303
Media Calibration

Effective November 30, 2000

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Change Log

Rev	Issue Date	Paragraphs Affected	Change Summary
Initial	1/15/2001	All	All

Note to Readers

There are two sets of document histories in the 810-005 document, and these histories are reflected in the header at the top of the page. First, the entire document is periodically released as a revision when major changes affect a majority of the modules. For example, this module is part of 810-005, Revision E. Second, the individual modules also change, starting as an initial issue that has no revision letter. When a module is changed, a change letter is appended to the module number on the second line of the header and a summary of the changes is entered in the module's change log.

This module supersedes module MED-10 in 810-005, Rev. D.

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1 Introduction

1.1 Purpose

This module describes the capabilities of the equipment used by the Deep Space Network (DSN) to obtain data from which correction factors can be determined for media effects that limit navigational accuracy. The data are forwarded from each Deep Space Communications Complex (DSCC) to the Network Operations Control Center (NOCC) where they are processed and archived.

1.2 Scope

The functional performance and data characteristics of the Deep Space Station (DSS) Media Calibration Subsystem (DMD) are described. The DMD is responsible for obtaining Global Positioning System (GPS) and ground weather data for the NOCC Tracking Subsystem (NTK) and Navigation Subsystem (NAV).

2 General Information

The DMD provides two types of data:

- GPS data consisting of L-band carrier phase and group delay of GPS satellite signals, in addition to ephemeris and almanac data for the GPS satellites.
- Weather data, consisting of temperature, barometric pressure, relative humidity, precipitation rate, total precipitation, wind speed, and wind direction.

2.1 Global Positioning System Data

The Global Positioning System GPS Operational Constellation consists of at least 24 satellites that orbit the earth with a 12 sidereal-hour period. There are often more than 24 as new satellites are launched to replace the older ones. The orbit is such that the satellites repeat the same track and configuration over any point approximately each 24 hours (4 minutes earlier each day). There are six orbital planes (with nominally four satellites in each), equally spaced (60 degrees apart), and inclined at about fifty-five degrees with respect to the equatorial plane. This constellation provides the user with between five and eight satellites visible from any point on the Earth. A minimum of four satellite signals must be received to estimate the four unknowns of position in three dimensions and time.

The DSCC GPS Receiver/Processor Assembly (GRA), which is part of the DMD, makes use of the GPS data to provide carrier phase and group delay for the GPS signals.

These data may then be used to characterize the Earth's ionosphere and troposphere along the line of sight from a given satellite to the DSCC.

2.1.1 GPS Signal Structure

The GPS satellite signals are complex in structure, with each L-band frequency being binary biphase-modulated with two pseudo-random noise codes, the Coarse Acquisition (C/A) and Precision (P) codes, and a navigation message.

The complete signal broadcast by a satellite may be represented as:

$$\begin{aligned} s(t) &= \left[A_C C(t) D(t) \sin(2\pi f_1 t) + A_P P(t) D(t) \cos(2\pi f_1 t) \right] \\ &+ \left[A_P P(t) D(t) \cos(2\pi f_2 t) \right] \end{aligned} \qquad (1)$$

where the first square bracket is the L1 signal at frequency f_1, and the second square bracket is the L2 signal at frequency f_2. The terms appearing above have the following definitions:

A_c and A_p	=	the constant amplitudes of the Coarse Acquisition (C/A) and Precision (P) codes
$C(t)$	=	the C/A-code modulation (= ±1)
$P(t)$	=	the P-code modulation (= ±1)
$D(t)$	=	the navigation message modulation (= ±1)
f_1	=	$154 f_0$ = 1575.42 MHz
f_2	=	$120 f_0$ = 1227.60 MHz.

The $C(t)$, $P(t)$, and $D(t)$ modulations are all synchronized to the fundamental clock frequency, f_0, such that they have the following frequencies:

f_0	=	10.23 MHz (Note 1)
$C(t)$	=	$f_0/10$ = 1.023 Mbps
$P(t)$	=	f_0 = 10.23 Mbps
$D(t)$	=	$f_0/204600$ = 50 bps.

Note (1): To partially compensate for general and special relativistic effects on the satellite clock (gravitational red shift and time dilation), the actual value of f_0 is 10.23 MHz – 4.55 mHz.

The complete C/A code contains 1023 cycles (or “chips”), has a total period of 1.0 ms, and is different for each satellite.

The P-code is more complicated and consists of two code segments (X1 and X2), which differ in length by 37 chips. These are added modulo 2 and timed in such a way that exactly 403,200 X1 code segments correspond to exactly one week, the period of the P-code. (The P-code actually has a total period of 37 weeks, with each satellite using only a single one-week segment of the total.) The duration of the X1 code segment is thus 1.5 seconds and contains exactly 15,345,000 chips at 10.23 Mbps. As is the case with the C/A code, the P-code is different for each satellite.

The navigation message also has a complex structure, with a total period of 12.5 minutes (one master frame) and is divided into frames, subframes, words, and bits. The first three subframes (lasting 6 seconds each) repeat every 30 seconds, while the last two subframes are different in each of 25 consecutive frames (pages), after which the entire message repeats.

2.1.2 GPS Receiver/Processor Assembly (GRA)

The GRA provides the following functional capabilities:

1) Automatically acquire and track the L1 and L2 GPS signals for specified satellites, usually all of those transiting

2) Extract and store GPS almanac and ephemeris data from the navigation message

3) Measure the differential P-code group delay between the L1 and L2 GPS signals

4) Measure the differential carrier phase between the L1 and L2 GPS signals.

The almanac data, contained in subframe 5 of the GPS navigation message, consist of approximate ephemeris data for all satellites and are used by the GRA for signal acquisition.

The ephemeris data for a specified satellite (subframes 2 and 3) provide a complete description of the orbit. When the data are combined with measured signal delays, the local position and atmospheric path that the signal has traversed can be determined.

Since the Department of Defense, which controls the GPS signal content, may elect at any time to encrypt the P-code (resulting in what is termed an anti-spoofing (A/S) mode of operation in which the encrypted, or Y-code, is unavailable to civilian users of the system) the GRA operates in two distinct modes to determine the differential group and phase delays of the satellite signals.

In the normal, coded mode, the known P-code is used to determine the carrier phase and group delay of each signal (L1 and L2) separately. The computed differences may then be used to characterize the propagation medium over the path of the signals. This provides the most precise determination due to the length of the P-code.

In the codeless mode, advantage is taken of the fact that the same unknown Y-code is transmitted on both the L1 and L2 channels with an unknown delay. The product of the two signals is formed and the differential group and phase delays are determined by cross-correlation. This method results in a somewhat reduced accuracy.

The GRA simultaneously receives and processes the signals from up to eight satellites selected to provide the longest unbroken tracks at any given time. In addition to the data described above, the system provides various status and health data on the signals being processed. Tables 1 through 4 list the GPS parameters measured, their ranges and accuracy, and the sample intervals provided.

2.1.3 Relation of Phase and Group Delay to Atmospheric Properties

The Earth's atmosphere may conveniently be divided into three regions according to the effects produced on the propagation of electromagnetic radiation:

(1) troposphere, stratosphere, and lower part of mesophere — region between the Earth's surface and about 60 km altitude consisting of neutral (unionized) gases

(2) ionosphere — region from about 60 km to between ~500 and 2000 km, depending on the extent of extraterrestrial ionizing radiation, consisting of partially ionized gases

(3) plasmasphere — ionized region extending from ~2000 km to about four Earth radii (26,000 km), where it blends into the solar wind of the Earth's magnetosphere

At the frequencies in which the DSN operates, tropospheric dispersion may be neglected and the refractivity represented by a dry and a wet component whose approximate total zenith phase and group delays are:

$$\Delta t_D \sim 7.6 \text{ ns},$$

$$\Delta t_W \sim 0.3 \text{ ns} - 1.4 \text{ ns}.$$

The first varies linearly with pressure at the Earth's surface; the second increases as the tropospheric moisture content increases.

Since tropospheric dispersion is negligible at L-band, these delays cancel when differential delays are computed or measured between f_1 and f_2.

In the ionized portion of the Earth's atmosphere, the medium displays anomalous dispersion at microwave frequencies. This causes the phase velocity to exceed, and the group velocity to be less than, the speed of light in a vacuum, c. Specifically, to a good approximation at L-band:

$$\frac{v}{c} = 1 + \frac{x}{2} \tag{2}$$

$$\frac{v_g}{c} = 1 - \frac{x}{2}. \tag{3}$$

Table 1. GPS Metric Data, Code Mode

Parameter	Units (1)	Approximate Decimal Range
Delay Calibration	2^{-7} ns	±255 ns
Output Interval	sec	1–300 s
L1-C/A Doppler Phase	2^{-16} cycles	±2.1 x 10^{9} cycles
L1-C/A Doppler Phase Noise	2^{-16} cycles	0–1 cycle
L1-P Doppler Phase	2^{-16} cycles	±2.1 x 10^{9} cycles
L1-P Doppler Phase Noise	2^{-16} cycles	0–1 cycle
L2-P Doppler Phase	2^{-16} cycles	±2.1 x 10^{9} cycles
L2-P Doppler Phase Noise	2^{-16} cycles	0–1 cycle
L1-C/A Group Delay	2^{-11} ns	±0.27 sec
L1-C/A Group Delay Noise	2^{-11} ns	0–32 ns
L1-P Group Delay	2^{-11} ns	±0.27 sec
L1-P Group Delay Noise	2^{-11} ns	0–32 ns
L2-P Group Delay	2^{-11} ns	±0.27 sec
L2-P Group Delay Noise	2^{-11} ns	0–32 ns
C/A SNR (1 sec)	2^{-4} volt/volt	0–4096
P1 SNR (1 sec)	2^{-4} volt/volt	0–4096
P2 SNR (1 sec)	2^{-4} volt/volt	0–4096
Receiver Clock Error	2^{-32} sec	±0.5 sec
L1-C/A Residual Phase	2^{-10} cycles	0–0.25 cycle

Note (1): Least significant bit transmitted by the GRA.

Table 2. GPS Metric Data, Non-Code Mode

Parameter	Units (1)	Approximate Decimal Range
Delay Calibration	2^{-7} ns	±255 ns
Output Interval	sec	1–300 sec
L1-C/A Doppler Phase	2^{-16} cycles	±2.1 x 10^9 cycles
L1-C/A Doppler Phase Noise	2^{-16} cycles	0–1 cycle
L1-L2 Doppler Phase	2^{-16} cycles	±2.1 x 10^9 cycles
L1-L2 Doppler Phase Noise	2^{-16} cycles	0–1 cycle
L1-C/A Group Delay	2^{-11} ns	±2.1 x 10^9 cycles
L1-C/A Group Delay Noise	2^{-11} ns	0–32 ns
P2-P1 Group Delay	2^{-9} ns	±1.1 s
P2-P1 Group Delay Noise	2^{-9} ns	0–128 ns
C/A SNR (1 s)	2^{-4} volt/volt	0–4096
P2-P1 SNR (1 s)	2^{-6} volt/volt	0–1024
Receiver Clock Error	2^{-32} s	±0.5 s
L1-C/A Residual Phase	2^{-10} cycles	0–0.25 cycle

Note (1): Least significant bit transmitted by the GRA.

Table 3. GPS Ephemeris Data

Parameter	Units (1)	Approximate Decimal Range
Sample Year (Modulo 100)	Year	0–99 yrs
Sample Day-of-Year	Days	0–366 days
Sample Hours	Hours	0–24 hrs
Sample Minutes	Minutes	0–60 minutes
Sample Seconds	seconds	0–60 s
GPS Week Number	N/A	
Satellite Number	N/A	
L2 Code Type/L2 Code On	N/A	
User Range Accuracy	N/A	
Issue of Data (Clock)	N/A	
Clock Data Reference Time (t_{oc})	2^4 s	0–6.0 x 10^5 s
Time Correction Coefficient (a_{f2})	2^{-55} s/s^2	±3.6 x 10^{-15} s/s^2
Time Correction Coefficient (a_{f1})	2^{-43}s/s	±3.7 x 10^{-9} s/s
Time Correction Coefficient (a_{f0})	2^{-31}s	±3.9 ms
Issue of Data (Ephemeris)	N/A	
Amplitude of Sine Harmonic Correction to the Orbit Radius (C_{rs})	2^{-5}m	±1.0 km
Mean Motion Difference From Computed Values (Delta N)	2^{-43} semicir/s	±1.2 x 10^{-5} mrad/s
Mean Anomaly at Reference Time (M_o)	2^{-31} semicir	±180 deg
Amplitude of Cosine Harmonic Correction to the Argument of Latitude (C_{uc})	2^{-29} radians	±6.1 x 10^{-2} mrad
Eccentricity (e)	2^{-33}	0–0.03
Amplitude of Sine Harmonic Correction to the Argument of Latitude (C_{us})	2^{-29} radians	±6.1 x 10^{-2} mrad
Square Root of Semi-Major Axis ($A^{1/2}$)	2^{-19} $m^{1/2}$	0–8200 $m^{1/2}$
Ephemeris Reference Time (t_{0E})	2^4 s	0–6.0 x 10^5 s

Note (1): Least significant bit transmitted by the GRA.

Table 3. GPS Ephemeris Data (Continued)

Parameter	Units (1)	Approximate Decimal Range
Amplitude of Cosine Harmonic Correction to Inclination (C_{ic})	2^{-29} radians	±6.1 x 10^{-2} mrad
Right Ascension at Reference Time ($Omega_0$)	2^{-31} semicir	±180 deg
Amplitude of Sine Harmonic Correction to Inclination (C_{is})	2^{-29} radians	±6.1 x 10^{-2} mrad
Inclination at Reference Time (i_0)	2^{-31} semicir	±180 deg
Amplitude of Cosine Harmonic Correction to the Orbit Radius (C_{rc})	2^{-5} m	±1.0 km
Argument of Perigee (Omega)	2^{-31} semicir	±180 deg
Right Ascension Rate (Omega DOT)	2^{-43} semicir/s	±3.0 x 10^{-3} mrad/s
Issue of Data (Ephemeris)	N/A	
Inclination Angle Rate (IDOT)	2^{-43} semicir/s	±1.2 x 10^{-5} mrad/s

Note (1): Least significant bit transmitted by the GRA.

Table 4. GPS Almanac Data

Parameter	Units (1)	Approximate Decimal Range
Sample Year (Modulo 100)	Year	0–99 yr.
Sample Day-of-Year	Days	0–366 days
Sample Hours	Hours	0–24 hrs
Sample Minutes	Minutes	0–60 minutes
Sample Seconds	s	0–60 s
GPS Week Number	N/A	
Satellite Number	N/A	
Data and Space Vehicle ID	N/A	
Eccentricity (e)	2^{-21}	0–0.03
Reference Time (t_{OA})	2^{+12} s	0–6.0 x 10^5 s
Delta Inclination (δ_i)	2^{-19} semicir	±11 deg
Right Ascension Rate (Omega DOT)	2^{-38} semicir/sec	±3.7 x 10^{-4} mrad/s
Square Root of Semi-Major Axis ($A^{1/2}$)	2^{-11} $m^{1/2}$	0–8200 $m^{1/2}$
Right Ascension at Reference Time ($Omega_0$)	2^{-23} semicir	±180 deg
Argument of Perigee (Omega)	2^{-23} semicir	±180 deg
Mean Anomaly (M_0)	2^{-23} semicir	±180 deg
Correction Term (a_{f0})	2^{-20} s	±0.03 deg
Correction Term (a_{f1})	2^{-38} s	±1.2 x 10^{-7} s/s

Note (1): Least significant bit transmitted by the GRA.

where:

v	=	phase velocity = ω/k
v_g	=	group velocity = $d\omega/dk$
k	=	*wave vector* ($\lambda/2\pi$)
x	=	$(f_p/f)^2 << 1$
f	=	frequency of interest
f_p	=	plasma frequency = $(Ne^2/m\varepsilon_0)^{1/2}/2\pi$
N	=	electron density (electrons/m^3)
e	=	electronic charge
m	=	electronic mass
ε_o	=	permittivity of free space.

In terms of the above, the phase (Δt) and group (Δt_g) delays at frequency f may be written:

$$\Delta t_g = -\Delta t = \left(\frac{1.345\times10^{-7}}{f^2}\right)\times \text{TEC}, \text{ s} \tag{4}$$

where $\text{TEC} = \int N\, dl$ is the total electron content (TEC) along the propagation path (electrons/m^2).

The corresponding differential delays are given by:

$$\delta t_g = -\delta t = 1.345\times10^{-7}\left(\frac{1}{f_2^{\,2}} - \frac{1}{f_1^{\,2}}\right)\times \text{TEC}, \text{ s} \tag{5}$$

where $\delta t_g = \Delta t_g(f_2) - \Delta t_g(f_1)$.

Since the TEC along the satellite line of sight may vary between ~10^{16} and 4×10^{18}m^{-2}, the group and phase delays typically range between ~0.5 ns and 90 ns, and the differential delays between ~0.35 ns and 35 ns, although larger values are often observed during periods of high solar activity.

2.2 Ground Weather Data

The ground weather data are generated by instruments located near the Signal Processing Centers (SPC) at each DSCC. In particular, the wind speed and direction sensors are adjacent to the 34m HEF antennas.

All data are asampled once per second by the instruments, and the resulting data stream is transmitted to the Subsystem Control and Monitor Assembly (SCA) of the DMD. Here the data are packaged and transmitted to the NTK and NAV at regular intervals and stored for up to five days for later recall. Table 5 lists the weather parameters measured, their ranges and accuracy, and the interval of transmission to the NTK, NAV, and DMC.

Table 5 Weather Data Transmitted from the SCA

Parameter	Range	Accuracy	Transmission Interval	
			Default	Range
Temperature	–50 to +50°C	±0.1°C	60 s	10 s to 1 hr
Barometric Pressure	600 to 1100 mbar	1.0 mb	60 s	10 s to 1 hr
Relative Humidity(1)	0 to 100%	2%	60 s	10 s to 1 hr
Dew Point Temperature	–40 to 50°C	±0.5°C	60 s	10 s to 1 hr
Precipitation Rate	0 to 250 mm/hr	5%	60 s	10 s to 1 hr
Total Precipitation	>0 mm	5%	60 s	10 s to 1 hr
Wind Speed(2)	0 to 100 km/hr	±0.6 km/hr	60 s	10 s to 1 hr
Wind Direction(2)	0 to 360 deg	±3.6 deg	60 s	10 s to 1 hr

See notes on following page.

(1) Relative humidity is calculated from the measured weather parameters according to the formula:

$$RH = 10^{x} \text{ percent,} \qquad (6)$$

where:

x = $2 + 2300\,(1/T - 1/T_d)$,

T = temperature in Kelvins

T_d = dew point temperature in Kelvins.

(2) Wind data are averaged over 10-s intervals by converting the polar velocity vector:

$$\mathbf{v_w} = S_w \hat{\mathbf{e}}(\theta) \qquad (7)$$

where

S_w = wind speed,

$\hat{\mathbf{e}}(\theta)$ = wind direction unit vector,

to rectangular form,

$$\mathbf{v_w} = S_x \hat{\mathbf{i}}(\theta) + S_y \hat{\mathbf{j}}(\theta) \qquad (8)$$

and computing $\langle S_W \rangle$ and $\langle \theta \rangle$, where

$\langle S_w \rangle^2$ = $\langle S_x \rangle^2 + \langle S_y \rangle^2$,

$\langle \theta \rangle$ = $\tan^{-1}(\langle S_x \rangle / \langle S_y \rangle)$,

S_x = $S_w \cos\theta$,

S_y = $S_w \sin\theta$.