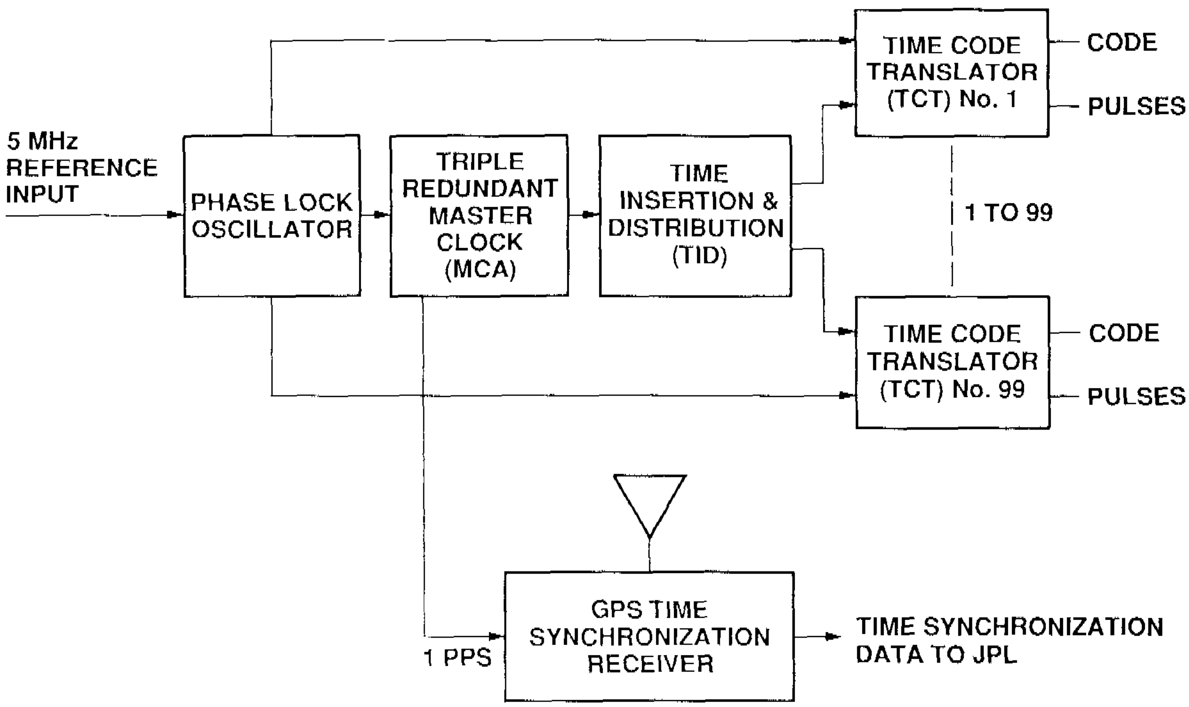

Figure 4. Timing Group

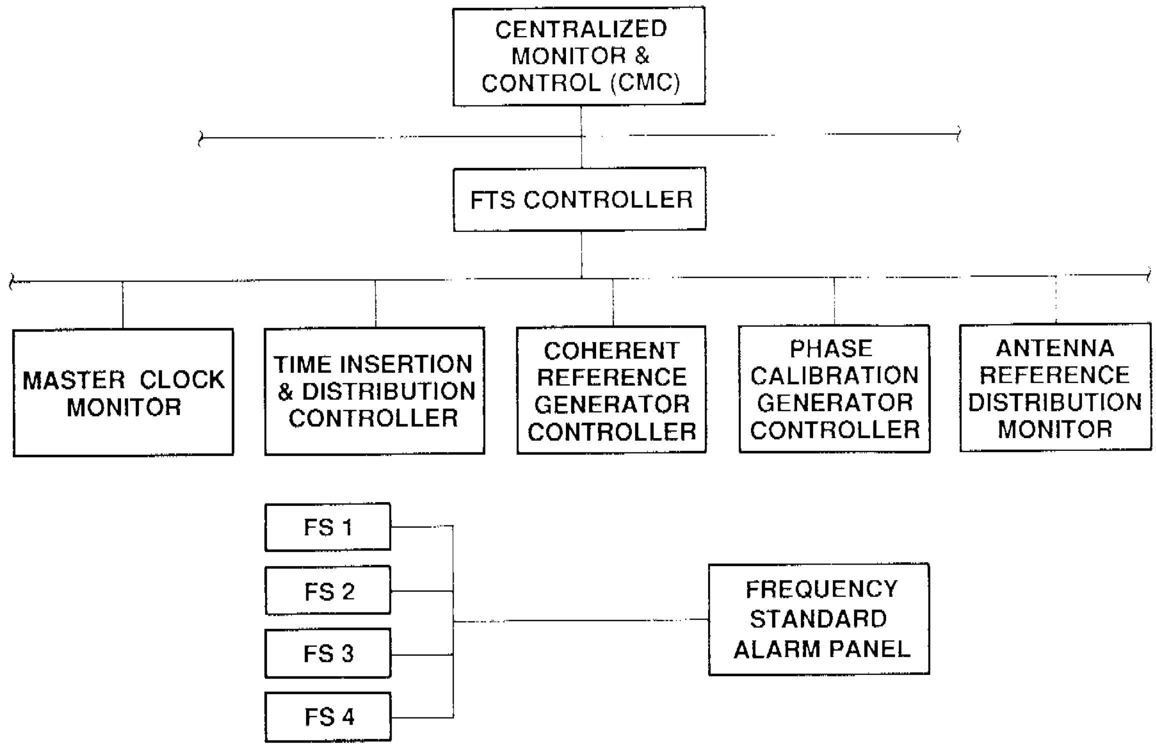

Figure 5. Monitor and Control

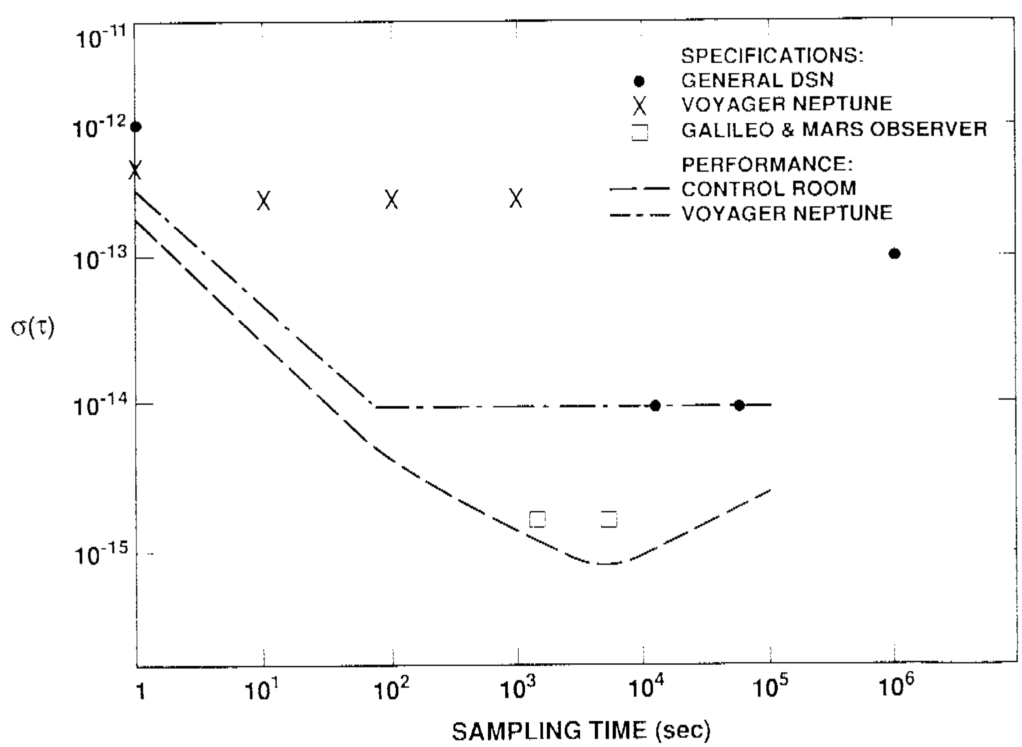

Figure 6. Allan Variance vs Sampling Time

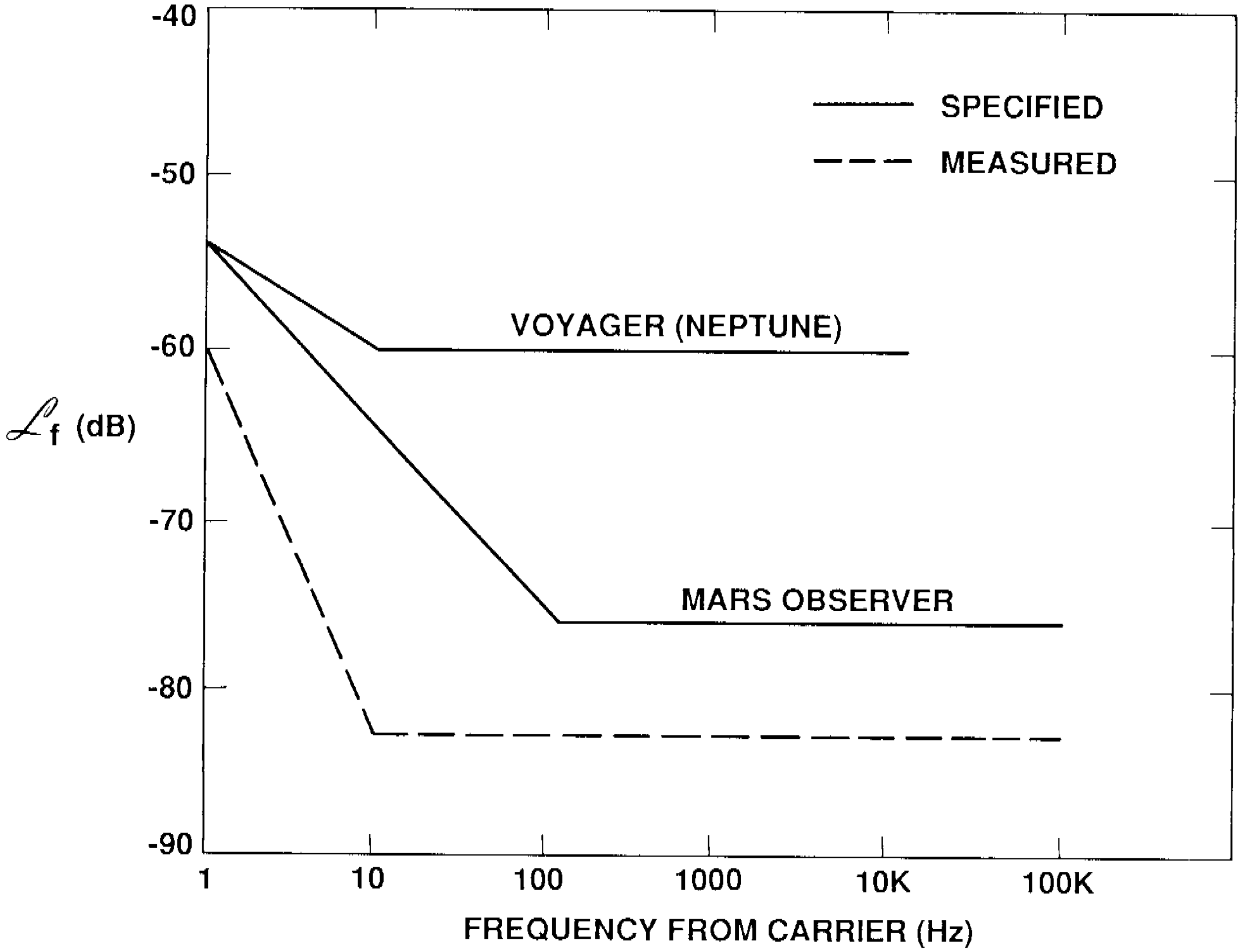

Figure 7. Power Spectral Density of Phase at X-Band

Table 1. Offset and Jitter Requirements and Performance

	SPECIFICATIONS	NOMINAL PERFORMANCE
FREQUENCY OFFSET	9×10^{-13} MAX	$<5 \times 10^{-13}$
FREQUENCY OFFSET KNOWLEDGE	3×10^{-13} MAX	$<1 \times 10^{-13}$
TIME OFFSET	20 μs MAX	<5 μs
TIME OFFSET KNOWLEDGE	10 μs MAX	<100 ns
TIMING JITTER (1, 10, 100, 1K PPS)	2 ns MAX @ 1σ	<2 ns @ 1σ
TCT OFFSET vs MCA	100 ns MAX	<100 ns

QUESTIONS AND ANSWERS

GERNOT WINKLER, USNO: You mentioned a future requirement for phase or frequency distribution to 1×10^{-15} at the antenna. Over what time interval.

MR. KUHNLE: 1000 to 3600 seconds. It is for some preliminary gravitational wave experiments that they are setting up to do with Galileo.

MR. MCNABB: In one of your early slides, you had cesium standards. I saw no multipliers, but you were coming out with 100 MHz. Where did that 100 MHz come from?

MR. KUHNLE: I left them off the diagram to keep the diagram from becoming too complicated. We do have 5MHz to 100 MHz multipliers and distribution amplifiers in an outboard box with the cesiums.