Phase Calibration Generator

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The Phase Calibration Generator (PCG) system first installed in the Deep Space Network (DSN) in 1987 has recently undergone major modifications that improve comb-tone phase stability and system reliability. Obsolete PCG controllers have also been replaced and upgraded with an improved user interface. The PCG system redesign, test results, and a new capability to generate tones at 32 GHz (Ka-band) are described.

I. Introduction

Signals from distant radio sources are detected in the Deep Space Network (DSN) by sensitive microwave receivers located at various antennas. The stability of the receiver is critical but is often difficult to control because of the extreme and exposed environment of the antenna and its electronics. For very long baseline interferometry (VLBI) applications, it is more cost effective to monitor phase variations of the open-loop detection system over the observation time by comparing received signals to a stable calibration tone locally generated in the detection bandwidth.

The Phase Calibration Generator (PCG) system, first installed in the DSN in 1987, provides high-stability calibration comb tones at 1.5 GHz (L-band), 2 GHz (S-band), and 8 GHz (X-band) to microwave receivers located in the DSN 34-m high-efficiency (HEF) antenna and 70-m antenna feed cones. The comb-tone output stability is referenced to a hydrogen maser frequency standard located in the DSN Signal Processing Center (SPC). In the original configuration [1], PCG transmitters located in the SPC and PCG receivers located in the antenna feed cones used a feedback-controlled system to cancel phase instability of the long cable feeding 20-MHz reference signals to the PCG equipment in the antenna. The resulting stabilized signals at the receiver were processed to generate pulses to drive frequency comb generator assemblies also located in the antenna feed cones. The PCG comb tones then were injected into the microwave receiver front end.

In this article, we describe the design drivers and modifications that improve performance and system reliability. The modifications have been implemented in the last 3 years under three separate tasks, each addressing the redesign of different elements of the PCG system:

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[1] Tracking Systems and Applications Section.

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(1) The delivery of a stable frequency reference to the receiver

(2) The generation of the calibration frequency comb spectrum

(3) The monitor and control system

The revised PCG system, configuration, and interconnections are shown in Fig. 1. In Section II, the delivery of a stable 1-MHz reference signal to each antenna site is described. Section III describes the generation of the calibration frequency comb spectrum. Section IV describes the monitor and control system. Finally, in Section V, we describe recent progress in the development of a comb generator for simultaneous output of tones at X-band and Ka-band (32 GHz).

II. PCG Elements to Replace the Transmitter–Receiver System

A. Stabilized Cable Replacement

The original PCG performance depended upon the integrity of the long coax cable run from the SPC, where the hydrogen masers and PCG transmitters were located, to the antenna feed cones that contain the PCG receivers and comb generators. Up to 14 connector interfaces were used in the cable between the PCG receiver and transmitter. Corrosion and vibration-induced stresses at connector interfaces during antenna tracking degraded PCG stability due to voltage standing wave ratio (VSWR), attenuation, and time delay variations in the cable. Subsequent to the PCG system installation, a fiber optic distribution assembly (FODA) has been installed in the DSN, which delivers 100-MHz reference carriers to the antennas with better stability than the feedback-stabilized PCG can provide [2]. The FODA utilizes a temperature-compensated fiber-optic (FO) cable (manufactured by Sumitomo), which has a temperature coefficient more than two orders of magnitude lower than the coax cable it replaces. By using this ultrastable fiber-optic signal delivery, a simplified PCG retrofit has been developed that taps into the FODA optical feed at the antenna and replaces the highly complex PCG feedback control system previously required for comb-tone stability. This has resulted in a PCG system with reduced complexity, improved reliability, and lower maintenance.

The redesign required a new PCG receiver that accepts the 100-MHz modulated optical carrier from the FODA and generates output pulses to drive the comb generator assemblies, plus a 20-MHz carrier output that is used to drive an L-band-to-S-band upconverter located in the 70-m antenna feed cone. New FODA fiber breakout box installations also were required in the antennas to provide the necessary fiber outputs to drive the PCG receivers.

B. PCG Comb-Tone Spacing

The PCG originally provided adjustable comb-tone spacing from 50 kHz to 1.0 MHz. Comb spacing was set with a $5/N$-MHz divide-by-N signal (with N assuming values between 5 and 99) generated in the PCG transmitter at the SPC. To take advantage of the 100-MHz reference carrier from the FODA and still provide comb spacing adjustable from the SPC would require a second transmission path. To minimize system complexity and improve reliability, the $5/N$ feature was dropped and a fixed 1.0-MHz comb-tone spacing was chosen.

C. PCG Receiver Redesign

By eliminating the feedback-cable stabilizer electronics and variable comb-tone spacing, the PCG receiver design has been considerably simplified. Figure 2 shows a block diagram for the new receiver. An ORTEL model 4560 photodiode receiver generates a 100-MHz carrier from the received optical input. The photodiode receiver 100-MHz output drives a pulse generator assembly consisting of a pair of low-noise, synchronous decade dividers to produce outputs at 10 MHz and 1.0 MHz. The 10-MHz output from the first decade divider is frequency doubled to 20 MHz, filtered to produce a low harmonic distortion

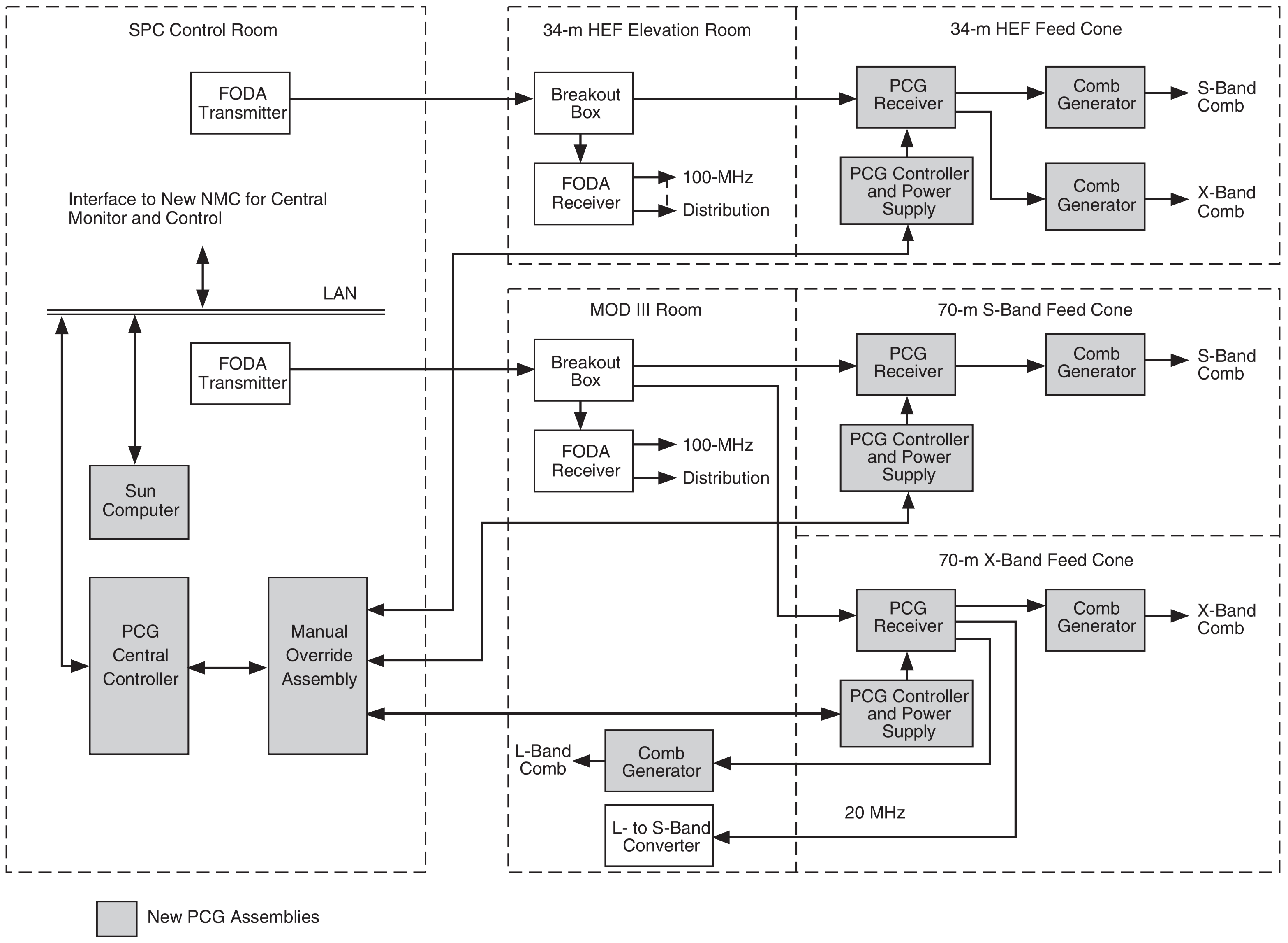

Fig. 1. PCG retrofit interconnections.

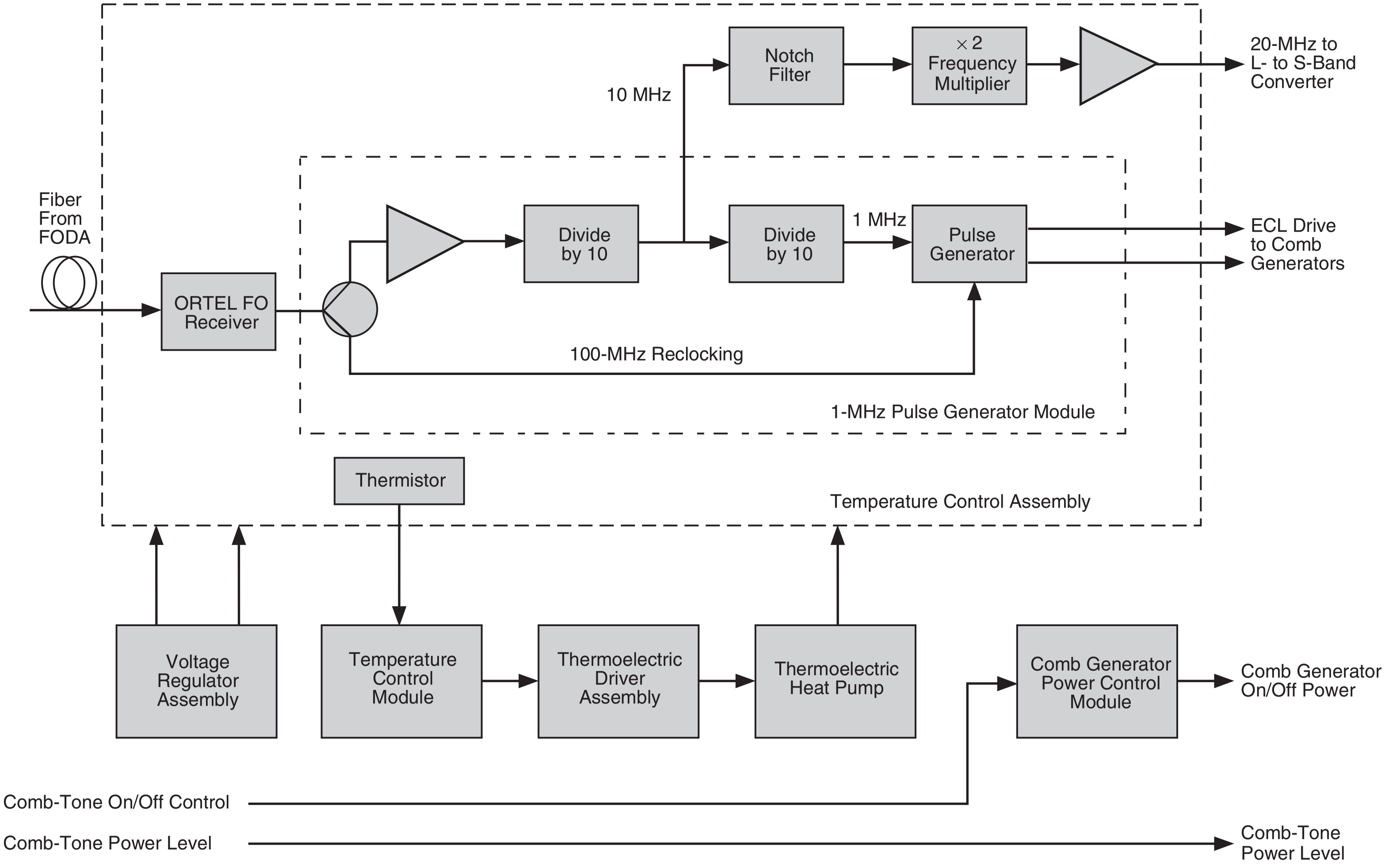

Fig. 2. PCG receiver block diagram.

sine-wave output, then amplified and output from the receiver. The 20-MHz output is sent to an L-band-to-S-band (1.7-GHz-to-2.2-GHz) upconverter assembly, where it is frequency multiplied by 31 to serve as a 620-MHz local oscillator (LO). The 1.0-MHz output from the second decade divider is reclocked with the more stable 100 MHz, then sent from the PCG receiver to drive the comb generator assemblies.

D. 1.0-MHz Pulse Output

The PCG receiver pulse generator supplies 5-ns-wide, 1.0-μs-spaced, emitter-coupled-logic (ECL) level outputs to drive the PCG comb generators. The 1.0-MHz decade divider output is fed to a pair of master–slave flip-flops that reclock the 1.0 MHz with the 100-MHz reference carrier. The flip-flop outputs are combined in logic-OR gates to produce 5-ns-wide, 1.0-μs-spaced, emitter-coupled logic output pulses that drive the comb generators.

E. Comb-Tone Stability

Allan deviation[2] of the new PCG receiver driving a PCG comb generator assembly (CGA) and Allan deviation of the FODA installations at DSS 14 (Goldstone, California) and DSS 63 (Madrid, Spain) DSN sites are given in Table 1. These data quantify the stability of the PCG and FODA systems only and do not include instabilities of the frequency standards.

PCG receiver/comb generator tests were performed at a fixed ambient temperature at the Frequency Standards Test Laboratory (FSTL). FODA performance includes in-system operating environment temperature excursions encountered at the DSN sites evident for average times longer than 1000 s.

Table 2 shows comb-tone carrier temperature stability for the averaged value of 15 new production run PCG receivers tested in the JPL FSTL. The 24-hour stability values are for a worst-case ±5 deg C temperature change over 24 hours for the PCG receiver in the feed cone. FODA stability is the averaged value of actual 24-hour measurements taken on FODA systems installed at 5 DSN antenna sites.

The above stability figures for the new PCG receiver and FODA reference-carrier delivery are comparable to the best-case performance estimates for the previous PCG system as reported in [1]. This performance could not be consistently achieved in DSN operations, possibly due to the complicated patch

Table 1. PCG system Allan deviation.

Tau	Design specification[a]	PCG receiver and CGA	DSS-14 FODA	DSS-63 FODA
1 s	1×10^{-12}	7×10^{-14}	2.3×10^{-14}	1.7×10^{-14}
10 s	Not specified	1×10^{-14}	3.0×10^{-15}	3.0×10^{-15}
100 s	Not specified	1.5×10^{-15}	7.0×10^{-16}	1.5×10^{-15}
1,000 s	Not specified	2×10^{-16}	5.0×10^{-16}	5.0×10^{-16}
10,000 s	7×10^{-14}	4×10^{-17}	5.0×10^{-16}	5.0×10^{-16}
12 h	1×10^{-14}	2×10^{-17}	4.0×10^{-16}	1.2×10^{-16}

[a] *Frequency and Timing Systems Requirements and Design,* DSMS 828-009 (internal document), Section 5.5, Jet Propulsion Laboratory, Pasadena, California, June 5, 2002.

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[2] The Allan deviation is the average of the neighboring frequency differences that have been averaged for a given length of time, T.

Table 2. PCG temperature stability.

Assembly	ps/deg C	ps/24 h
New PCG receiver	0.9	9
FODA	—	2
Total	—	11

of coaxial cables between the SPC and the antenna cone. With the new design, anomalous phase jumps due to movement of coaxial cables during antenna tracking are gone. Consistently high performance can now be realized.

F. PCG Receiver 20-MHz Phase Noise

The previous PCG design generated a 20-MHz carrier in the PCG transmitter, which was then sent to the PCG receiver along with the $5/N$ signal. Narrow-bandwidth crystal filters in the receiver removed the $5/N$ frequency components from the 20-MHz carrier. The 20-MHz signal then was output from the receiver to be used as the reference carrier for an L-band-to-S-band upconverter assembly.

The new PCG generates a 20-MHz carrier by filtering the square-wave output from the first frequency divider to produce a 10-MHz carrier with low harmonic content, then frequency multiplying by 2 to produce 20 MHz. A five-pole bandpass filter and a high reverse isolation amplifier at the 20-MHz output further attenuate the digital divider and frequency multiplier harmonics. Phase noise values of the previous PCG transmitter/receiver and the new FODA/PCG design are compared in Table 3(a). Twenty-MHz spurious output specifications and measured performance of the new design are given in Table 3(b).

G. PCG Receiver Packaging, Size, and Weight

Eliminating the cable phase stabilizer electronics reduces circuit complexity and component count, allowing a reduction in the PCG receiver size and weight. The original receiver measured $51 \times 61 \times 25$ cm and weighed about 41 kg. The new receiver measures $41 \times 41 \times 15$ cm and weighs 20 kg, which is

Table 3(a). 20-MHz phase noise performance.

Frequency offset, Hz	Original PCG, $\mathcal{L}$(fm)/Hz	New PCG, $\mathcal{L}$(fm)/Hz
1	−106	−113
10	−113	-124
100	−124	−131
>1000	−127	−132

Table 3(b). 20-MHz spurious outputs.

Spurious outputs	Specification	Measured value
Harmonic outputs	−50 dBc maximum	−50 dBc (40 MHz)
Subharmonics	−60 dBc maximum	−88 dBc (10 MHz)
Spurious (within 2 MHz of 20 MHz)	−85 dBc maximum	−110 dBc (19 MHz)

more readily handled by one person in the limited access space in the antenna feed cones. For temperature control, the electronic circuits are installed on a thermally stabilized cold plate, located inside a foam-insulated enclosure. Proportional temperature control electronics drive a thermoelectric heat pump to maintain the cold-plate temperature at 25 deg C. A fan attached to the thermoelectric heat pump dissipates heat generated by the electronics. The temperature controller reduces ambient temperature changes by a factor of 100. In contrast, the previous receiver operated with a similar thermal gain, but at a temperature of 60 deg C. Reliability of the new PCG should be improved by reducing the receiver operating temperature from 60 deg C to 25 deg C.

III. Comb Generator Redesign

Several factors were drivers for the development of a new comb generator. Comb-tone phase of existing generators drifts for the first few minutes after turning on comb tones, and changes in antenna attitude cause thermal gradients that degrade phase stability. Also, the generators' mean time between failures (MTBF) is reduced because of the 60 deg C internal set-point operating temperature, and maintainability has become a problem due to unavailability of discontinued components.

The goal of the new design was to replace existing comb generators with current-generation components operating at a lower set-point temperature and to improve the thermal stabilization of critical circuit elements that influence phase stability during warm-up and with changes in antenna elevation angle. Figure 3 is a block diagram of the complete comb generator assembly.

A. Microwave Assembly

The microwave assembly of the old comb generator contained critical components, including the step-recovery diode (SRD), that are no longer manufactured and have no comparable replacements. In addition, the diode and associated hand-formed circuit elements were difficult to assemble. The use of conductive epoxy for attachment precluded easy repair of damaged components. The new microwave assembly uses a beam-lead step-recovery diode attached to microwave transmission-line elements etched on a microstrip-type circuit board. This assembly is more easily constructed and repaired, and consistent performance is obtained.

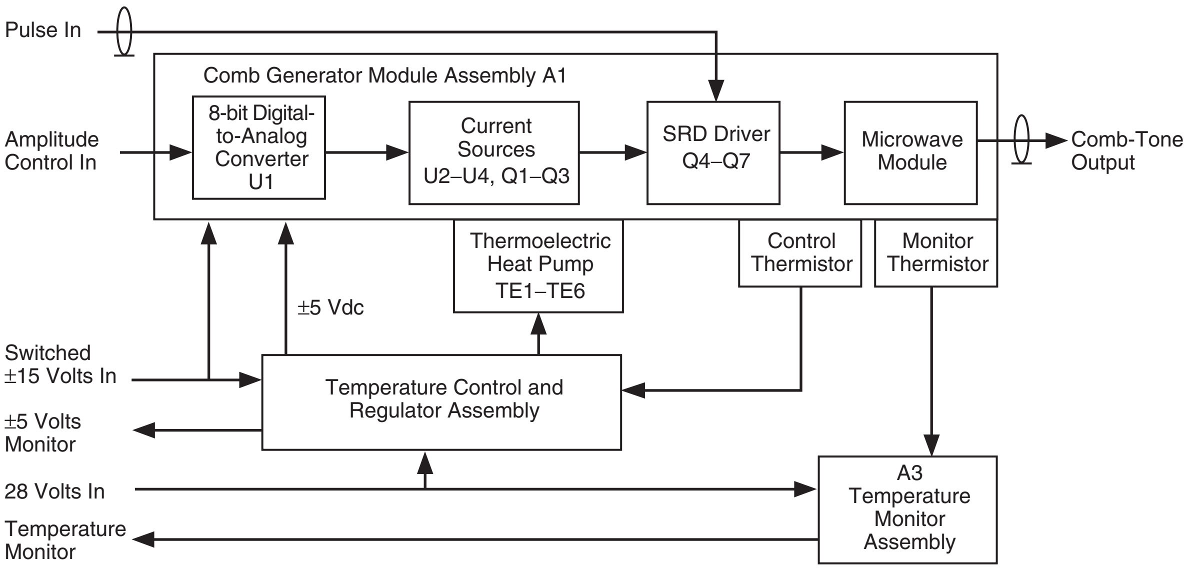


Fig. 3. Comb generator block diagram.

B. Warm-Up Stability

A warm-up period of several minutes is required after turning on comb tones to achieve acceptable comb-tone stability. This is caused in part by the step-recovery diode's temperature rise when drive power is applied to the diode. The new comb generator reduces these thermal effects by improvements made to heat sinking the diode. A low thermal-impedance path from the diode to the temperature-stabilized enclosure is established by grounding the diode cathode directly to the output connector and module enclosure. Stabilization time for the new design is about 9 minutes, and total drift is about 120 ps, in contrast to a 12-minute stabilization period and 250-ps total drift for the previous design.

C. Comb Generator Phase Versus Attitude Sensitivity

The PCG comb tones exhibit systematic phase sensitivity to the antenna's elevation angle. This is caused by thermal gradients created by convection heat flow in the comb generator that changes the temperature of critical components as the assembly's attitude is changed. Comb generator module sensitivity to attitude has been measured in the FSTL. The original comb generator design exhibits a 12-ps change for a 90-deg rotation around the most sensitive axis, and the new comb generator has a 2.5-ps change for the same axis rotation.

D. Module Temperature Control

Thermoelectric heat pumps are used to control the comb generator's operating temperature. In both the previous and the new designs, the temperature-critical electronic assemblies are mounted on a temperature-stabilized cold plate and installed in a foam-insulated enclosure. Thermoelectric elements control the heat flow between the cold plate and the comb generator enclosure covers. In the new comb generator design, the covers are machined with large "waffle-iron" heat-radiating surfaces for efficient convection heat flow in any attitude. To improve component MTBF, the new generator's electronics are operated at 40 deg C, as compared to 60 deg C for the previous design.

E. Comb Generator Interchangeability

Replacement comb generators are required to be completely interchangeable with the previous comb generators so that comb generators can be quickly and easily replaced in the antennas. The control and monitor electrical interface with the PCG receiver and the comb-tone output to the microwave users has been made identical to the previous design, with the exception discussed in Section III.F. The mechanical outline, including the base-plate mounting hole pattern, is identical to the previous comb generator design.

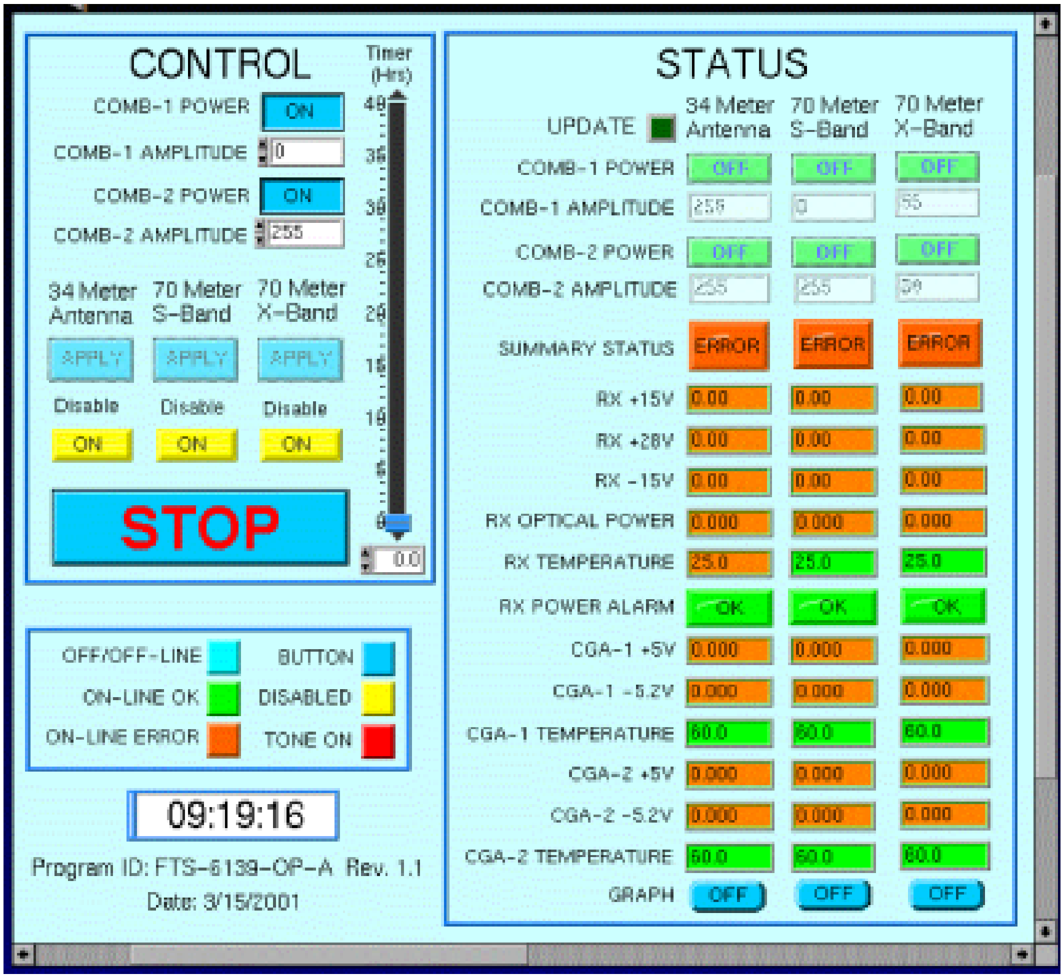
F. Multiband Operation

The previous CGA design was built in three different models for use at L-band, S-band, and X-band. The X-band model differed from the others in the bias current of the final stage, which was optimized for maximum output power at 8 GHz. The L-band unit included an internal 20-dB attenuator to reduce the excess amplitude of 2-GHz comb tones to a more suitable level.

In the new design, one model serves all three frequency bands. When used in an L-band application, an external 20-dB attenuator is fitted to reduce the comb-tone amplitude. The use of one part number where there were previously three reduces the number of spares required and simplifies maintenance.

IV. FTS Monitor and Control

The DSN FTS monitor and control system, which includes the PCG installation, recently has been upgraded and modernized with new computer hardware and operating software. The previous FTS monitor and control hardware had been designed around the currently unsupportable Intel 8614 single-board computer system. These obsolete controllers have been replaced with a commercial, off-the-shelf (COTS) rack-mount PC. New operating software using LABVIEW, developed with improved user displays, also has been incorporated in the redesign. The new operating software offers new monitoring capabilities, such as generating a log file that shows the date and the comb-tone on/off status and operating power level of each comb generator. There is also a graphical display of the optical power level to the PCG receiver and operating temperature of the comb generator as a function of time. Figure 4 shows the primary user display for controlling and monitoring the operation of up to 6 comb generators. Figure 5 shows the data-logging display, which gives an historical record of operator commands.



COMB-1 POWER ON
COMB-1 AMPLITUDE 0
COMB-2 POWER ON
COMB-2 AMPLITUDE 255
Timer 0.0

09:19:16

Program ID: FTS-6139-OP-A Rev. 1.1
Date: 3/15/2001

	34 Meter Antenna	70 Meter S-Band	70 Meter X-Band
COMB-1 POWER	OFF	OFF	OFF
COMB-1 AMPLITUDE	255	0	55
COMB-2 POWER	OFF	OFF	OFF
COMB-2 AMPLITUDE	255	255	59
SUMMARY STATUS	ERROR	ERROR	ERROR
RX +15V	0.00	0.00	0.00
RX +28V	0.00	0.00	0.00
RX -15V	0.00	0.00	0.00
RX OPTICAL POWER	0.000	0.000	0.000
RX TEMPERATURE	25.0	25.0	25.0
RX POWER ALARM	OK	OK	OK
CGA-1 +5V	0.000	0.000	0.000
CGA-1 -5.2V	0.000	0.000	0.000
CGA-1 TEMPERATURE	60.0	60.0	60.0
CGA-2 +5V	0.000	0.000	0.000
CGA-2 -5.2V	0.000	0.000	0.000
CGA-2 TEMPERATURE	60.0	60.0	60.0
GRAPH	OFF	OFF	OFF

Fig. 4. PCG control software front panel.

Date	Time	Antenna	Comb-1 Pwr	Comb-1 Amp	Comb-2 Pwr	Comb-2 Amp
6/7/00	5:08 PM	70M S-Band	Off	0	Off	0
6/7/00	5:08 PM	70M S-Band	Off	0	On	65
6/7/00	5:08 PM	70M X-Band	On	65	Off	6
6/7/00	5:09 PM	34M Ant. Is Disabled				
6/7/00	5:12 PM	70M X-Band	Off	0	On	6

Fig. 5. Command log file.

The Intel 8614 in the original PCG central controller has been replaced with a COTS computer, and the Intel 8614-based PCG remote controllers in the antennas have been replaced with Advantech ADAM 5000 data acquisition modules. These modules accept a wide range of analog and digital input/output (I/O) interface plug-ins and also contain an RS-485 data communications port. The data acquisition module's power requirements are much lower than those of the Intel 8614 and associated support board assemblies it replaces, so that smaller power supplies could be used in the new PCG remote controller.

The above changes have allowed the PCG remote controller to be smaller in size and weight than the original controller. The original 51 × 51 × 25 cm PCG remote-controller enclosure weighed 43 kg, while the new controller is 41 × 41 × 15 cm in size and weighs 23 kg.

A. Communications Interface

The previous PCG central control computer communicated with the remote controller via RS-232 over full-duplex line drivers, using a three twisted-conductor pair cable. Two conductor pairs were used for uplink commands and downlink data monitoring, and the third pair served to reset the Intel 8614 computer. The existing PCG communication cables to the antennas have been reused in the retrofit. The control and monitor functions to the PCG now are supported by RS-485, which handles higher data rates over longer distances than does RS-232 and requires only a single twisted-conductor pair for bi-directional data. This permits the remaining conductor pairs to be used to support an added manual override function in the PCG. An RS-485/RS-232 data converter provides the interface between the COTS computer's RS-232 port and the ADAM 5000 data acquisition module's RS-485 port.

B. PCG Manual Override Function

The PCG system redesign includes a manual override assembly, located in the SPC, to provide an alternate path to shut off comb tones in case of a PCG computer failure. The manual override bypasses the control computer and the RS-485 control link to override computer control and shut off comb tones. The override assembly utilizes one twisted-conductor pair to send a comb-tone inhibit command to the remote controller assembly and another twisted-conductor pair to send back a remote controller verification that comb tones are commanded to be off. In operation, activating a manual override toggle switch sends a dc control current through the communication cable to an optocoupler integrated circuit (IC) in the remote controller. The optocoupler output then drives a logic-circuit gating switch that shuts off operating power to the comb generator. Feedback to the SPC is provided with a second optocoupler that switches current to a comb-tone-status light emitting diode (LED) in the manual override assembly to verify that the manual override command has shut off comb tones.

C. Network Monitor and Control Interface for the Central Control

Operational control of the PCG from locations remote to the PCG controller is supported through a local area network (LAN). A SUN Ultra 5 computer provides the interface between the local PCG controller and network monitor and control (NMC).

V. Ka-Band PCG Developments

The existing PCG system supports the 34-m HEF and 70-m antennas and generates comb tones up through X-band. Comb-tone power is insufficient for operation at Ka-band with the existing step-recovery diode design. Recently we have been developing a Ka-band comb generator to answer the need for a highly stable phase-calibration source for use at X-, K-, and Ka-bands.

The Ka-band CGA generates stable comb tones spaced 5 MHz apart, spanning the frequency range from 3 GHz to 40 GHz. This is accomplished by switching a low-inductance tunnel diode through its negative-resistance region at a 5-MHz rate to generate 14-ps positive-going transitions synchronized to a stable 100-MHz reference signal. To prevent periodic nulls in the spectrum, the negative-going transition is kept relatively slow by opening a PIN diode gating switch to block the tunnel diode's return transition.

Comb-tone spacing can be reduced from 5 MHz to 1 MHz when desired. This is accomplished by using the gating switch to block four of the five transitions in each 1-μs period, effectively reducing the output periodicity to 1 MHz. Maintaining a constant 5-MHz drive into the tunnel diode, whether operating in the 1-MHz or the 5-MHz line-spacing mode, keeps the power dissipation in the diode constant. This helps to avoid temperature-related drift when changing the tone-spacing mode.

The housings, thermal stabilization, and power-supply circuitry are modifications of existing DSN S-band and X-band comb generators. New RF circuitry was developed based on a 22-GHz comb generator design.[3]

A block diagram of the comb generator assembly is shown in Fig. 6. The major elements of the comb generator assembly are the tunnel diode driver assembly A1, the harmonic generator module A3, the gating switch A4, and a temperature control system consisting of the temperature control and regulator assembly A2, thermoelectric elements TE1 through TE6, and monitor and control thermistors.

A. Tunnel Diode Driver Assembly

The tunnel diode driver electronics use conventional ECL digital gates and a modular RF amplifier to develop a low-jitter diode-drive waveform. A high-speed input comparator is used so that the output will be relatively insensitive to changes in amplitude of the input reference signal. The use of generic COTS components offers the advantages of comparatively low cost and a likelihood of continued availability for years into the future. The circuit board was designed to fit the existing PCG comb generator module housing so that packaging compatibility could be maintained.

B. Harmonic Generator Module

The harmonic generator module developed here uses the same low-inductance tunnel diode that was used in the Haystack design. In all other respects, this is a completely new design. The diode is mounted in a solid 1.905-cm brass block mounted directly on the cold plate for best possible thermal stability. Lossy elements were removed to increase the output power at the higher frequency range. To eliminate unnecessary interconnection losses, a male K-type output connector is oriented so that it can mate directly to the gating switch without cables or adapters.

C. Gating Switch

The pulse gating switch is a COTS part. A suitable switch specified for both X-band and Ka-band use could not be identified. Several switches were tested, including two rated for 2- to 18-GHz service and one rated for 20- to 40-GHz service. We found that the 20- to 40-GHz switch (General Microwave F9014) had very good insertion loss and acceptable isolation at X-band. This switch was used in the final product.

D. Performance Goals

The performance goals for the Ka-band comb generator are outlined in Table 4. These goals are based in part on the capabilities of the Haystack comb generator. The output-level goal was increased above the performance level of the Haystack comb generator to a level more acceptable to DSN users.

E. Measured Performance

Measurements of the Ka-band generator show a short-term stability ($\tau = 1$ s) and long-term stability ($10,000$ s $< \tau < 100,000$ s) well within the design goals. Output power over the frequency range from

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[3] "Haystack Observatory VLBA Acquisition Memorandum 284," Massachusetts Institute of Technology, Cambridge, Massachusetts, October 7, 1991.

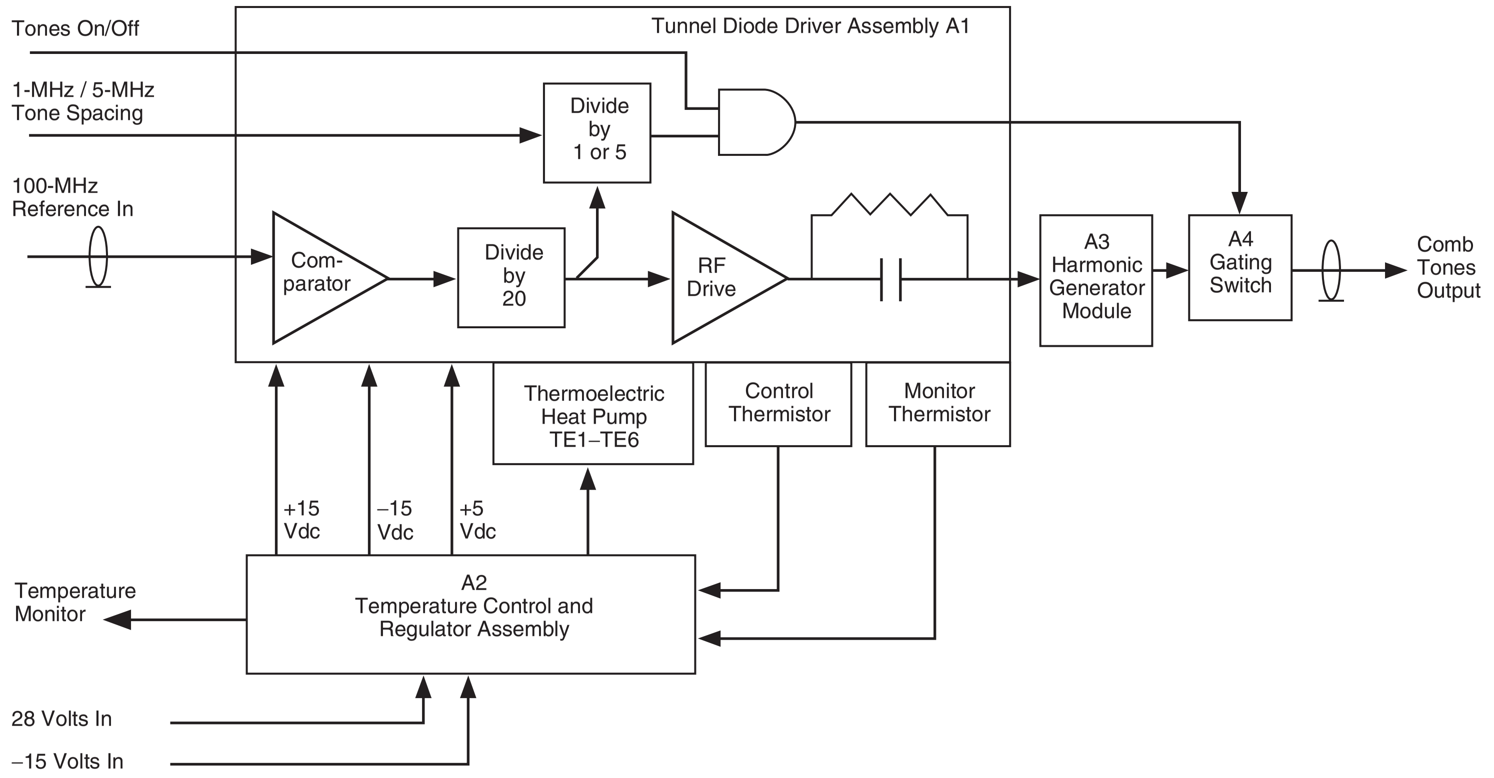

Fig. 6. Functional diagram of the Ka-band comb generator.

32 GHz to 33 GHz exceeds the goal by at least 1 dB at all frequencies. Although the temperature stability was not explicitly measured in a controlled environment, the base-plate temperature varied by approximately 0.01 deg C over normal fluctuations in laboratory temperature. Amplitude flatness is close to the design goal, although there are variations of ±3 dB between 31 GHz and 34 GHz.

Measured performance of the Ka-band comb generator compared to the design goals is summarized in Table 5. Note that the stability data were measured from a 12-day data run (October 20 through 31, 2002).

Table 4. Ka-band comb generator goals.

Parameter	Design goal	Conditions
Stability σ (rms noise)	1×10^{-13}	$\tau = 1$ s
	1×10^{-14}	10 s
	1×10^{-15}	100 s
	5×10^{-16}	1000 to 10^5 s
Output level	> -110 dBm per line	1-MHz comb spacing at 33 GHz
	> -96 dBm per line	5-MHz comb spacing at 33 GHz
Amplitude flatness	±2 dB	10% bandwidth, stable with time
Temperature	±0.1 deg C stability	—
	±0.01 deg C monitor precision	
Comb spacing	1 MHz/5 MHz selectable	—

Table 5. Ka-band comb generator measured performance versus goals.

Parameter	Design goal	Measured performance
Stability σ (rms noise)		
$\tau = 1$ s	1×10^{-13}	5×10^{-14}
$\tau = 10$ s	1×10^{-14}	8×10^{-15}
$\tau = 100$ s	1×10^{-15}	1×10^{-15}
$\tau = 1000$ s	8×10^{-16}	1.2×10^{-16}
$10,000 \text{ s} < \tau < 100,000 \text{ s}$	5×10^{-16}	$< 5 \times 10^{-17}$
Output level at 33 GHz	> -110 dBm at 1-MHz spacing	-106.5 dBm
	> -96 dBm at 5-MHz spacing	-92.5 dBm
Amplitude flatness	±2 dB over 10% bandwidth	±1.7 dB, 32–33 GHz
Temperature	±0.1 deg C stability	Not measured
	±0.01 deg C monitor precision	Better than 0.01 deg
Comb Spacing	1 MHz/5 MHz selectable	1 MHz/5 MHz selectable

VI. Summary

The Phase Calibration Generator system modifications under three tasks have been completed and implemented at the Goldstone, Canberra, and Madrid antenna sites. The previous design PCG transmitters, receivers, and monitor and control equipment have been replaced with the new assemblies at all three sites, and the system is fully operational. The results of replacing the stabilized coax cable distribution to the antennas with a fiber-optic link have produced a more stable PCG system with better reliability and long-term sustainability. The new monitor and control equipment provides an improved user-friendly graphical interface. With the subsequent installation of the new S- and X-band comb generator assemblies, improvements will be seen in the phase stability of generated comb tones. A capability at Ka-band also has been developed and currently is being evaluated at DSS 13 and DSS 25 for possible permanent installation in all beam-waveguide antennas supporting Ka-band.

Acknowledgments

Contributions to the comb generator diode design were made by Richard Sydnor. Jorge Gonzales and Steven Cole contributed to development and implementation of the monitor and control software. Bill Diener supported test measurements and implementation, and Robert Tjoelker supervised the PCG development activity.

References

[1] E. H. Sigman, "Phase Calibration Generator," *The Telecommunications and Data Acquisition Progress Report 42-92, October–December 1987,* Jet Propulsion Laboratory, Pasadena, California, pp. 89–104, February 15, 1988. http://tmo.jpl.nasa.gov/tmo/progress_report/42-92/92K.PDF

[2] M. Calhoun, R. Sydnor, and W. Diener, "A Stabilized 100-Megahertz and 1-Gigahertz Reference Frequency Distribution for Cassini Radio Science," *The Interplanetary Network Progress Report 42-148, October–December 2001,* Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, February 15, 2002. http://ipnpr.jpl.nasa.gov/tmo/progress_report/42-148/148L.pdf