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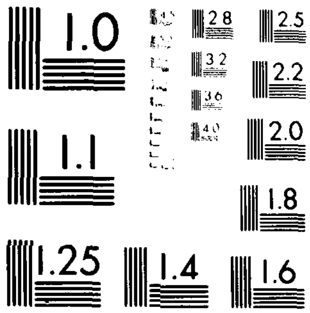

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GPS USER EQUIPMENT PERFORMANCE EVALUATION

ITT Defense Communications Division
492 River Road, Nutley, NJ 07110

1 November 1979

TECHNICAL REPORT AFAL-TR-79-1143
Final Report for Period 25 June 76 to 1 April 79

Approved for public release; distribution unlimited.

Prepared for
AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433

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[illegible] technical report has been reviewed and is approved for publication.

[illegible] G. BENNETT, Capt, USAF
Group Leader, AFAL/[illegible]-4

FOR THE COMMANDER

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(19) REPORT DOCUMENTATION PAGE

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(18)

1. REPORT NUMBER: AFAL-TR-79-1143	2. GOVT ACCESSION NO.: AD-A084 842
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): (6) GPS USER EQUIPMENT PERFORMANCE EVALUATION	5. TYPE OF REPORT & PERIOD COVERED: FINAL for Period 25 Jun 76 to 1 April 79
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s): (15) F33615-76-C-1164
9. PERFORMING ORGANIZATION NAME AND ADDRESS: ITT DEFENSE COMMUNICATIONS DIVISION, ~~492 RIVER ROAD~~, NUTLEY, NJ 07110	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) 666A-06-12
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE AVIONICS LAB. (AFAL/RWA) WRIGHT-PATTERSON AFB, OHIO 45433	12. REPORT DATE: (11) Nov [redacted] 79
	13. NUMBER OF PAGES: 82
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

Final ... 25 Jun 76-1 Apr 79.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Global Positioning System
Global Positioning
Positioning, Global
Navigation Satellite
Satellite, Navigation
Worldwide Radio Navigation
Inertial Measurement
Lever Arm Effect

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The significance of this research and development project to the Air Force is that it provides for a hot-bench simulation facility to validate GPS (Global Positioning System) User Equipment performance under various flight dynamics and environments and provides a data base for comparison with flight test results. This would also enable systematic evaluation of the performance of the GPS User Equipment in a simulated hostile electromagnetic environment.

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Abstract (Continued)

This simulation includes the generation of: GPS RF signals, jammer RF signals, white Gaussian noise, GPS navigation data, on-board sensor signals (i.e. IMU and altimeter), path loss and antenna pattern. As part of the simulation, error models for various functions and phenomena including IMU, altimeter, ionospheric and tropospheric delay, gravity anomaly, ephemeris, and clock error are included. The simulator precisely couples the changes in RF signals to the physical dynamics of the system (i.e., user, satellite, and jammer motions), including lever arm effects.

The GPSE is currently designed to simulate five GPS satellite RF signs and five jammer RF signals. The entire simulation is under computer control in real time, utilizing as the input pre-computed data defining the user flight profile, jammer, and satellite motion.

This report discusses in detail studies made, the techniques employed, and pertinent observations made in the performance of the contract. The report ends with a discussion of the results and a few suggestions for the future projects.

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SECTION I

INTRODUCTION

The Global Positioning System (GPS) is a satellite navigation system currently under development by Headquarters, Space and Missile Systems Organization (SAMSO), Air Force Systems Command, for the Department of Defense. The GPS will ultimately provide a highly accurate worldwide radio navigation capability to suitably equipped military, as well as civilian user systems. The User System Segment consists of User Equipment (UE) which processes the navigation signals from each of four GPS satellites to determine user navigation parameters such as latitude, longitude, altitude, velocity, and system time. User Equipment is composed of a small antenna, an L-band receiver which measures pseudo-ranges and pseudo-range rates to the satellites, a data processor which converts the receiver outputs into the desired navigation parameters, a control/display, and power supplies. Depending upon the application and performance requirements, the GPS ranging data may be supplemented with other navigation information from auxiliary sensors, such as an altimeter and an inertial measurement unit (IMU).

The GPS Evaluator (Figure 1) is designed to provide a simulated test bed to test the General Development Model (GDM) of the User System Segment developed by the Air Force Avionics Laboratory (AFAL). The GPSE is also capable of testing other User Systems with minor changes. The GPSE provides simulated GPS navigation signals, jamming and noise signals and auxiliary sensor data to the GDM. The GPSE will serve to validate the GDM, provide a data base for comparison with flight test results and systematically evaluate the performance of the GDM. In addition, the system will collect the user instrumentation data in a manner suitable for analysis and perform statistical analysis on the user data.

Initially as proposed, the GPSE was to simulate four GPS satellites, five jammers (four CW and one PN modulated) with individual J/S capability of up to 67 dB and one L Band Gaussian white noise generator. The design was later upgraded to generate a fifth satellite to facilitate satellite switchover and enable truthful simulation of extended flight duration (up to 10 hours). The project was initiated in mid '76 and the final system was delivered to the Air Force Avionics Laboratories, Wright Patterson AFB in April 1979.

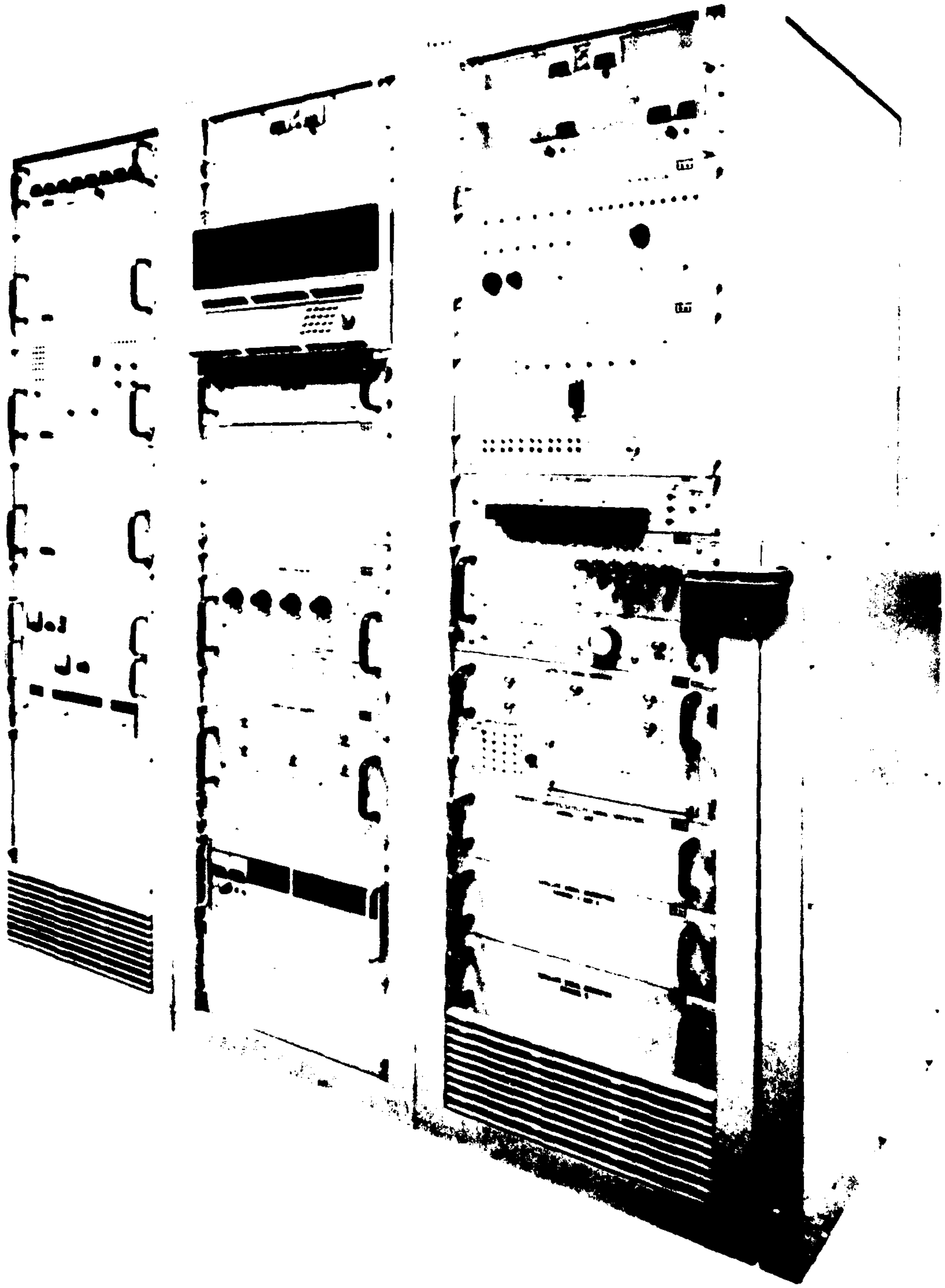

Figure 1. GPSE Evaluator

The primary features of the GPSE are given below:

- Faithful, precise, repeatable simulation of total environment including:

  Satellite signal characteristics, including GPS up-link navigation data

  Flight dynamics including lever arm effects

  Jammer signals -- CW, PN, special purpose

  Antenna patterns

  System temperature

  Error models

- Adaptable to various user equipments including missiles
- Flexible error models
- Flexible mission scenarios
- RF signals precisely coupled to user dynamics
- Optimized for use in conjunction with flight tests
- Efficient use of processor resources--Disc operated system
- Separate maintenance and test interface
- Maximum use of low-risk off-the-shelf hardware
- Expandable up to nine satellite channels
- J/S capability expandable up to 67 dB

The software system is characterized by the following features:

- Coded in RATFOR (structured in FORTRAN).
- Segmented program structure
- Modular database
- Simulation efficiency and flexibility
  - pre-computed ideal (truth) data
  - real time error data
  - post run analysis data

The GPSE is currently configured to interface with the GDM of the GPS User Equipment. As such, it will operate in the following modes:

Specification Validation Mode (GDM)

- Signal reacquisition
- Synchronization recovery
- Jamming immunity
- NAV data recovery

Navigation Mode (GDM)

- 10 hour flights
- 40 segments per flight
- Simulate specified range of user and jammer dynamics

Built-in Test (BIT) Mode

- Use built-in test facilities
- On-line automatic fault detection to assembly/unit level
- Off-line manual fault isolation to replaceable module using test programs, built-in and laboratory test equipment

Calibration Mode

- Use built-in test facilities
- RF power levels
- "Zero" range set
- User timing synchronization

SECTION II

SYSTEM

CONCEPT

The complete GPSE requirements were studied as an entity and the system was designed from top down. Various studies for the newly encountered simulation and processing problems were made and published. Two of the studies, Trade-Off Analysis - Lever Arm Effects (Appendix A) and Post Run Processing Concept Study (Appendix B) are enclosed as examples.

A math model for the system was developed and was based upon the division of the computing task into three basic categories.

A. Pre-computed portion

B. Real time portion

C. Post run portion

This division is based upon the following premises:

- All "truth" data will be pre-computed, up to a maximum data rate of 10 per second.

  The "truth" includes:

  Selected user flight profile
  Selected jammer flight profiles
  Selected ephemerides for 5 satellites
  Selected ionosphere model
  Selected troposphere model
  Selected jammer scenario
  (Power level and jammer type)

- The data required at 50 per second will either be computed in real time, or interpolated in real time from the pre-computed 10 per second data

- All error models will be implemented in real time, in order to provide for the maximum amount of simulation flexibility. Error models include:

Satellite clock true error

Measurement error in satellite clock error

Satellite ephemeris measurement error

Ionosphere model measurement error

IMU error model

Barometric altimeter error model

Gravity anomalies

- GDM (or other test receiver) instrumentation data (position and velocity) will be computed in real time, and stored for post-analysis. Other GDM parameters of interest, such as status signals, acquisition times, etc., will also be stored for post-analysis.

PRE-COMPUTED PORTION

This category may be divided into two basic functions. The first function is to provide data which is required at the beginning of a run. Generally, this data remains without change for the duration of the run. However, with certain restrictions, some of this data can be changed during the run. The second function is to provide dynamic data (up to a 10 per second rate) which is continually changing during the run.

A functional diagram of the first function is provided in Figure 2. The time ephemeris parameters are used both to generate the dynamic satellite trajectories, and to serve as "truth" data. In the real time portion, the selected ephemeris error model is added to the "truth" data. In the real time portion, the selected ionosphere measurement error model is added to the "truth" data to generate another part of the SSGA data stream.

The true ephemeris parameters can be changed during the run, provided that there is no discontinuity in either satellite position or satellite velocity at the transition point. The true ionosphere coefficients can also be changed during

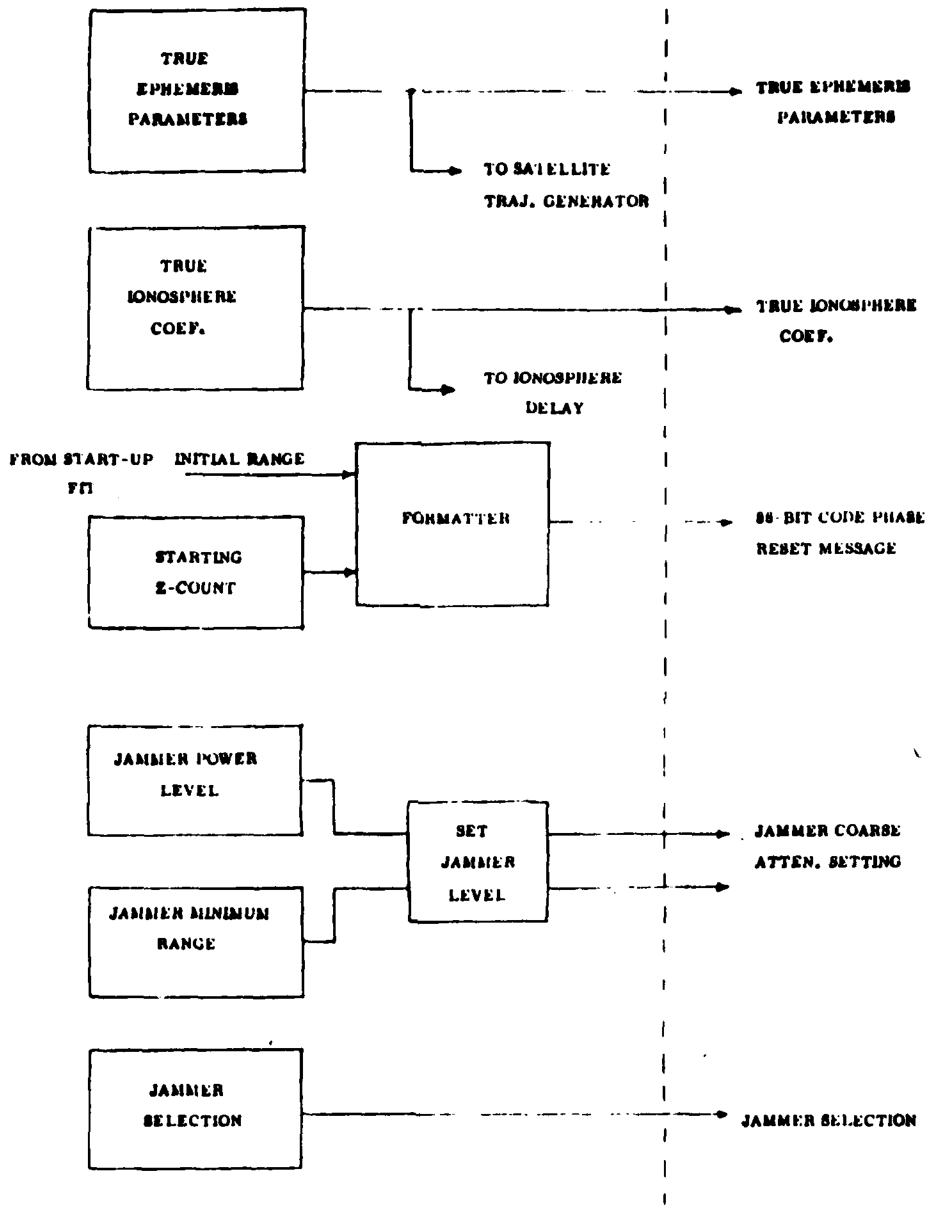

Figure 2. Pre-Computed Fixed and Initialization Data

the run, provided that there is no discontinuity in ionosphere delay at the transition point.

Because of acceleration limitations in the DFSA, the range rate input to the DFSA must start at zero, and must be changed (at less than 250 meters/sec^2) until it matches the actual range rate. This operation requires a range offset from the true initial range. Also, it may be desired to have a Z-count at the start of the run which is not close to zero (start of the week). The values of starting Z-count, initial range, and range offset are processed to determine a required code phase jump which will be implemented by means of the SSGA base-band units. This jump must be an integral number of P chips, where one P chip represents a distance of:

$$\frac{2.997925 \times 10^8}{1.023 \times 10^7} \text{ meters} = 29.2 \text{ meters}$$

Once the number of P chips in the required jump has been determined (any integer up to 6.2×10^{12}), this number must be processed to result in an 88 bit code phase reset message which is transmitted to the SSGA baseband units. This procedure must be followed for each of the 5 satellites, and is performed only at the beginning of the run.

One or more jamming scenarios during the run will require pre-selection of jammer type (CW, SPJ, CW/PNBPSK) for channel #1, and jammer power level for each of the 5 jammer channels. In association with the jammer power level, and the actual jammer minimum range, a reference range is selected which is equal to or less than the actual minimum range, and which will yield an integral multiple of 5 dB for the coarse attenuator setting in the SCA. The dynamic path loss output for each jammer channel is then computed from the ratio of actual range to reference range (ratio squared converted to dB). The coarse attenuator setting and reference range may be changed as desired during the run, provided that the associated jammer channel is turned off while the change is being made.

A functional diagram of the second function (dynamic data) is provided in Figure 3. The user flight profile generator provides outputs of position, velocity and velocity rates of the aircraft c/g, along with sines and cosines of the 3 Euler angles (roll, pitch, azimuth) representing aircraft attitude with respect to the ideal IMU platform reference axes. The velocity rates and velocities are combined with Earth rate, in the section labeled "Ideal IMU", to give accelerations (excluding gravity) and inertial rates as would be sensed by an ideal IMU. Ideal gravity is also computed as a function of latitude and height in this section. For use in the user clock error model, the acceleration along the crystal sensitive axis is computed based upon the velocity rates and the aircraft attitude.

The satellite trajectory generator generates position and velocity of each of the 5 satellites referred to ECEF axes. The position data is based upon the equations listed on Table IX, page 48, of ICD MH-00002-400, and the selected set of ephemeris parameters as indicated in Figure 2. Velocity data is needed only for a range correction to account for satellite motion during the finite transmission time, and is derived by simple differencing of successive satellite positions (at 0.1 second intervals). Each satellite position is then combined with the user position, in the section labeled "Satellite - User Geometry", to give direction of the line-of-sight (with respect to the ideal IMU reference axes) and precision range for each of the 5 satellites.

The jammer flight profile generator generates jammer position for each of up to 5 jammers, based upon preselected flight paths. In the section labeled "Jammer-User-Geometry", the relative velocity components between the jammer and the user are integrated to give direction with respect to the ideal IMU reference axes and range. The direction information is used in the real time portion to generate antenna pattern attenuation values for the jammer signals. The range information is used with the reference range information (referred to in Figure 2) to generate

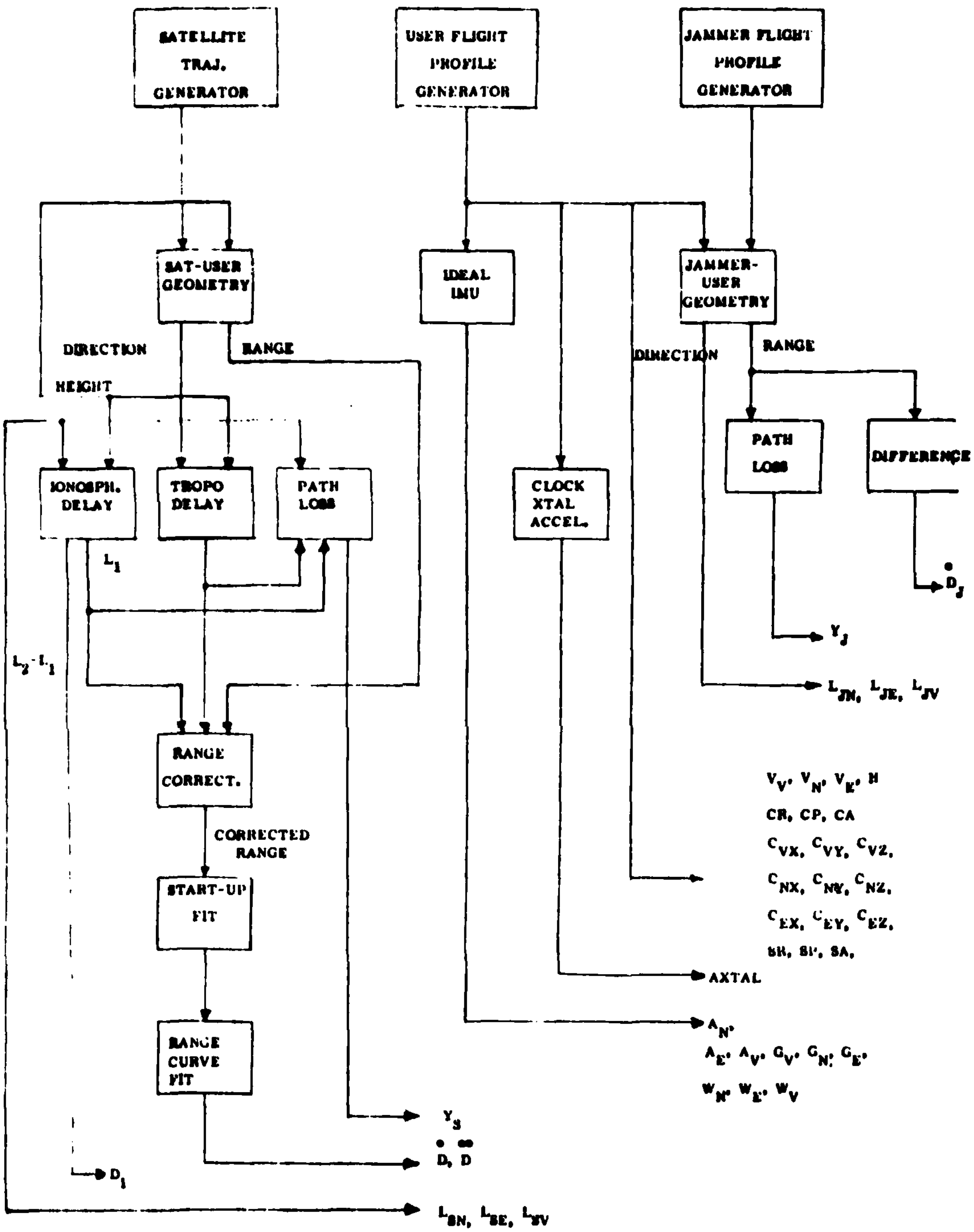

Figure 3. Pre-Computed Dynamic Data

path loss attenuation commands to the SCA for each of the 5 jammer channels. Successive differences of each jammer range are used to generate user to jammer doppler values.

Detailed descriptions of the various computation blocks and the actual implementation information can be found in the computer program product specification for the Data Processing Assembly (ITT Specification No. 1263058).

REAL TIME PORTION

A functional diagram of the real time operations is provided in Figure 4. Entries on the left side of the figure are inputs from the pre-computed portion Figure 3). Data rates are indicated in parentheses below the entries. Where no data rate is shown, the inputs are changed only infrequently if at all.

Attitude Data

Attitude data (sine and cosine of roll, pitch, and azimuth) is interpolated at .02 second intervals from the 10 per second, input data, using a third order curve fit for roll, and a linear interpolation for pitch and azimuth. Errors from the IMU attitude error model are then added to the "truth" data to give simulated IMU attitude outputs to the GDM at 50 per second. The "truth" attitude data is also used for baseline antenna pattern calculations.

For the baseline antenna, the cosine of the offset angle between the satellite or jammer line of sight being considered and the antenna centerline (coincident with the aircraft vertical) is computed. The cosine of the offset angle is then converted to a pattern attenuation (in dB) by means of a table look-up for the applicable antenna element. In the satellite baseline mode, the look-up is implemented for both the upper (U) and middle (M) elements. In the inverted range mode, only the lower (L) beam is implemented, and outputs with a U subscript then represent the lower beam attenuation.

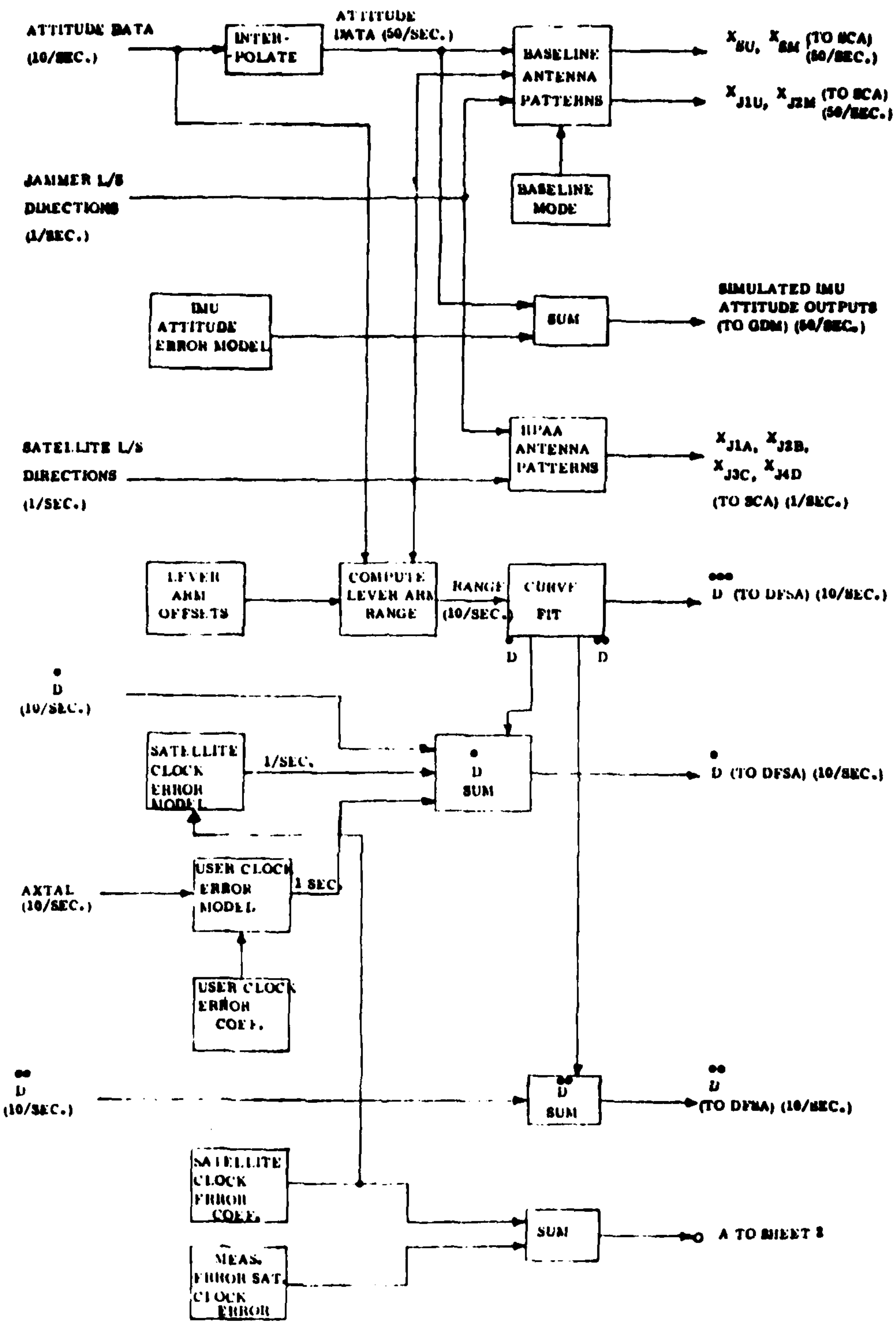

Figure 4. Real Time Operations (Sheet 1 of 3)

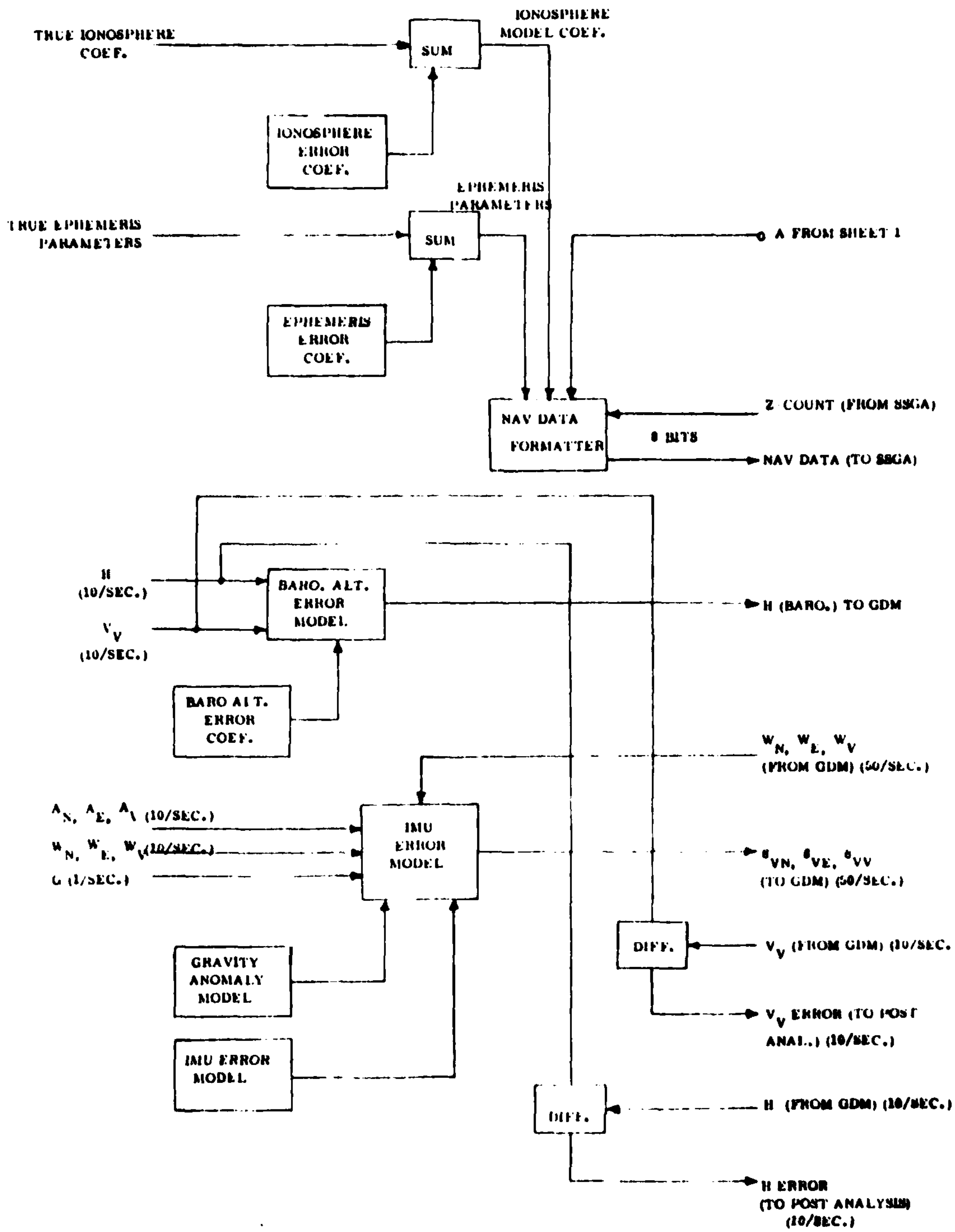

Figure 4. Real Time Operations (Sheet 2 of 3)

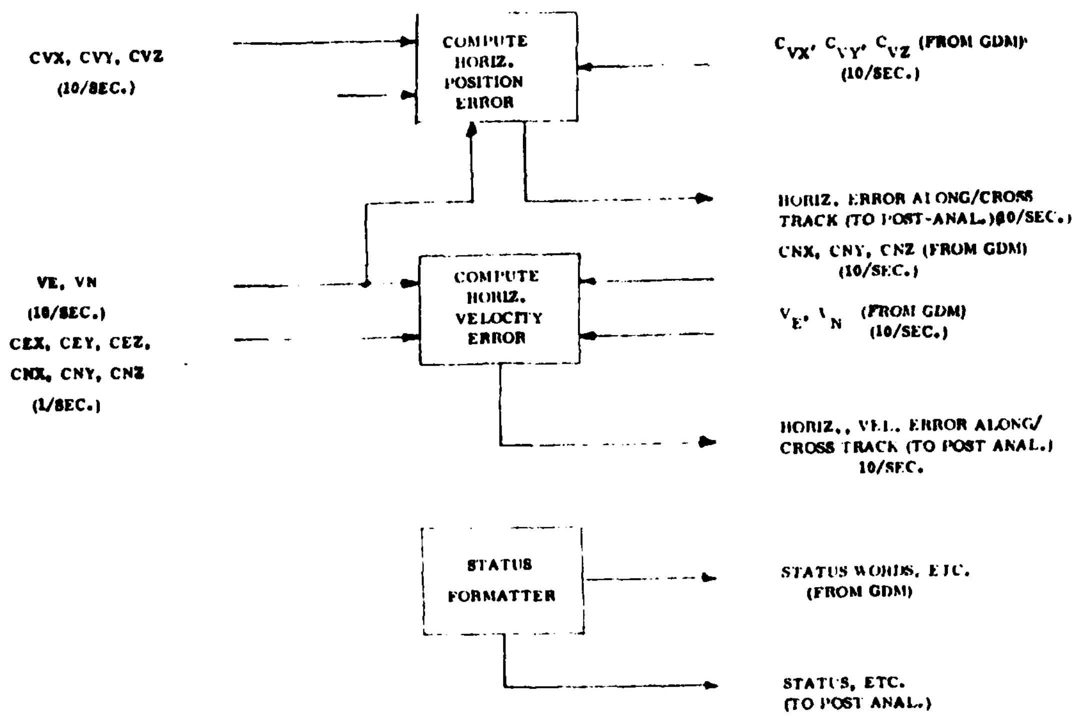

Figure 4. Real Time Operations (Sheet 3 of 3)

For the lever arm calculations, the lever arm offsets (fixed during a run) are transformed to components with respect to the ideal IMU reference axes by rotation through the attitude angles. These components are then resolved along the line-of-sight to each of the 5 satellites, using the satellite line-of-sight directions which are pre computed. The resultant components along the line-of-sight then represent range deviation for each of the 5 satellites.

HPAA Antenna Patterns

For the HPAA antenna attenuations, in the present configuration, the antenna center line is assumed to be stabilized along the line-of-sight of the satellite to which the beam is assigned. Therefore, attitude angles of the aircraft have no effect upon the pattern attenuations. Pattern attenuations for all satellite signals are therefore set to 0 dB. Pattern attenuations for each of the 5 jammer signals used (one for each beam) are then determined by computing the cosine of the angle between each jammer and its associated satellite, based upon L/S direction data which is pre-computed. The cosine of the angle is then used as an entry to a look-up table which delineates the HPAA beam pattern. Output of the look up is the jammer signal attenuation in dB.

Range Corrections

Returning now to the lever arm range deviations which have been computed, a third order curve fit process is used with the 0.1 second range values to obtain values of $\dot{D}$, $\ddot{D}$, and $\dddot{D}$ for each range deviation, which are each updated at a 10 per second rate. The $\ddot{D}$ values are added to the $\ddot{D}$ computed for the basic range, resulting in the correct $\dot{D}$ input to the DFSA at a 10 per second rate.

The $\dot{D}$ value transmitted to the DFSA must also contain deviations resulting from satellite and user clock errors. The value of $\ddot{D}$ for these clock errors does not have to be implemented, because the clock errors change slowly. The satellite clock error is represented by a second order polynomial. The user clock error is also represented by a second order polynomial, along with an error rate term which is proportional to aircraft acceleration along the crystal sensitive axis (A_{XTAL}). The zero order coefficients of the clock error models (initial time errors) will be implemented by injecting the required range rate (D) during the start-up procedure.

NAV Data Generation

The true satellite clock error coefficients, as implemented by operator selection, along with the true ionosphere coefficients and the true ephemeris parameters, as generated in the pre-computed portion, are summed with selected error coefficients before being formatted for transmission to the SSGA basebands by the NAV data stream. This group of error coefficients simulates the effect of ground station measurement errors in the actual system. The value of each of these error quantities is completely under the control of the simulation operator, and can be changed based upon a Z-count schedule, similar to the way the NAV data is changed in the actual system.

Barometric Altimeter

The simulated barometric altimeter output is based upon true height (H) and vertical rate (V_V) inputs from the pre-computed portion, and the operator selected coefficients of the barometric altimeter error model. The required output rate is 10 times per second. The error model includes the effects of:

Lag due to pilot static sensor
Lag due to the air data computer
Random low frequency noise
Variation in true height of isobar, resulting from water vapor content and non-standard temperature gradients in the troposphere

IMU Simulation

True accelerations, inertial rates, and gravity variation from the pre-computed portion, along with commanded inertial rates from the GDM, and gravity deviations from the gravity anomaly model, are processed in relation to IMU error model coefficients which are selected by the operator, to generate simulated accelerometer outputs (integrated acceleration) for transmission to the GDM at a 50 per second rate. The actual computation is performed at a 10 per second rate. In order to match the computing rate to the GDM data rate of 50 per second, inertial rate commands are accumulated in groups of 5 to give an average rate command for the 0.1 second interval; and the integrated acceleration outputs have 5 successive equal increments to represent the actual integrated acceleration over the 0.1 second interval. Deviations resulting from lack of .02 second granularity are completely negligible in the simulation.

The gravity anomaly model generates horizontal and vertical gravity anomalies which are low frequency random noise with the effective correlation time inversely proportional to aircraft horizontal speed. The generated gravity anomalies are added to the true acceleration and gravity inputs.

The IMU error model also includes the effects of the following:

- Gyro random drift rate
- Gyro acceleration sensitive drift rate
- Gyro bias drift rate
- Gyro torquer scale error
- Accelerometer bias error
- Accelerometer scale error

GDM Instrumentation Errors

True height and vertical velocity from the pre-computed portion are compared to GDM generated values to determine errors at a 10 per second rate to be stored and used for the post-analysis.

To determine horizontal position errors, direction cosines of the vertical to ECEF axes, as generated in the "truth" data, are compared to equivalent direction cosines as generated in the GDM. From this data, the angular separation between the true vertical and the indicated vertical is computed. The horizontal position error is then this angular separation (in radians) multiplied by the effective Earth radius. This horizontal position error is then resolved into "along track" and "cross track" components, at a 10 per second rate, for storage and use in the post-analysis.

To determine horizontal velocity errors, indicated velocities, with respect to wander North and East, from the GDM, must first be rotated around the vertical by the wander angle error, before being compared to the true wander North and East components which are pre-computed. The effective wander angle error is determined by comparing wander North direction cosines as generated in the GDM with those in the "truth" data, and then multiplying the differences by true wander East direction cosines. The rotated values of GDM velocity components are then compared to the true velocity components to determine velocity errors along each horizontal axis. The errors, generated at a 10 per second rate, resolved into "along track" and "cross track" errors, are stored for use in the post-analysis.

Detailed Descriptions

Detailed descriptions of the various blocks of Figure 4 and the actual implementation information can be found in the computer program product specification for the Data Processor assembly (ITT Specification No. 1263058).

SECTION III

SYSTEM DESCRIPTION

The GPSE system block diagram is shown in Figure 5. It consists of the following major elements:

- Control Display Assembly (CDA)
- Data Processor Assembly (DPA)
- Unit Device Controller Assembly (UDCA)
- Satellite Signal Generator Assembly (SSGA)
- Dynamic Frequency Synthesizer Assembly (DFSA)
- Jamming Generator Assembly (JGA)
- Signal Combiner/Noise Generator Assembly (SCA/NGA)
- Functional Test Assembly (FTA)
- Frequency Standard Assembly (FSA)
- GDM Interface Module (GDMIM)

Refer to Figure 6 for typical installation of GPSE User Equipment Performance Evaluator.

The CDA provides the primary operator interface with the GPSE. From this location, the operator can control all phases of the simulation. Specifically, the CDA operator will be able to:

- Perform the startup sequence
- Generate trajectory tapes
- Select error model parameters
- Run the real time mission
- Call up quick look displays during real time operation
- Collect data for post run analysis
- Perform post run analyses

The DPA consists of the following major elements (Figure 7):

PDP 11/70 with:

Cache memory

128K Word Core Memory (interleaved)

Real Time Clock

Floating Point Unit

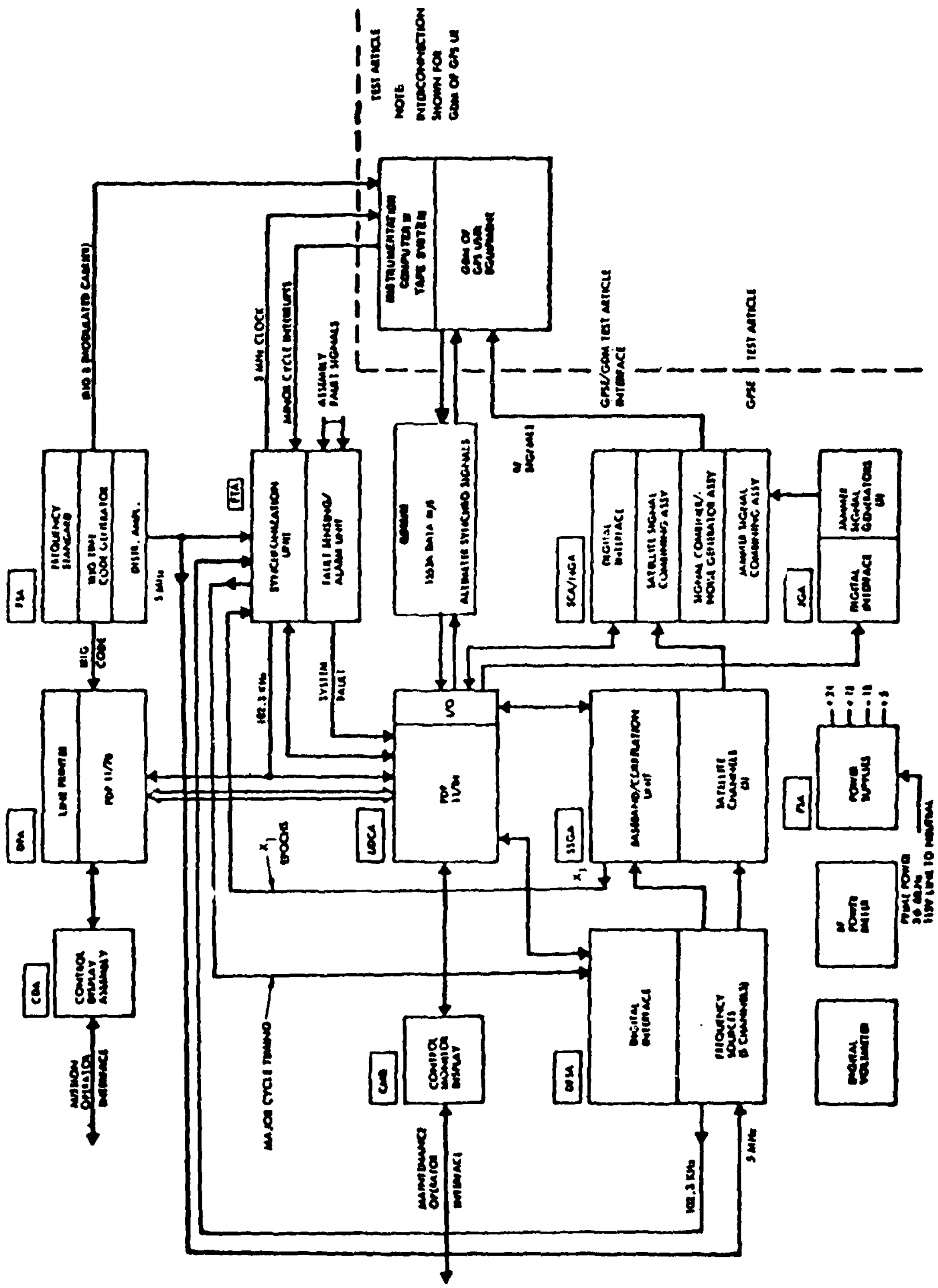

Figure 5. GPSE System Block Diagram

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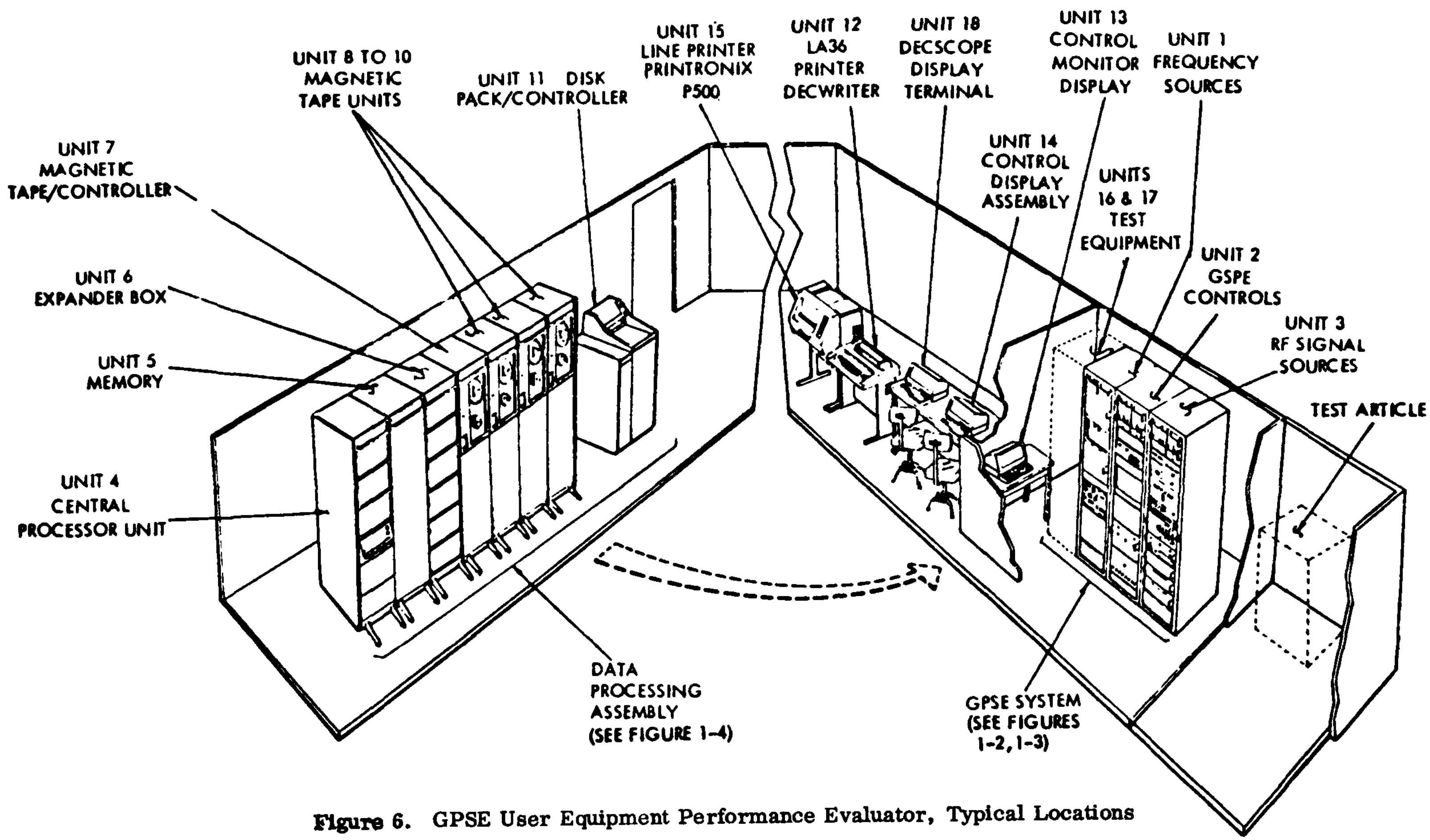

Figure 6. GPSE User Equipment Performance Evaluator, Typical Locations

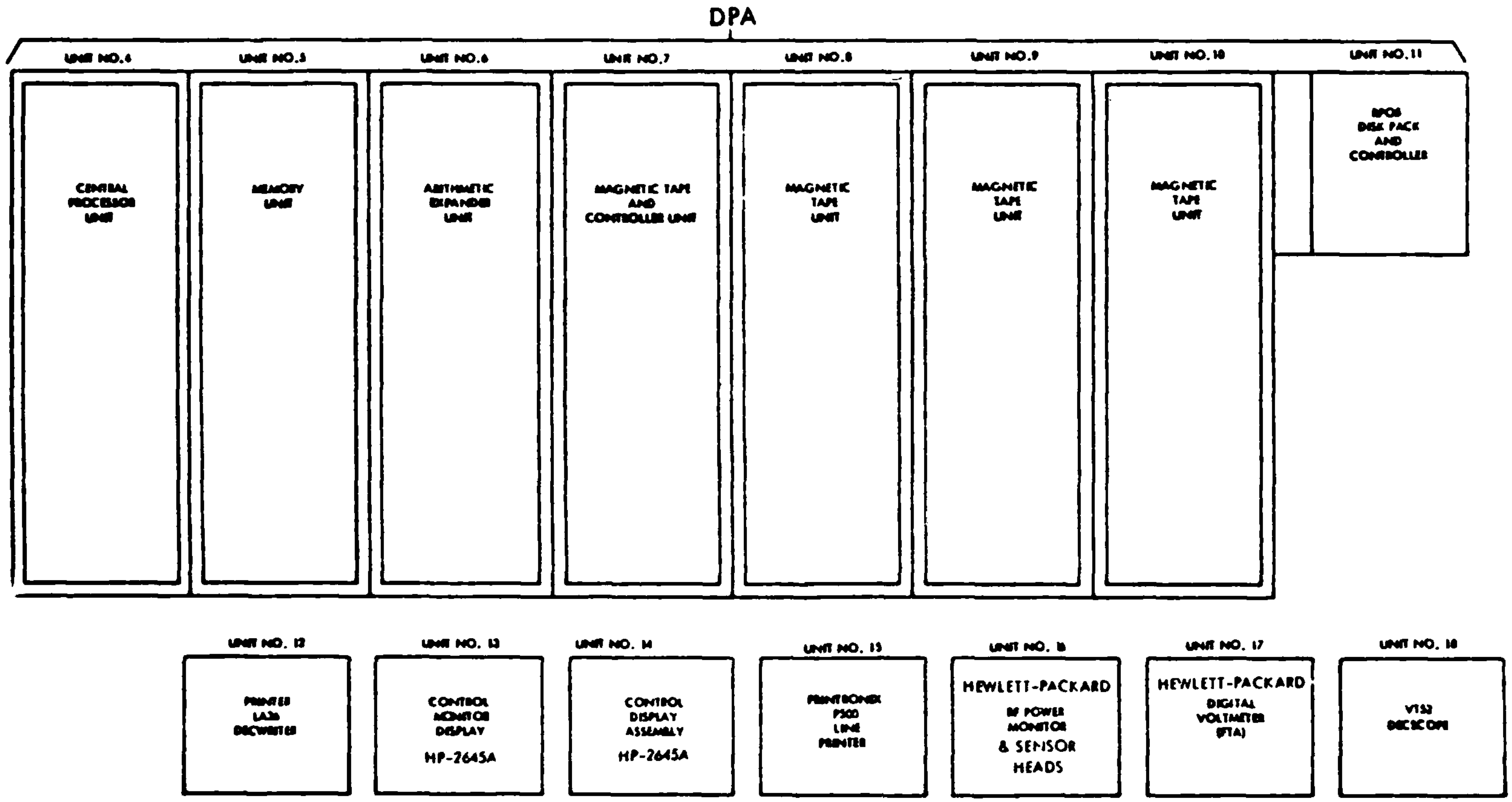

Figure 7. Data Processing Assembly (DPA) and Peripheral Equipment

- 44 M Wd Disk Pack Drive and Controller
- Magnetic Tape Unit and Controller plus 3 Expansion Drives
- RSX11-M Operating System
- Fortran IV Plus

The DPA with its associated software provides the means for driving the various hardware elements comprising the GPSE. The DPA can operate in the following modes: Pre-computed Data (PCD), Real Time Segment (RTS) and Post Run Data (PRD) under operator control.

The UDCA performs the following primary functions:

- Receive digital data from DPA, buffer and transfer to other GPSE assemblies
- Receive digital data from other GPSE assemblies, buffer and transfer to DPA
- Provide an alternate GPSE man/machine interface
- Provide capability to "exercise" GPSE assemblies without DPA

Data from the GPSE hardware assemblies as well as the user equipment is collected by the UDCA, reformatted, and sent to the DPA, and vice versa, via a data bus interface.

The UDCA consists of the following elements:

- Processor Unit PDP 11/04 CPU with 32K memory
  Programmable Real Time Clock
  General Device Interfaces
  Serial Line Interface
- CMD Terminal (HP2645A)
- I/O Controller Unit

The SSGA generates RF signals identical to those of the actual GPS Satellite, inasmuch as the SSGA is composed of units electrically identical to the actual GPS flight hardware. The basic SSGA configuration contains five satellite simulators, each generating both L_1 and L_2 band signals as in the actual flight hardware. The principal difference is that each band of each channel will have separate carrier and modulation sources so that the various frequency dependent propagation effects can be simulated. Navigation data such as satellite ephemerides, clock drift, etc., is input to the SSGA modulation source via the UDCA data bus.

The DFSA provides independent carrier and code clock signals to each RF channel of the SSGA. These signals are precisely phase controlled and monitored by the real time software system so as to ensure an accurate and repeatable simulation of range dynamics of the satellite/user paths.

The JGA provides four CW signals and a PN modulated RF signal so as to simulate up to 5 jammers, with individual J/S capability up to 67 dB. The JGA is capable of carrier frequency control by the real time program. This control can be used to simulate a prescribed jammer frequency strategy.

The outputs of the SSGA and JGA are fed to the SCA/NGA where they are combined with an L-Band Gaussian white noise generator to create the total RF environment. The noise generator, in conjunction with level control of the satellite signal, provides a means for controllably simulating the presence of a preamplifier that might be used in conjunctio with the user vehicle antenna.

The FTA has the following capabilities:

- Monitor unit fault indicators and RF level outputs to actuate alarm and send fault signal to DPA in event of system failure
- Isolate fault to a given drawer, and display location of faulty drawer
- Provide means for more detailed fault location
- Provide diagnostic capability means of digital voltmeter, power meter, and spectrum analyzer
- Provide means for system timing synchronization
- Provide means for satellite signal code correlation with self-contained reference code

Fault detection is provided by the monitoring of a variety of DC voltages depicting such observables as RF power level, power supply voltage, and phase lock loop status. With these observations, detected faults can be automatically localized to the drawer level where prescribed trouble shooting procedures, both manual and processor controlled, can be invoked to isolate and repair the failure. The required synchronization of the GPSE clock with appropriate internal user events is achieved by shifting the phase of the user clock input until proper synchronism is observed. Circuitry for establishing and observing GPSE/User Synchronism is provided in the FTA.

The GDMIM provides the hardware means for interfacing with the GDM of the GPS User Equipment. Its design is unique to the specific interface, and provides the GPSE with a modular change capability to accommodate other users. This interface carries both sensor data (i.e., IMU, altimeter, antenna control, and status) as well as instrumentation data between the GPSE and the GDM.

The SCA/NGA combines the satellite, jammer, and noise signals under processor control so as to simulate the various propagation and antenna pattern effects present. The output of the SCA/NGA feeds the RF inputs of the GDM as well as the FTA. The latter provides a means for calibrating and monitoring the RF signals.

The FSA provides the basic reference clock (5 MHz) used by both the GPSE and the User Equipment. The use of a common clock reference provides a means for controllably and repeatably introducing prescribed clock errors into the system, if desired.

SYSTEM PERFORMANCE CHARACTERISTICS

The GPSE performance can be characterized in terms of the following two simulation elements: physical dynamics and signal characteristics. Tables 1 and 2 show the vehicle and jammer dynamic simulation capabilities, respectively. In order to ensure precise evaluation, the accumulated range delay error over a 10-hour period will be less than 0.1 meters. Lever arm effects due to displacement of the antenna from the center of motion of up to 5 meters can be simulated, for roll rates up to 400 degrees per second at acceleration up to 1,200 degrees per second. Table 3 shows the major signal characteristics of the GPSE.

TABLE 1. USER VEHICLE DYNAMICS

Velocity (Meters/Sec)	0-6500
Acceleration (Meters/Sec^2)	0-100
Jerk (Meters/Sec^3)	0-100
Angular Rate (Degrees/Sec)	
Roll	0-400
Pitch	0-100
Yaw	0-150

TABLE 2. JAMMER VEHICLE DYNAMICS

Velocity (Meters/Sec)	0-600
Acceleration (Meters/Sec^2)	0-20
Jerk (Meters/Sec^3)	0-100

TABLE 3. GPSE MAJOR CHARACTERISTICS

SATELLITE SIGNALS		JAMMING SIGNAL	
Carrier Frequency	1575.42 MHz (L_1) 1227.6 MHz (L_2)	Output Frequency nominal	1575.42 MHz (L_1 - Band) or 1227.6 MHz (L_2 - Band)
Bandwidth	20 MHz around L_1 and L_2		
Output Power	-48.3 dBW to -178.3 dBW	Total No. of Channels (Including Modulated/CW Channel)	5
Number of Channels	L_1 - 5 L_2 - 5	No. of PN Modulated Channels	1
Phase Noise (Max.)	100 m rad RMS measured in a phase locked loop with 10 Hz single sided noise bandwidth.	Power Output-Each Channel	-35 dBW
Group Delay Variation (Per Channel)	1.8 n sec RMS (Max.)	Frequency Control Range at F_0	±40 KHz
Signal Level Accuracy	±2dB	Frequency Stability at F_0	±2 KHz
Signal Level Repeatability	± 0.5 dB	Harmonic Outputs	15 dB below carrier
J/S Accuracy	± 0.5 dB	Modulation Source (Channel 1)	Pseudo-Noise
		Modulation Type	BPSK, Synchronous Keying
		Code Format	(GPS ICD - MH06-00002-400)
WHITE NOISE SIGNAL			
Center Frequencies	1575.42 MHz and 1227.6 MHz	Chip Rates	10.23 MBS/1.023 MBS
Band	20 MHz around each center frequency	Amplitude Control	Simulate prescribed antenna pattern and range variations.
Power	-69.1 dBW max. in 20 MHz		

SECTION IV

HARDWARE CONFIGURATION

The GPSE, exclusive of the DPA and its peripherals, will be housed in three cabinet units as shown in Figures 1 and 8. The partitioning of functions is chosen so as to optimize electromagnetic compatibility between reference signals (unit 1), jamming and digital control signals (unit 2), and satellite signals (unit 3).

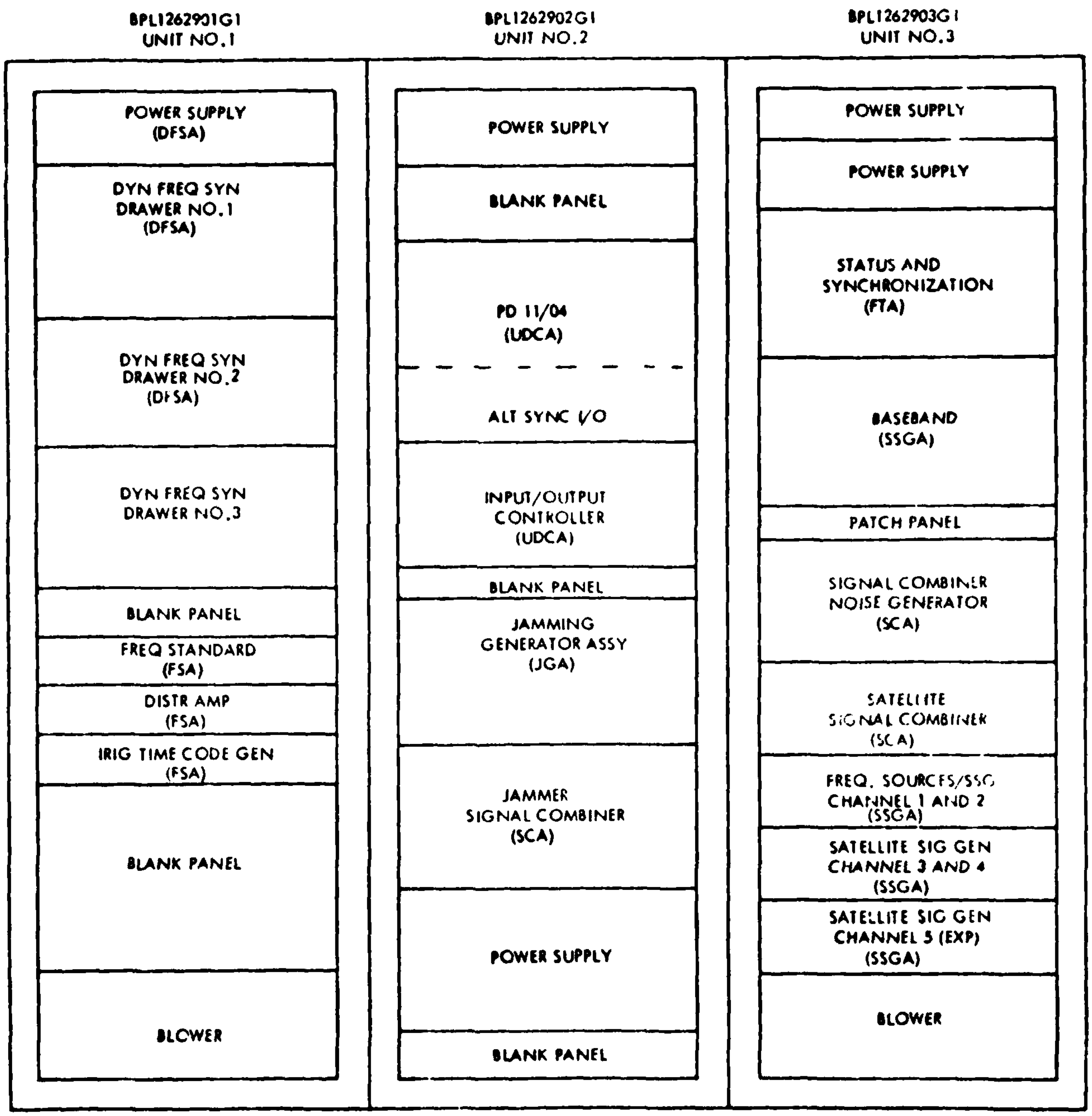

Figure 8. GPSE Hardware Configuration, (Diagram)

SECTION V

SOFTWARE CONFIGURATION

The GPSE software system consists of two major sets of programs, namely: UDCA programs and DPA programs. The DPA programs are responsible for the simulation computations, real time control and subsequent analysis. The UDCA programs are responsible for the transfer of data between DPA and the rest of GPSE hardware assemblies and for control and execution of hardware test and maintenance programs.

UDCA PROGRAMS

The UDCA Computer Program runs as a task on PDP 11/04 processor. The program was developed on PDP 11/70 computer system with RSX-11/M operating system. The operator interaction, when required, is done via the Control Monitor and Display (CMD) terminal (HP2645A) interfaced to the UDCA. The program is designed to accomplish all real time and off-line software functions necessary to perform the following tasks.

- Transfer in real time all data received from the Data Processing Assembly
- (DPA) to the hardware assemblies of the GPSE and to the GPS User Equipment.
- Transfer in real time all data received from the GPSE hardware assemblies and from the GPS User Equipment to the DPA.
- Control the synchronization and calibration of all GPSE assemblies with the GPS User Equipment.
- Exercise each hardware assembly of the GPSE, one at a time, by introducing known inputs and capturing the resultant outputs in real time. This is known as Test Integration and Maintenance (TIM) mode.

In the test and maintenance mode, the UDCA software provides a means for exercising the various hardware assemblies comprising the GPSE. These exercises are stored on cassette tapes and are designed to enable verification of the correct operation of the various assemblies.

This operating mode enables efficient separation of system software problems from hardware problems, thereby expediting the maintenance activity. The run up and calibration mode supports the synchronization of the GPSE/User combination. In this procedure the UDCA supplies the timing control to the DPA that is required to simulate the sensor outputs to the user equipment under test in precise synchronism with the RF signal timing. In addition, the UDCA calibration mode is used to provide the output control processes by which the various calibration procedures are performed. This includes RF level, frequency, and timing.

The real time data transfer mode is the primary operational mode of the UDCA. In this mode, the UDCA gathers, formats, and distributes data between the DPA, the GPSE hardware assemblies, and the User Equipment. The specific GPSE assemblies involved are: DFSA, SSGA, SCA, FTA, and GDMIM.

Further details of the functions performed and the actual implementation can be found in the computer program product specification and the user's manual (ITT Specification 1263057).

DPA PROGRAMS

The primary functions of the DPA software are to perform the digital calculations required in the simulation (implementation of GPSE math model) of the GPS environment and the User Equipment sensors. The DPA interfaces with the Control Display Assembly (CDA) for the purpose of communication with the system operator.
The DPA shall additionally interface with the UDCA for the purpose of communication with the rest of the GPSE assemblies.

The design of the computer programs was based on the following objectives:

- Segmented Program Structure
- Modular Functional Design
- Modular Data Base

- Simulation efficiency and flexibility
- Efficient man/machine interface

The DPA programs are written in Rational FORTRAN and, at present, are designed to operate with PDP 11/70 Computer System and RSX-11M Operating System. However, they could be adapted to other computer systems with minor modifications.

The DPA Program is configured as 4 distinct software segments entitled:

- System start-up (SSU)
- Pre-computed simulation (PCS)
- Real time simulation (RTS)
- Post run analysis (PRA)

Each segment consists of a series of interrelated RSX-11M tasks. Each task consists of a number of CPC's, comprising a main program and a hierarchy of subroutines and functions.

Intertask and intersegment communication takes place through use of a shared global common data region. Task management is performed through the issuance of directives to the RSX-11M Operating System. The inter-relationship between various DPA software segments is illustrated in Figure 9. The functional assignments of each of the segments are described in the subsequent paragraphs. Further details of assignments and the actual implementation can be found in the DPA computer program product specification (ITT Specification 1262991).

START-UP SEGMENT

The DPACP start-up segment is responsible for interacting with the system operator during initial system start-up. This interaction is carried on through the CDA (HP2645A) and shall occur regardless of whether the DPA is to be used to support a pre-computed run, a real time simulation, or a post run analysis. The start-up segment performs the following specific functions:

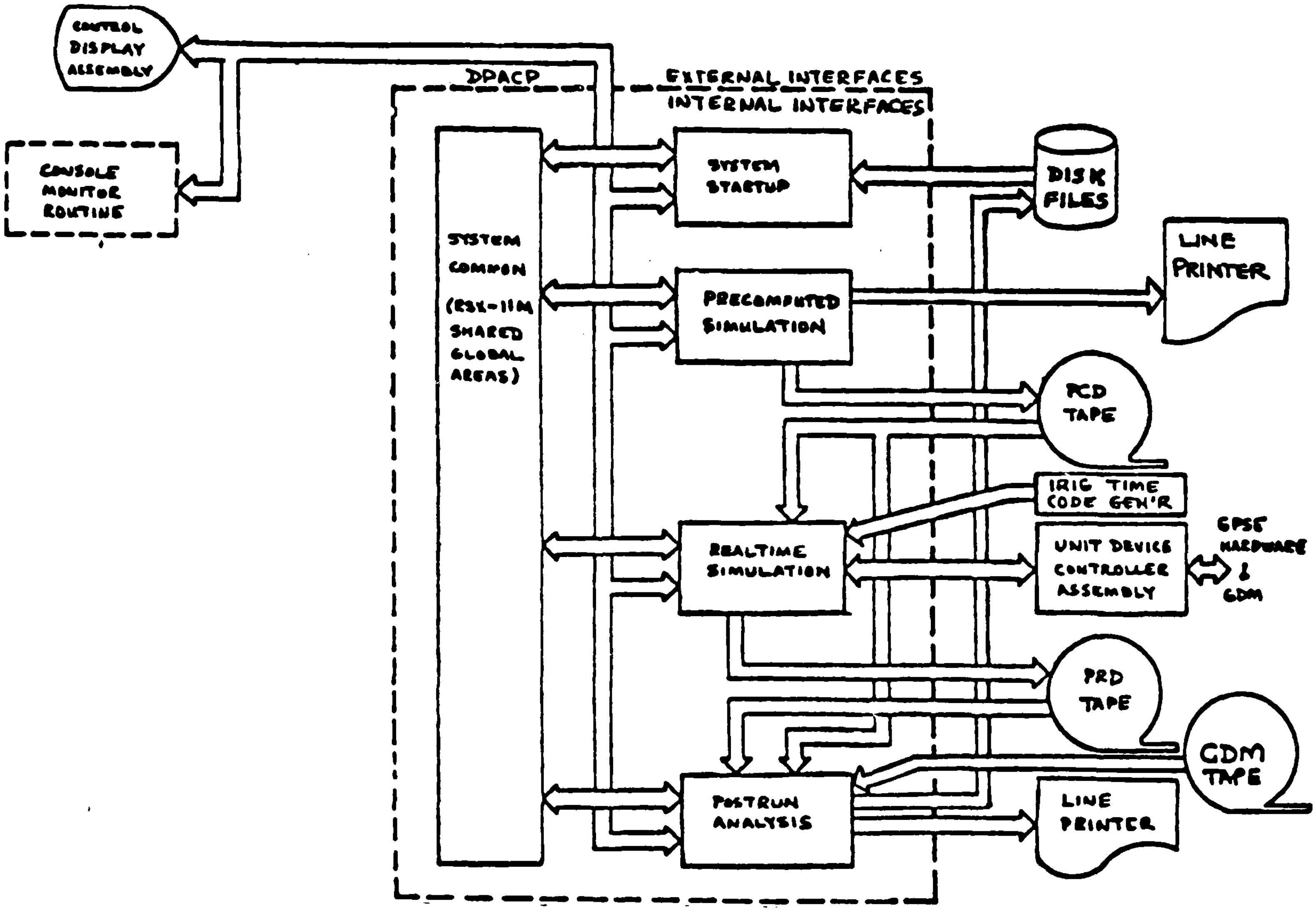

Figure 9. DPA Program: Functional Block Diagram

a. The start-up segment communicates with the system operator via the CDA in order to establish the type of run to be made and the data files required for that run.

b. The start-up segment verifies that the system equipment configuration is appropriate for the task to be performed. In the case of a real time run, this includes verification of the presence and readiness of GPSE hardware.

c. If data files are required for the run, the start-up segment requests the operator to identify those files and shall verify that the requested files exist. It shall also load those files into memory.

d. The start-up segment is responsible for establishing DPA synchronization with the UDCA.

e. The start-up segment communicates with the operator via the CDA in order to request tapes be mounted on the appropriate tape drives.

f. The start-up segment passes control to either the pre-computed segment, real time segment, or post run segment when it has completed its other functions.

PRE-COMPUTED SEGMENT

The DPACP pre-computed segment is responsible for performing the precision calculations required to define user vehicle, satellite vehicle, and jammer vehicle trajectories. Pre-computation of this data eases the throughput requirements placed upon the DPA during the real time simulation. The data flow between pre-computed segment and other segments and devices is illustrated in Figure 10. The pre-computed segment performs the following functions:

a. The pre-computed segment interfaces with the control display assembly for the purpose of accepting system operator inputs and for the purpose of providing information to the system operator concerning the status of the pre-computed run at any given time while it is executing.

b. The pre-computed segment interfaces with the pre-computed data (PCD) tape for the purpose of recording the pre-computed data for later use by the real time and post run segments.

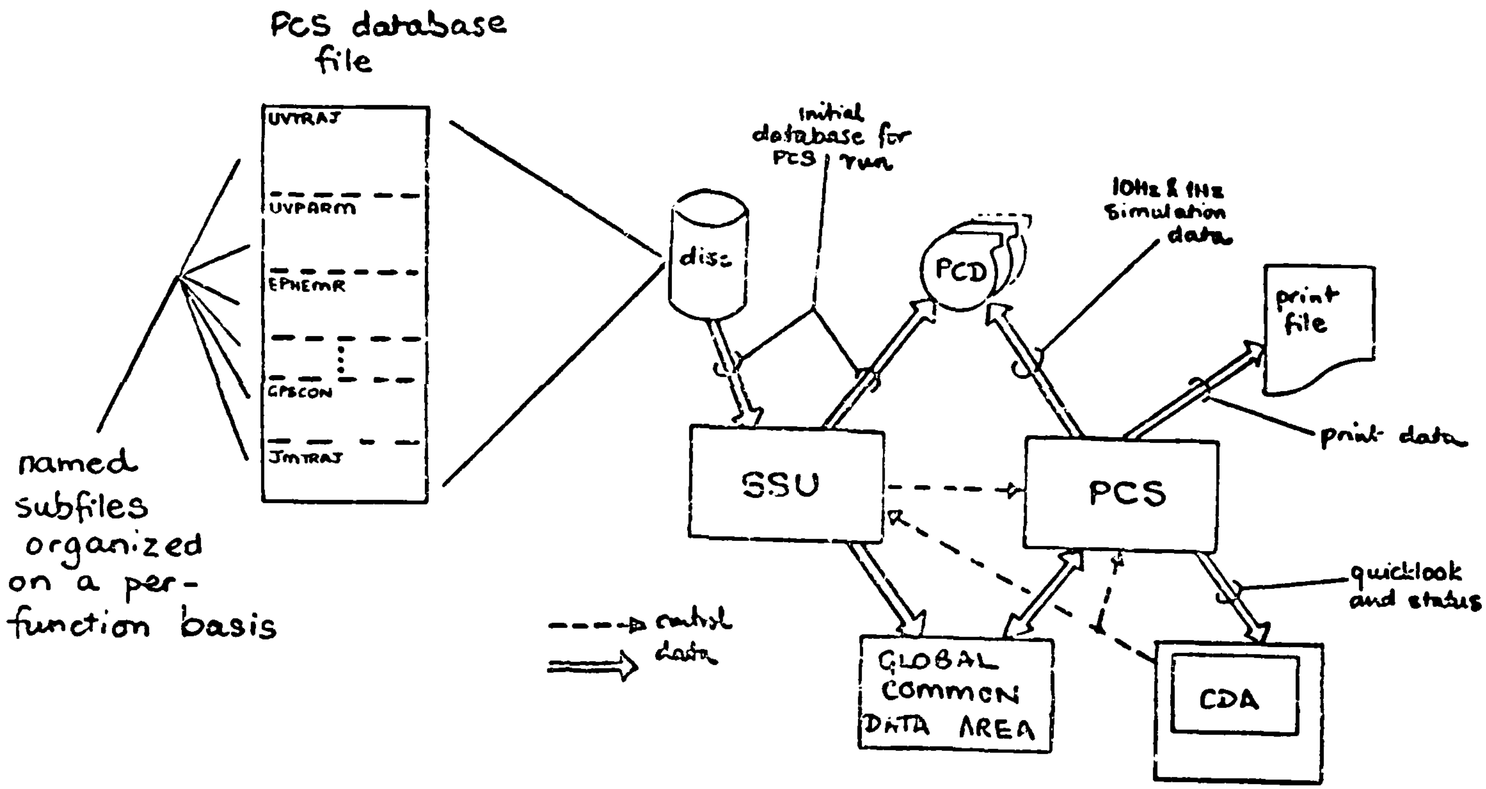

Figure 10. Pre-Computed Segment Data Flow

c. The pre-computed segment accesses data prestored in core by the start-up segment for the purpose of reading initial condition information.

d. The pre-computed segment calculates the user vehicle trajectory based upon prestored inputs. It provides user vehicle position, velocity, acceleration, and attitude data. This data is computed at a rate of 10 times per simulated second.

e. The pre-computed segment simulates an ideal IMU in the user vehicle. It provides specific force data, platform rotation data, and body attitude data. This data is computed at rates of 10 and 50 times per simulated second as appropriate.

f. The pre-computed segment simulates user antenna lever arm motion and calculates antenna position. This data is computed at a rate of 10 times per simulated second.

g. The pre-computed segment calculates the satellite vehicle trajectories based upon prestored ephemeris inputs. It provides the user antenna to satellite true ranges and line-of-sight directions. This data is computed at 10 times per simulated second.

h. The pre-computed segment calculates satellite clock drifts, atmospheric propagation delays, and signal attenuation. It also calculates signal equivalent ranges and range derivatives. This data is computed at 10 times and 1 time per simulated second as appropriate.

REAL TIME SEGMENT

The DPACP real time segment is responsible for performing those calculations required by the real time simulation and not already performed by the pre-computed segment. This consists primarily of the implementation of the various error models and the real time manipulation of data in order to respond to the requirements of the GDM and other system elements. The data flow between real time segment and other segments and devices is illustrated in Figure 11. The real time segment shall perform the following specific functions:

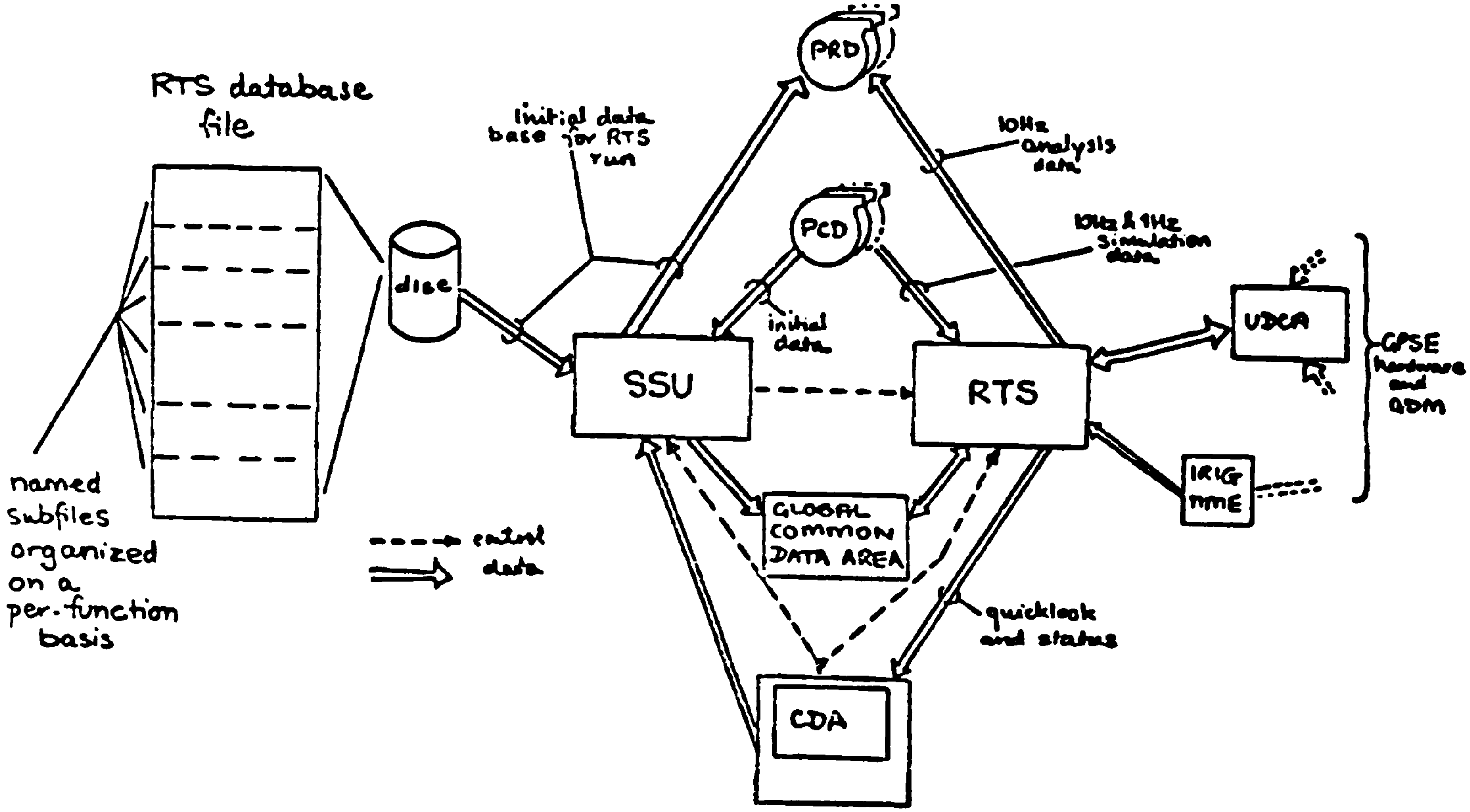

Figure 11. Real Time Segment Data Flow

a. The real time segment interfaces with the control display assembly for the purpose of accepting system operator inputs (commands) and for the purpose of displaying data to the system operator during the real time simulation.

b. The real time segment interfaces with the PCD tape for the purpose of reading the pre-computed data. The PCD tape is read at a rate that will satisfy the real time requirements of the simulation. The real time segment shall additionally verify that all reels of a multi-reel PCD tape are in fact continuations of that same tape and are therefore applicable to the run in progress.

c. The real time segment interfaces with the post run data (PRD) tape for the purpose of recording the data generated during the real time simulation run. The data written to the PRD tape shall be identifiable as having resulted from data contained on the specific PCD tape used for the subject run.

d. The real time segment accesses data prestored in core by the start-up segment for initial condition information and parameter definition. Such files, in conjunction with the PCD tape, provide the bulk of the input data required by the real time segment.

e. The real time segment includes a gravity perturbation model, an IMU model which includes accelerometer, gyro, and resolver error sources, and a barometric altimeter error model. The real time segment also includes a user clock drift model.

f. The real time segment includes an antenna pattern model (HPAA, isotrophic, and hemispheric).

g. The real time segment shall include a satellite data formatter which shall structure the five subframes of data transmitted by each satellite.

h. The real time segment interfaces with the unit device controller assembly (UDCA) for the purpose of transmitting data to the GDM and other elements of the GPSE. Additionally, the real time segment receives data from the GDM and the other elements of the GPSE via this interface.

i. The real time segment interfaces with the IRIG time code generator for the purpose of recording IRIG B time code data on the post run data (PRD) tape.

POST RUN SEGMENT

The DPACP post run segment is responsible for performing statistical analyses in a non-real time environment on the data generated during a real time simulation. This involves the comparison of GDM generated data with simulated "truth" data (pre-computed and real time). Additionally, the post run segment shall oro-vide the system operator with a means of viewing the contents of both the PCD and PRD tapes. The data flow between post run segment and other segments and devices is illustrated in Figure 12. The post run segment performs the following specific functions.

a. The post run segment interfaces with the control display assembly for the purpose of accepting system operator inputs (commands) and for the purpose of displaying data to the system operator during a post run analysis.

b. The post run segment interfaces with the PCD tape for the purpose of reading the pre-computed data. The post run segment verifies that all reels of a multi-reel PCD tape are in fact continuations of that same tape and are therefore applicable to the post run analysis in progress.

c. The post run segment interfaces with the PRD tape for the purpose of reading the real time data. The post run segment verifies that all reels of a multi-reel PRD tape are in fact continuations of that same tape and are therefore applicable to the post run analysis in progress. The post run segment also verifies that the particular combination of PCD and PRD tapes being analyzed is compatible.

d. The post run segment performs data time correlation between the data read from the PCD tape and the data read from the PRD tape. This insures that all statistical and error computations are performed on data referenced to the same point in time.

e. The post run segment performs error and statistical computations for the purpose of evaluating the performance of the GDM during the real time simulation.

f. The post run segment provides the system operator with the capability to direct the results of the post run analysis to the CDA and/or to a line printer.

g. The post run segment provides the system operator with the capability to search out specific records on either the PCD or PRD tape and to display record data on the CDA or a line printer.

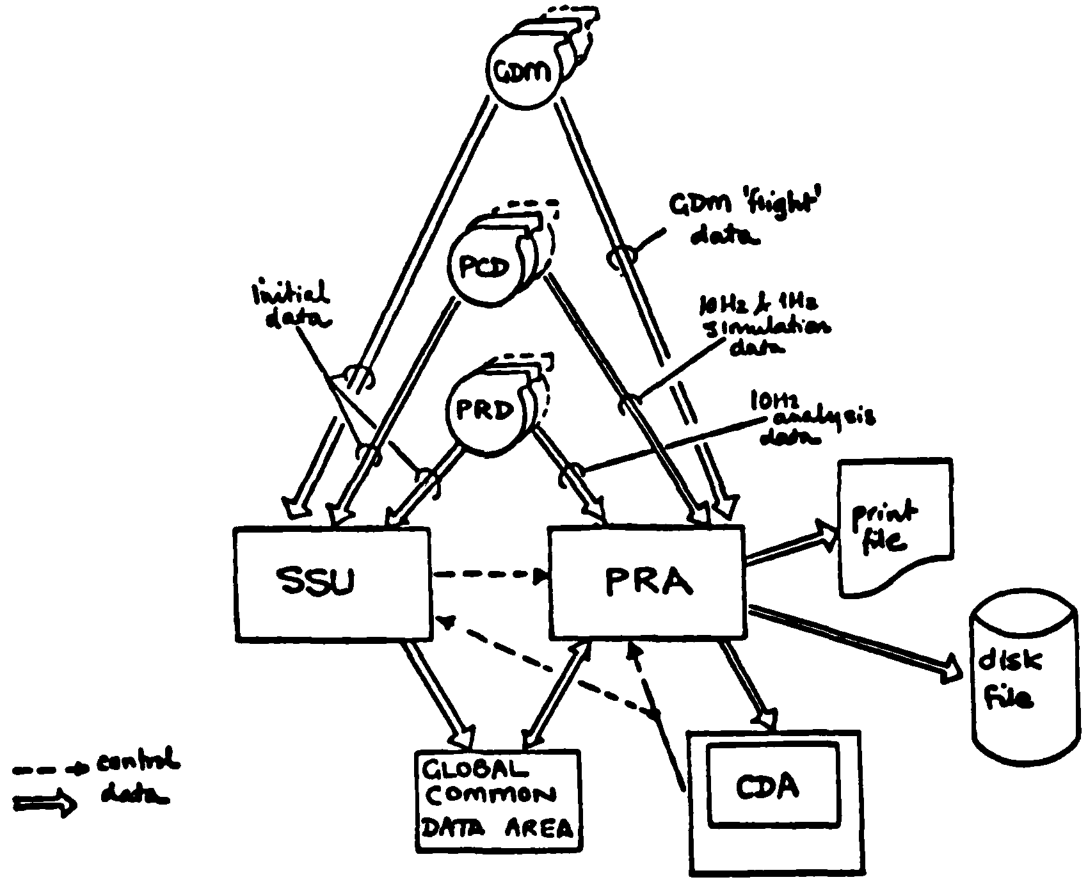

Figure 12. Post Run Analysis Segment Data Flow

SECTION VI

SYSTEM TEST PLAN

The test method chosen to test the GPS Evaluator is commonly called the "Building Block Technique". Using this technique, a system evolves from a small nucleus subsystem by the addition of functional assemblies, similar to that depicted in Figure 13. At the hub of the nucleus is the UDCA. Special test software and data were introduced by the UDCA to exercise each functional assembly or configuration item (CI) under test to prove that the CI meets related B1 specification requirements. The same software and the tests later formed the basis for the subsequent evaluation of this assembly as it was integrated into the growing system. The only exceptions to this were two CI's, namely: UDCA and DPA. These CI tests were performed by Digital Equipment Corporation using DEC diagnostic programs.

The test programs for the subsequent CI's did, when required, rely upon or utilize the previously assembled CI's. The CI tests were followed by a subsystem test. The subsystem test, utilizing the subsets of DPA programs, exercised one or more CI's to prove that they meet the requirements of GPSE system.

Upon completion of the system evolution, prior to shipment to AFAL, preliminary Acceptance Tests were performed on the totally integrated GPS Evaluator system. Upon preliminary inspection and installation at AFAL, the GPSE and the GDM of GPS User Equipment were integrated and the final testing of the GPSE was performed. The CI acceptance tests, subsystem tests, and the integration tests were conducted according to Government approved test plans and test procedures.

SOFTWARE TEST PLAN

As previously described, the DPA and the UDCA programs are subdivided into various Computer Program Components (CPC) determined by each of the functions to be performed. Hierarchies of these CPC's are combined into functional units. These functional units are similarly combined to form tasks and the tasks in turn form into segments. The structure of a typical segment is illustrated in Figure 13.

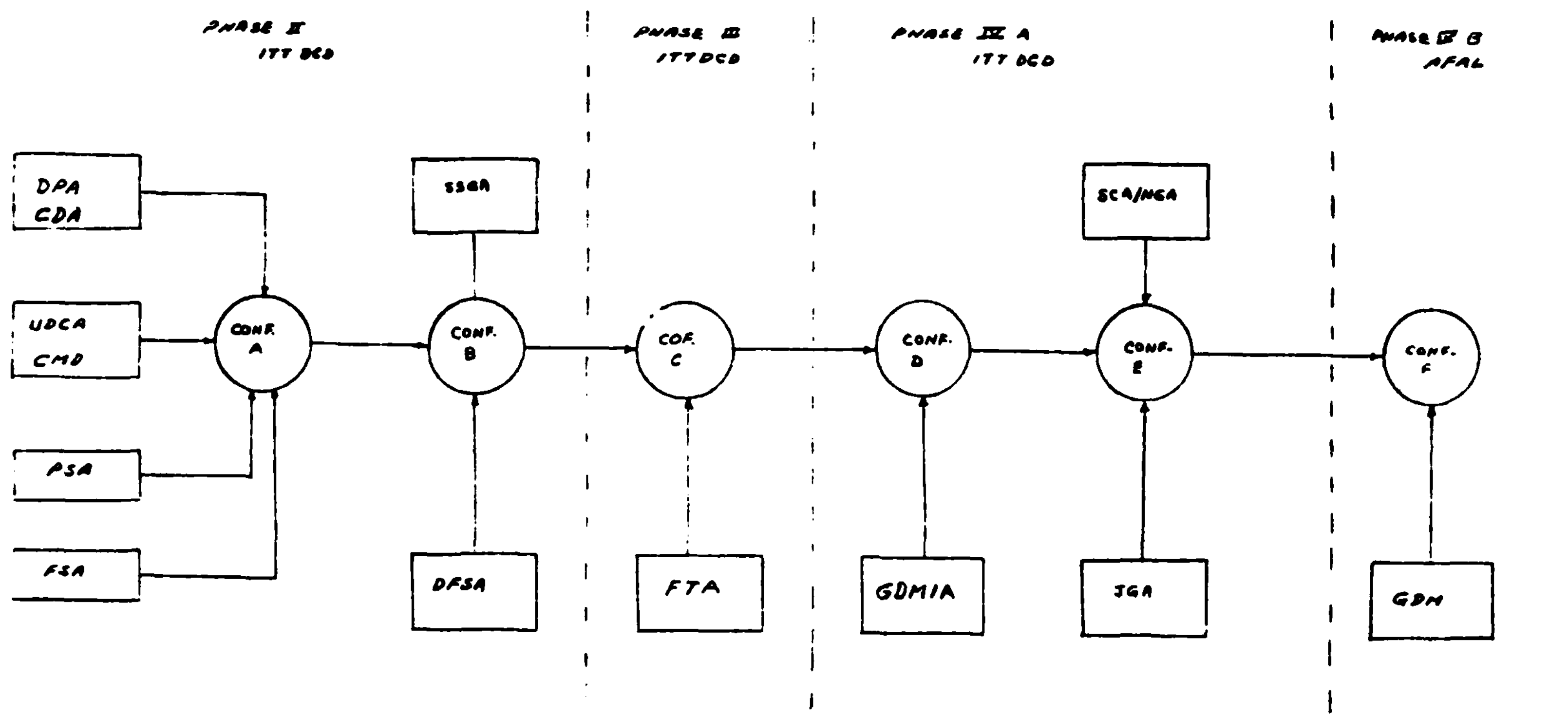

Figure 13. Evolution of the GPSE System

□ : C.I. TEST
○ : SUBSYSTEM TEST

The test plan recognized the functional unit as the basic item under test. Each of the functional units was tested stand-along and then integrated in a top down hierarchical manner. Accordingly, three levels of testing were defined. Each of the tests for all of the functional units, segments, and the programs was carried out according to a previously approved test plan.

a. Unit Testing. The purpose of unit testing is to establish the integrity of the functio.ıal unit under test as an entity. Unit testing involved testing of all the CPC's comprising the unit. Unit testing ensured the following objectives were met:

- That the functional unit fulfills the requirements stated in its applicable specification, and has been coded in accordance with that specification
- That the source code conforms to a uniform stylistic convention, and attains an adequate standard of readability
- That all paths of execution within the functional unit have been exercised, and found to operate normally
- That data inputs/outputs required for interface to other functional units are present
- That the sizes and/or execution times of certain critical functional units do not exceed permissible limits
- That error conditions are properly handled

b. Integration Testing. The purpose of the integration testing is to verify that the functional unit programs properly interface, that the program does operate in its intended software environment, and that all functions are performed as required. Testing will be consistent with the top down method of computer program development in which the top level is developed first and the immediate lower levels are represented by "stubs". When testing of the top level module has been successfully completed, its stub are replaced with next level modules. The integration and test of the program modules proceeds in like manner to the lowest level module.

Test tools, including environmental simulation programs and program stubs, were previously specified and approved. The tests were designed to meet the following objectives:

- Data passage section, functional units is correct
- The control logic for the sequential operation of the functional units is correct
- I/O timing requirements of each task (if any) are met

c. <u>System Integration Testing</u>. The system integration tests are designed to verify that the computer program successfully meets the requirements of the software specifications when operated with hardware system under operational environment. The operational environment for testing, the tests to be performed, and required results were specified in the system test plan.

SECTION VII

OPERATIONS AND MAINTENANCE

The GPS Evaluator system has been developed utilizing latest design techniques so that the system is easy to operate and maintain and also adaptable to various user equipment. However, like many other systems of such magnitude and complexity, routine maintenance and occasional repairs must be anticipated. Also, personnel must be trained to operate such a system properly and efficiently. These requirements were always kept in sight during the complete development and design phase of the GPSE project. Such planning resulted in the production of the following specific learning/training tools (documentation) apart from the required hardware and software functional/product specifications.

GPSE Operation and Maintenance Manual

DPA User's Manual

UDCA User's Manual

Operations and Maintenance Training

GPSE OPERATIONS AND MAINTENANCE MANUAL

The GPSE consists of two types of assemblies/subsystems.

a. Off-the-Shelf Purchased Assemblies: These primarily consisted of the computer (hardware and software) systems; namely PDP 11/70 and PDP 11/04, the Frequency Source, the IRIG Time Code Generator, etc. The documentation generated and supplied by the vendors was supplied to the government for any future maintenance.

b. Special Design Assemblies: These assemblies were specially designed for the GPSE system by ITT or subcontract engineers. Operation and maintenance information was generated for each of the assemblies and modules contained therein. The assignments for this effort were made during the design stage to each of the task leaders. The document generated contained at least the following information regarding each of the assemblies.

- Applicable documents/drawings
- Equipment (Functional and Physical) description
- Theory of operation
- Interface definition
- Test/Trouble shooting procedure

The GPSE Operations and Maintenance (O & M) Manual consists of system operation instructions, preventive maintenance, and calibration instructions and the assembly/module operation and maintenance information (as described above). The O & M Manual is complemented by a handy, easy to use handbook containing all applicable drawings referenced. The drawings are reduced to "B" size for ease of handling.

SOFTWARE (DPA AND UDCA) USER'S MANUAL

The software tasks were treated in a similar manner as the hardware tasks. All the off-the-shelf software purchased (namely, RSX-11M Operating System) was accompanied by the documentation supplied by vendor (Digital Equipment Corp.). Software User's Manuals for both DPA and UDCA computer programs were generated. The following major topics were covered:

- Software capabilities and structure
- Primary output media and formats
- Primary input media and format
- Operating Instructions
- Maintenance Procedures

OPERATIONS AND MAINTENANCE TRAINING

A four-week long operations and maintenance training program was conducted during the final system integration and testing phase. The training planning information containing the course objective, schedule, and the student qualifications was generated and approved by AFAL prior to the actual training.

The presentations regarding each of the major assemblies and computer programs were made by the same engineers who designed the hardware and software. Each of the class-room sessions was followed by actual demonstration in the GPSE test laboratory.

SECTION VIII

GPSE-GDM TESTS

Upon completion of system integration, the GPSE system was interfaced to the General Development Model (GDM) of GPS User Equipment as part of acceptance test. The GDM was procured by the Air Force Avionics Laboratory, Dayton, Ohio.

Initial interface tests took place at ITT Defense Communications Division's facility at Nutley, New Jersey. GPSE-GDM interface, as defined by the interface control document ITT specification no. 1263099, was at first checked out for mechanical and electrical compatibility. Both the GPSE and GDM systems were then shipped to Air Force Avionics Laboratory located at Wright Patterson Air Force Base in Dayton, Ohio.

Both systems were then installed and independently checked out. All of the system integration tests for the GPSE assemblies were repeated as part of installation tests. The GPSE then was interfaced to the GDM and, after initial check-out, final acceptance tests were conducted according to the GPSE Acceptance Test Plan (ITT Specification no. 1263650).

ACCEPTANCE TEST

The acceptance tests were designed to demonstrate that:

- GPSE hardware and software meets or exceeds the performance specification required by GPSE system specification (ITT Specification 1263016)
- GPSE can simulate user motion up to 10 hours duration without any hardware malfunction
- GPSE hardware and software are reliable and repeatable
- GPSE meets the hardware and software requirements of GDM

ACCEPTANCE TEST REPORT

The acceptance tests were conducted in the presence of AFAL personnel and the results were documented in the Acceptance Test Report (ITT Specification No. 1263660).

In the course of the tests it was discovered that the PRN (Baseband) code correlator, as it was designed, would not work reliably and was not repeatable. The design principle was fine. However, the practical limitation of implementation inhibited it from being consistent from baseband to baseband. An alternate procedure, however, was developed which proved to be accurate (as the Baseband Correlator would have been) and reliable. The procedure was documented in Baseband Correlation Procedure (ITT Specification No. 1263653).

The rest of the test results show that the GPSE does meet the requirements described in the previous paragraph. However, the tests as to the navigation accuracy were non-conclusive due to the unreliability and unavailability of the GDM system. It is expected that the attempts to check the navigation accuracy of the GPSE shall continue and also that GPSE shall be proved to be truthful, reliable, and repeatable.

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

The GPSE project successfully proved that it is possible to simulate complete GPS environment including dynamic jamming and User Equipment instrumentation. This was never done before. The GPSE would prove to be a valuable tool to validate and, particularly, evaluate future GPS User Equipment systems. The GPSE experience would be valuable in that it would lead to better and more cost effective UE test systems in the future. The GPSE at present would provide a cheaper (although not so good) alternative to flight test the GPS User Equipment.

Despite the success, however, as in any other research and development projects, many lessons were learned and recommendations were made which should be useful in improving the GPSE or in specifying future test equipments. A few of the recommendations are listed below:

- Automatic Satellite Selection:
  The satellite code select plugs have to be physically changed every time a new satellite has to be simulated. A simple modification can bring this selection under computer (UDCA) control, thus making the job of GPSE operator much easier and less time consuming.

- Automatic GPSE-UE Synchronization:
  The present design requires operator intervention. This can also be brought under UDCA control with minimal change.

- Automatic Baseband Correlation:
  The present design requires the operator to align all five basebands with a reference baseband in order to minimize initial range error (an offset). Although somewhat complex, it is possible to utilize the UDCA computer to perform this function, too. This would not only be less time consuming, but also make GPSE simulation more consistent and repeatable.

- Improved Jammers:

  The present GPSE jammers and noise generator could be made more complex, thereby providing for a more sophisticated hostile environment.

- Increase Satellite Generators:

  The GPSE effectively simulates four satellites (fifth one is used for changeover), which is the minimum GPS requirement for position resolution in real time. Under the GPS orbit configuration, it is possible to have as many as 11 satellites in view. This would require UE to select four out of up to eleven satellites. The present GPSE configuration does not check this (UE) algorithm.

- Increase Choice of Antenna Types:

  The GPSE, at present, gives a choice of three antenna types; isotropic, hemispheric, and HPAA. This, in the future, could be increased or improved very easily.

APPENDIX A

TRADE-OFF ANALYSIS

LEVER ARM EFFECTS

GENERAL BACKGROUND

Lever arm effects arise during attitude changes of an aircraft because of the displacement of the antenna from the aircraft center of gravity. Incremental velocity components are induced at the antenna which are the product of the lever arm displacement by the body rotation rate about axes orthogonal to the lever arm vector. These induced velocities introduce doppler changes in a signal being received from a relatively stationary source such as a satellite. Because of the large body rotation rates and accelerations, these doppler changes, if uncompensated, can cause the carrier tracking loops in the user receiver to lose lock. The simulation must therefore generate a model of these doppler changes, which accurately represents the real world situation, in order to test the effect of these changes upon the user receiver under the most severe body rotation environment to be encountered in the real world.

BASIS FOR TRADE OFF

- Real time processing load
- Capabilities of DFSA
- Fidelity of simulation of dynamics in computed output
- Maximum fexibility and legacy

CONCLUSIONS

The selected approach for simulation of lever arm effects, based upon the results of this analysis, is to compute range derivatives ($\dot{D}$, $\ddot{D}$, $\dddot{D}$) at an update rate of 10 per second, using a third order curve fit to range deviation values computed at the same rate of 10 per second. This is based on the following considerations:

a. The real time processing load is minimized by the use of a computing time interval (T_C) equal to 0.1 seconds for lever arm effects. This is the same value used for center of gravity motion in the pre-computed portion.

b. The range acceleration and jerk capabilities of the DFSA are adequate to provide for a lever arm displacement of 5 meters under the most severe dynamic environment.

c. The use of jerk inputs, at the update rate of 10 per second, produces a range rate ($\dot{D}$) profile which closely matches the real world profile, with no discontinuities in $\dot{D}$.

d. The approach derived from this analysis for simulation of lever arm effects can be easily extended to missile applications (more severe dynamics but smaller lever arms), and is applicable to any type of user equipment.

ANALYSIS

a. Body Rotation Environment

The GPSE specification lists the maximum body rotation rate (about the roll axis) as 400 degrees per second. Information from AFAL sets a limit on roll acceleration at 1200 degrees per second squared. These limits have been used to generate a worst case roll angle profile which is plotted in Figure A-1.

The maximum roll rate of 400 deg/sec corresponds to 7 radians per second. If $\triangle_L$ is the lever arm displacement in meters, then the centripetal acceleration at the antenna, at the maximum roll rate, is given by:

$$A = (7)^2 \times \triangle_L \quad \text{meters/sec}^2$$

From physical strength considerations of the actual antenna structure, a reasonable value of this maximum acceleration is 250 meters/sec^2 (approx. 25 g). Under this restriction, the maximum value of $\triangle_L$ to be used for the maximum roll rate conditions would be:

$$(\triangle_L)_{max} = \frac{250}{49} \cong 5 \text{ meters}$$

Accordingly, a lever arm displacement of 5 meters, either along the aircraft vertical axis or along the wing axis, has been used in this trade off analysis, along with the roll angle profile of Figure A-1. The line-of-sight has been assumed to be in the vertical direction.

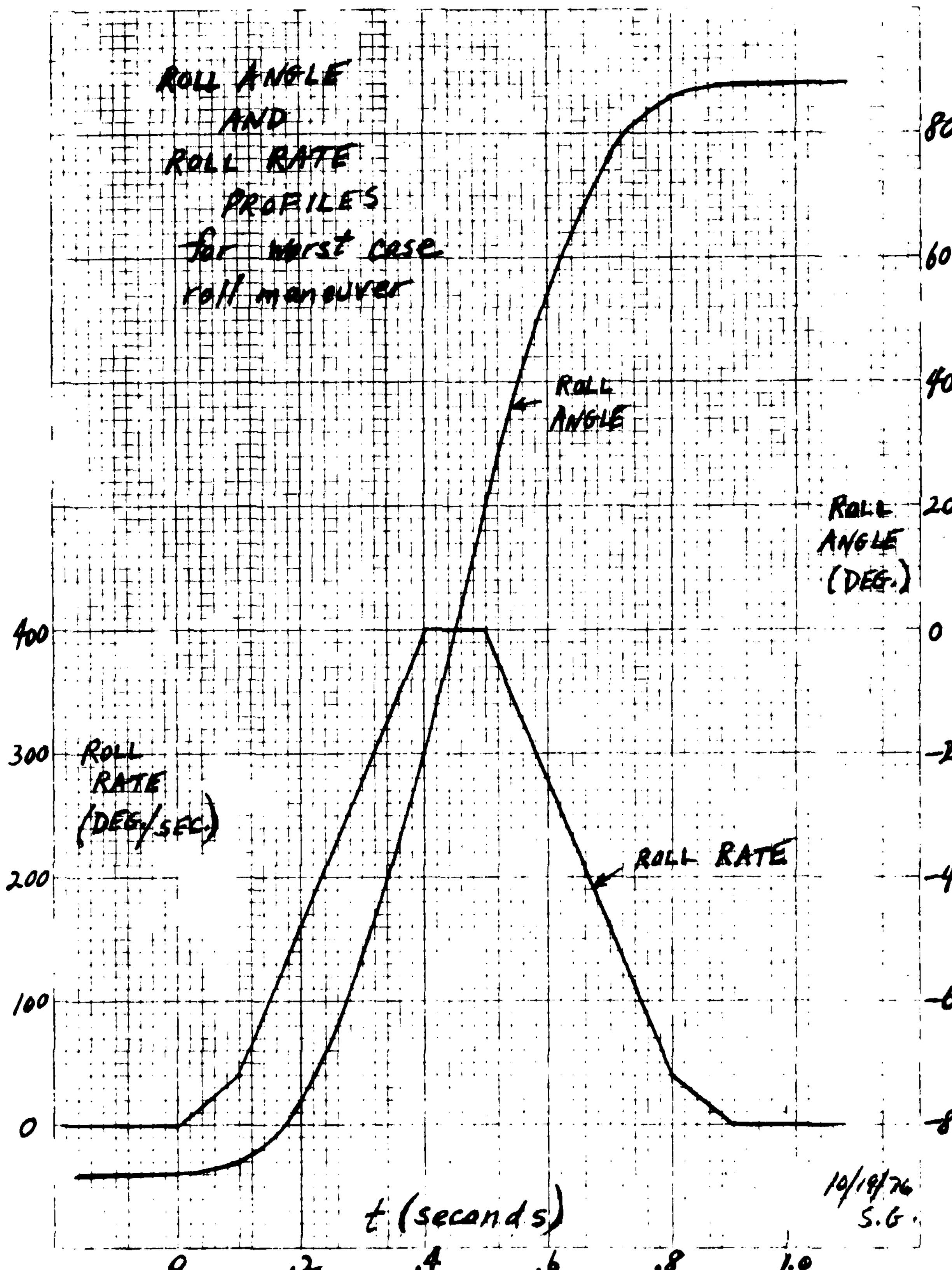

Figure A-1. Roll Angle and Roll Rate Profiles for Worst Case Roll Maneuver

b. Trade Off Parameters

From other simulation considerations, including processing time for the real time portion and tape storage capability for the pre-computed portion, the computing time interval, T_c, has been selected to be 0.1 seconds. This time is also the time between updates to the DFSA. This correspondence between the pre-computed interval and the real time interval greatly simplifies the software design. For purposes of this trade off analysis, we have used this same value of T_c, although the fidelity of the generated velocity profile can obviously be improved by shortening the interval.

We have considered two alternatives, A and B. For alternative, A, values of $\dot{D}$ and $\ddot{D}$ are computed for the lever arm effects by the parabolic curve fit formulas listed in the GPSE Math model on page A-13 of Appendix I. For alternative B, values of $\dot{D}$, $\ddot{D}$ and $\dddot{D}$ are computed by the 3rd order curve fit formulas listed on page B-4 of Appendix II. In both cases, the value of 0.1 seconds is used for T_c.

Alternative A obviously requires less software and computing time than does alternative B. On the other hand, the fidelity of the $\dot{D}$ profile is considerably better for alternative B than it is for alternative A.

For each alternative, the resulting $\dot{D}$ profile is calculated for each of the two lever arm displacement alternatives (along aircraft vertical or along the wing axis).

A. TRADE OFF ANALYSIS RESULTS

For each of the 4 possible conditions, the values of:

t = time from start of maneuver (sec)

R = roll angle (degrees)

Δ_{LOS} = lever arm displacement along line of sight (meters)

$\dot{D}$, $\ddot{D}$, $\dddot{D}$ = inputs to DFSA (meters/sec, etc.)

are tabulated in the following:

Alternative A - No jerk term - Displacement along wing axis

t	R	ΔLOS	$\dot{D}$	$\ddot{D}$
-0.2	-88	-4.997	0	0
-0.1	-88	-4.997	-.023	0.46
0	-88	-4.997	-.250	6.82
0.1	-86	-4.988	-.630	39.86
0.2	-76	-4.851	2.567	109.93
0.3	-54	-4.045	16.815	130.69
0.4	-20	-1.710	34.202	0
0.5	20	1.710	29.884	-130.69
0.6	54	4.045	13.561	-109.93
0.7	76	4.851	3.357	-39.86
0.8	86	4.988	.432	-6.82
0.9	88	4.997	.023	-0.46
1.0	88	4.997	0	0
1.1	88	4.997	0	0

Alternative A - No jerk term - Displacement along aircraft vertical

t	R	ΔLOS	$\dot{D}$	$\ddot{D}$
-0.2	-88	-.174	0	0
-0.1	-88	-.174	.436	-8.71
0	-88	-.174	.409	-43.04
0.1	-86	-.349	-4.721	-77.75
0.2	-76	-1.210	-15.046	-44.94
0.3	-54	-2.939	-21.919	86.47
0.4	-20	-4.698	-8.798	175.95
0.5	20	-4.698	13.272	86.47
0.6	54	-2.939	19.540	-44.94
0.7	76	-1.210	12.496	-77.75
0.8	86	-.349	3.895	-43.04
0.9	88	-.174	.436	-8.71
1.0	88	-.174	0	0
1.1	88	-.174	0	0

Alternative B - With jerk - Displacement along wing axis

t	R	Δ LOS	$\dot{D}$	$\ddot{D}$	$\dddot{D}$
-0.3	-88	-4.997	0	0	0
-0.2	-88	-4.997	0	0.15	-5
-0.1	-88	-4.997	-.008	1.51	-41
0	-88	-4.997	-.060	4.36	-40
0.1	-86	-4.988	.177	3.82	597
0.2	-76	-4.851	3.546	34.78	1667
0.3	-54	-4.045	15.361	167.47	-231
0.4	-20	-1.710	30.954	194.87	-3897
0.5	20	1.710	30.954	-144.39	-231
0.6	54	4.045	15.361	-201.52	1667
0.7	76	4.851	3.546	-63.56	597
0.8	86	4.988	.177	-0.38	-40
0.9	88	4.997	-.060	2.57	-41
1.0	88	4.997	-.008	0.30	-5
1.1	88	4.997	0	0	0
1.2	88	4.997	0	0	0

Alternative B - With jerk - Displacement along aircraft vertical

t	R	Δ_{LOS}	$\dot{D}$	$\ddot{D}$	$\dddot{D}$
-0.3	-88	-.174	0	0	0
-0.2	-88	-.174	0	-2.90	87
-0.1	-88	-.174	.145	0.18	-92
0	-88	-.174	-.299	-0.66	-846
0.1	-86	-.349	-4.597	-62.66	-527
0.2	-76	-1.210	-13.498	-105.00	873
0.3	-54	-2.939	-19.634	-64.57	3160
0.4	-20	-4.698	-10.289	205.78	0
0.5	20	-4.698	10.289	251.47	-3160
0.6	54	-2.939	19.634	-17.73	-873
0.7	76	-1.210	13.498	-115.35	527
0.8	86	-.349	4.597	-85.30	846
0.9	88	-.174	.299	-9.07	92
1.0	88	-.174	-.145	5.81	-87
1.1	88	-.174	0	0	0
1.2	88	-.174	0	0	0

The $\dot{D}$ profiles, derived from the preceding tables, are plotted for the 4 test conditions in Figures A-2, 3, 4 and 5. Note that, for alternative A (Figures A-2, A-3), there are $\dot{D}$ discontinuities at the 0.1 second transition points, amounting to as much as 4 or 5 meters per second. For alternative B (Figures A-4, A-5), there are no $\dot{D}$ discontinuities, but there are discontinuities in $\ddot{D}$. In order to better illustrate these $\ddot{D}$ discontinuities, the $\ddot{D}$ profiles are plotted for the 4 test conditions in Figures A-6 and A-7 (solid line for alternative B and dotted lines for alternative A). Note that the $\ddot{D}$ discontinuities are as high as 130 meters/sec^2 for alternative A, and as high as 50 meters/sec^2 for alternative B.

Comparing Figures A-2 and A-3 with their counterparts in Figures A-4 and A-5, it is seen that alternative B gives a much smoother $\dot{D}$ profile than does alternative A. It should be pointed out, however, that integration of the $\dot{D}$ profile, for any of the alternatives, always gives the precisely correct value of Δ_{LOS} at the 0.1 second time marks.

We have consulted with CSDL on the performance characteristics of the DFSA, in regard to the effect upon performance of the derivative discontinuities and the increased $\ddot{D}$ and $\dddot{D}$ limits. They feel strongly that there will be no problem in breaking lock in their phase locked loops under these conditions for either of the alternatives.

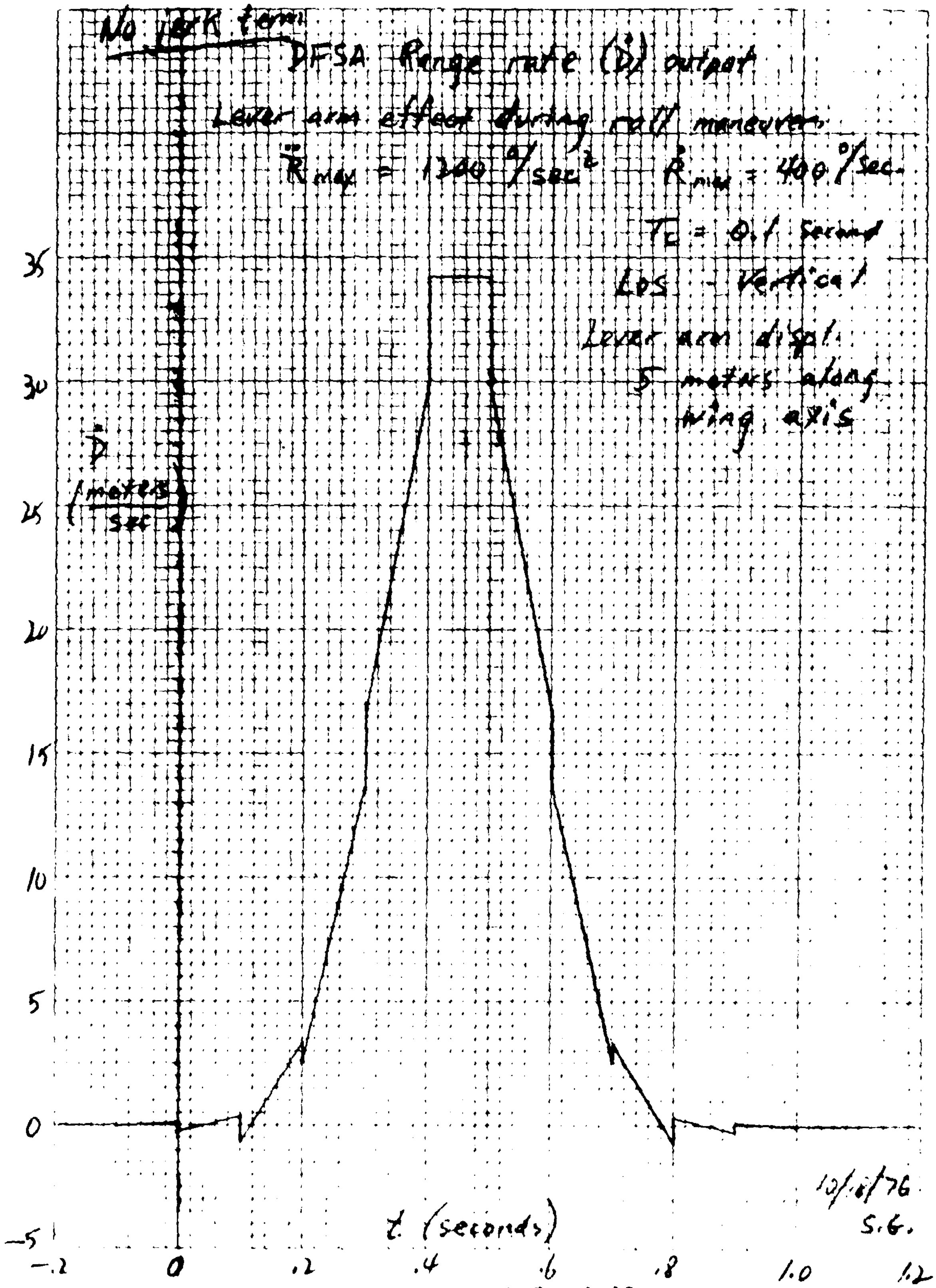

Figure A-2. Alternative A (Sheet 1 of 2)

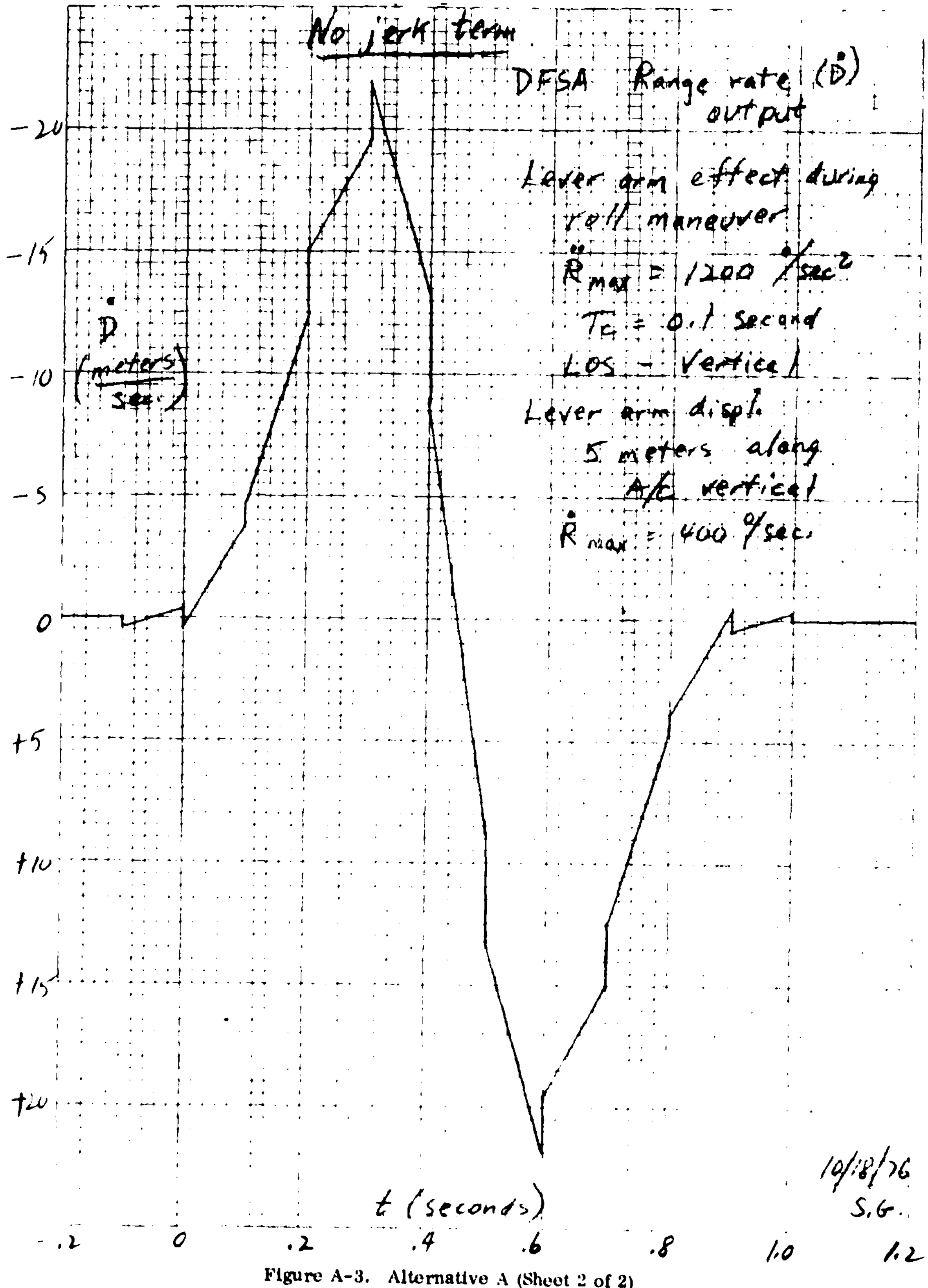

Figure A-3. Alternative A (Sheet 2 of 2)

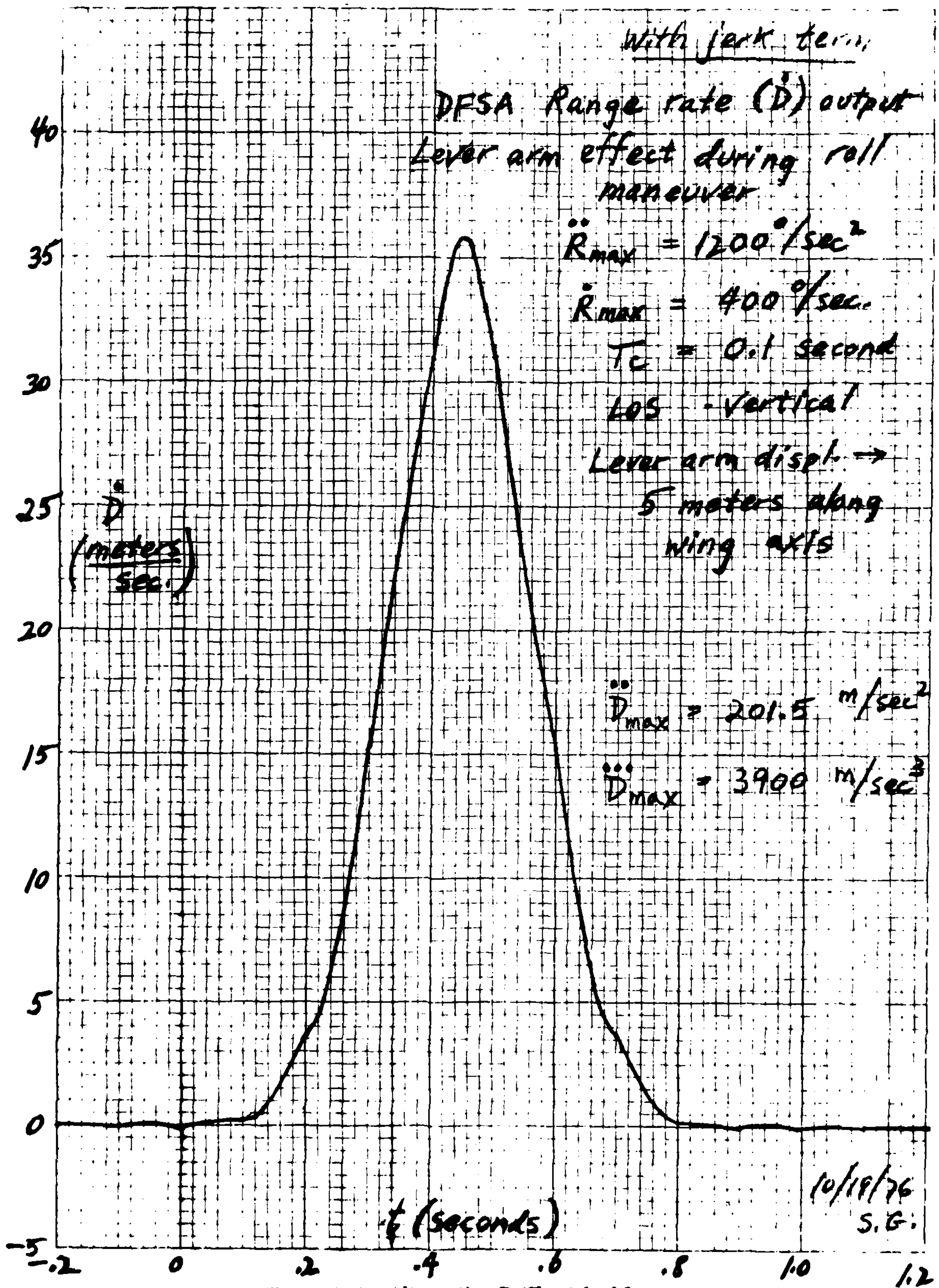

Figure A-4. Alternative B (Sheet 1 of 2)

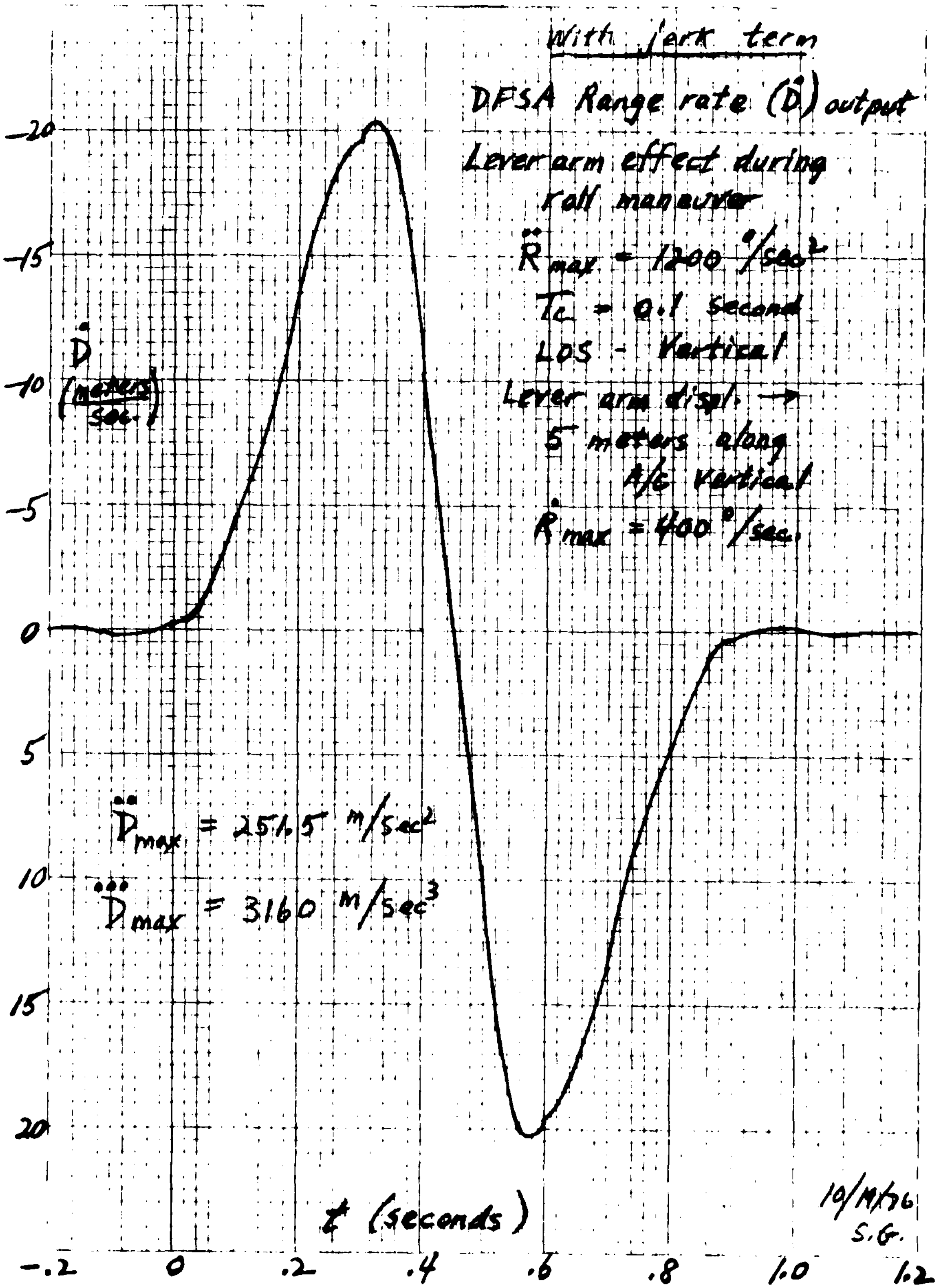

Figure A-5. Alternative B (Sheet 2 of 2)

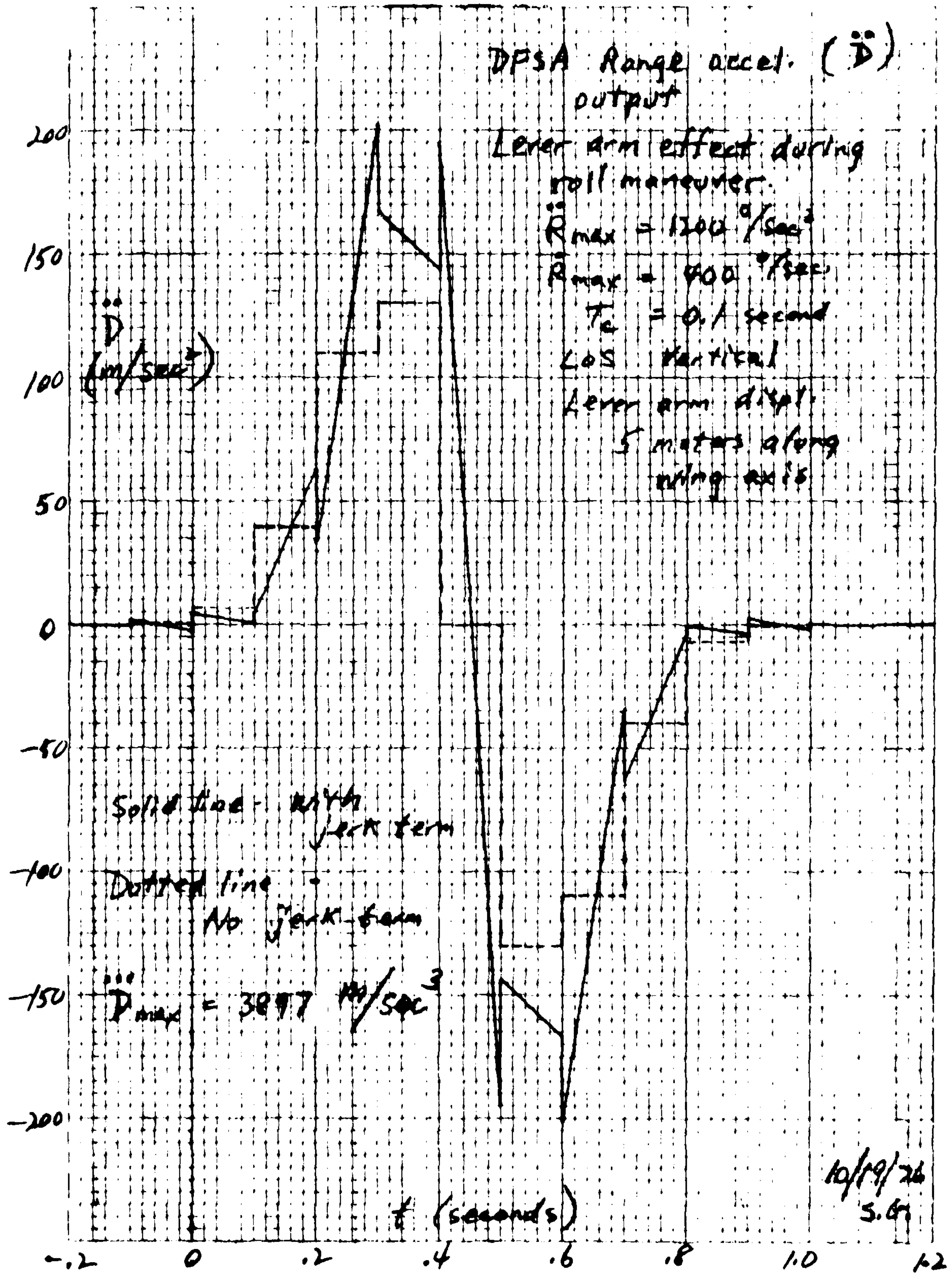

Figure A-6. D Profiles (Sheet 1 of 2)

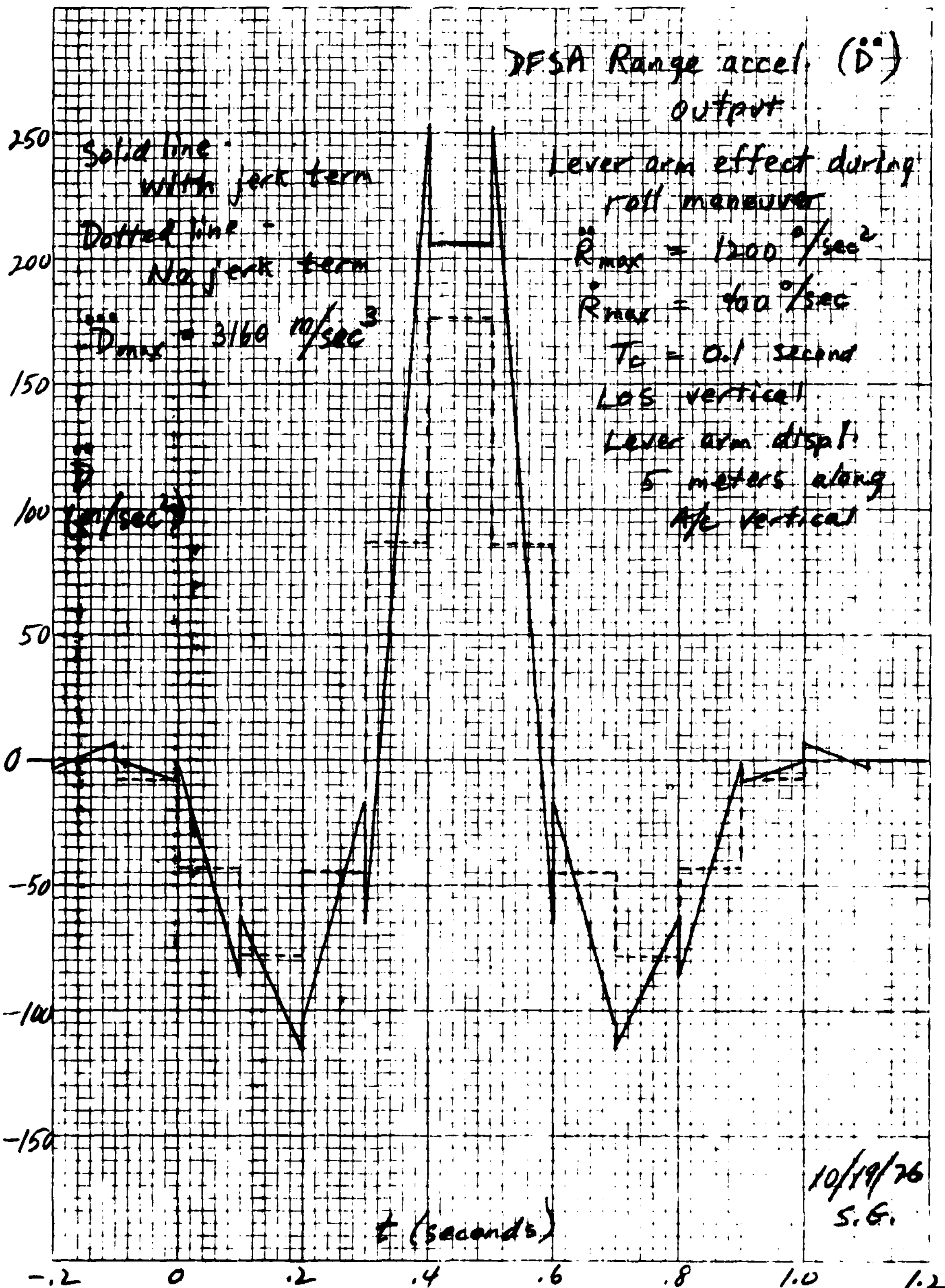

Figure A-7. D Profiles (Sheet 2 of 2)

APPENDIX B

POST RUN PROCESSING CONCEPT STUDY

INTRODUCTION

This appendix presents the functional concepts that are planned for use in generating the post run processing DPA software for the GPS Evaluator System as applied to the GDM User Equipment. The type of data to be collected, as well as the type of analyses that are planned, are presented.

The post run analysis (PRA) will be divided into two major tasks:

- PRA for Navigation Mode
- PRA for Specification Validation Mode

Concepts for the two modes will be discussed separately.

PRA FOR NAVIGATION MODE

Truth data for user aircraft position and velocity will be stored on the pre-computed tape. Similar data, as generated by the GDM, will be time tagged and stored, during the run, on the PRA tape. For the post run analysis, data from the two tapes will be read off and processed.

Attitude data (sine and cosine of azimuth, pitch, and roll) will also be present on the pre-computed data. However, the GDM being tested does not generate its own attitude data. The unit under test simply reads attitude outputs from the IMU simulator, which is part of the GPS Evaluator. Therefore, a post run analysis of attitude data would simply indicate what the GPSE is doing, and would not be dependent upon any performance capability of the GDM unit being tested. Because of this, post run analysis of attitude data can be omitted.

The GPSE and the GDM being tested will be time synchronized, before the start of the run, such that the truth data from the GPSE and the instrumentation data from the GDM will both always be referred to integral 100 millisecond time tags. The post run analysis will simply match up these time tags before comparison to determine error quantities. Since the time tags will be precisely synchronized, no interpolation process will be required.

The truth data on the pre-computed tape, relating to user aircraft position and velocity, will consist of the following:

<u>Every 100 Milliseconds</u>

Time tag	t
Aircraft height	H
Direction cosines, local vertical to ECEF axes	C_{vx}, C_{vy}, C_{vz}

Aircraft velocity components, referred to platform axes $\Big\}$ V_N, V_E, V_V

Every 1 second

Direction cosines, (wander N, E) to ECEF axes $\Big\}$ $\begin{cases} C_{nx}, C_{ny}, C_{nz} \\ C_{Ex}, C_{Ey}, C_{Ez} \end{cases}$

The instrumentation data from the GDM will include the same data, based upon its own determination of the platform axis orientations, with the exception of the direction cosines C_{Ex}, C_{Ey}, C_{Ez}. In the following description, GDM instrumentation data will be indicated by a prime superscript on the symbol.

The post run analysis will sample the truth data and GDM instrumentation data at some time interval which is an integral multiple of 100 milliseconds for comparison and determination of error quantities. The value of this integral multiple will be under control of the operator.

The basic error quantities to be determined are:

- Height error $e\ (P_V)$
- Horizontal position error (magnitude only) $e\ (P_H)$
- Vertical velocity error $e\ (V_V)$
- Horizontal velocity error (magnitude only) $e\ (V_H)$

Relationships for determination of these 4 basic errors are:

$$e\ (P_V) = H' - H$$

$$e\ (R_A) = R_E \begin{pmatrix} (C_{vy} C_{vx}' - C_{vx} C_{vy}')^2 \\ + (C_{vz} C_{vy}' - C_{vy} C_{vz}')^2 \\ + (C_{vx} C_{vz}' - C_{vz} C_{vx}')^2 \end{pmatrix}^{1/2}$$

In the above, R_E is the nominal Earth radius. Since this is only a scaling factor for error quantities, compensation for height and latitude variation is not necessary.

$$e(V_V) = V_v' - V_v$$

To determine $e(V_H)$ it is necessary to compute, as an intermediate quantity, the platform rotation error about the vertical axis. This rotation error (in wander angle) is designated as $e(\alpha)$, in radians.

$$\begin{aligned} e(\alpha) = {} & C_{Ex}(C'_{Nx} - C_{Nx}) \\ & + C_{Ey}(C_{Ny}' - C_{Ny}) \\ & + C_{Ez}(C_{Nz}' - C_{Nz}) \end{aligned}$$

From this, the horizontal velocity error magnitude is determined as:

$$e(V_H) = \left(\begin{array}{l} (V_N' - V_N)^2 + (V_E' - V_E)^2 \\ + \left[(V_N')^2 + (V_E')^2\right]\left[e(\alpha)\right]^2 \\ + 2e(\alpha)(V_N' V_E - V_E' V_N \end{array} \right)^{\frac{1}{2}}$$

If desired, the horizontal position error, $e(P_H)$, and the horizontal velocity error, $e(V_H)$ may be resolved into orthogonal components. Choice of reference axes are:

- True North, East
- Wander North, East
- Along and across ground track

Resolution into true North and East components will have a singularity at the North or South poles. The other two sets of reference axes will not have any singularity.

For the wander North, East resolution:

$$\begin{aligned} e(P_N) = R_E\Big[& C_{Nx}(C_{vx}' - C_{vx}) \\ & + C_{Ny}(C'_{vy} - C_{vy}) \\ & + C_{Nz}(C'_{vz} - C_{vz})\Big] \end{aligned}$$

$$\begin{aligned} e(P_E) = R_E\Big[& C_{Ex}(C_{vx}' - C_{vx}) \\ & + C_{Ey}(C_{vy}' - C_{vy}) \\ & + C_{Ez}(C_{vz}' - C_{vz})\Big] \end{aligned}$$

$$e(V_N) = V_N' - V_N + V_E' \, e(\alpha)$$

$$e(V_E) = V_E' - V_E - V_N' \, e(\alpha)$$

For the along (AT) and across (CT) track resolution:

$$V_H = \left(V_N^{\,2} + V_E^{\,2} \right)^{\frac{1}{2}}$$

$$e(P_{AT}) = \frac{V_N \, e(P_N) + V_E \, e(P_E)}{V_H}$$

$$e(P_{CT}) = \frac{V_N \, e(P_E) - V_E \, e(P_N)}{V_H}$$

$$e(V_{AT}) = \frac{V_N \, e(V_N) + V_E \, e(V_E)}{V_H}$$

$$e(V_{CT}) = \frac{V_N \, e(V_E) - V_E \, e(V_N)}{V_H}$$

For the true North (TN) and true East (TE) resolution:

$$\cos \phi = \left(1 - C_{vz}^{\,2} \right)^{\frac{1}{2}}$$

where ϕ is the latitude of the user.

$$e(P_{TN}) = \frac{C_{Nz} \, e(P_N) + C_{Ez} \, e(P_E)}{\cos \phi}$$

$$e(P_{TE}) = \frac{C_{Nz} \, e(P_E) - C_{Ez} \, e(P_N)}{\cos \phi}$$

$$e(V_{TN}) = \frac{C_{Nz} \, e(V_N) + C_{Ez} \, e(V_E)}{\cos \phi}$$

$$e(V_{TE}) = \frac{C_{Nz} \, e(V_E) - C_{Ez} \, e(V_N)}{\cos \phi}$$

For each time sequence of error quantities, the post run analysis will generate statistical quantities such as bias value and standard deviation for print out and evaluation. In additon, quick look results will be processed for display to the operator.

PRA FOR SPECIFICATIONS VALIDATION MODE

There are 4 specification validation modes for the GPSE, as referenced in spec. RWM-SS-302, paragraph 3.1.1.2.3. The reference is to spec. RWM-SS-202, as follows:

3.2.1.1.1 Signal re-acquisition

3.2.1.1.2 Synchronization recovery

3.2.1.1.3 Jamming immunity

3.2.1.1.4 Data recovery

a. Signal Re-Acquisition

Input parameters, as listed in para. 3.2.1.1.1 of RWM-SS-202, are:

- Loss period (seconds)
- J/S ratio (dB)
- Position uncertainty (meters)
- Velocity uncertainty (m/sec)
- Acceleration uncertainty (m/sec^2)
- Jerk uncertainty (m/sec^3)

Output parameters are:

- Re-acquisition time (seconds)
- Probability of re-acquisition

The acceleration and jerk uncertainties are listed as "Inertial Compatible". Since the GPSE simulates an actual IMU as realistically as possible, the acceleration and jerk uncertainties will always be "Inertial Compatible," and there is not need to record or process outputs related to these quantities.

The length of the loss period will be determined by means of the time tags associated with the GDM event markers denoting "loss of signal" and "reappearance of signal".

The J/S ratio as a continuous time function will be available from the pre-processed tape in terms of signal attenuation outputs for each satellite and each jammer:

Y_S for the satellites

Y_J for the jammers

Since position and velocity errors (GDM outputs referred to pre-computed truth data) are available as part of the Navigation Mode PRA (see Section 2 of this document), the values of the position and velocity uncertainty at the time of "reappearance of signal" are known. These uncertainties can be controlled by suitable choice of error quantities into the IMU model.

The user flight profile and jammer scenario will be planned to exercise the signal re-acquisition performance of the GDM over the complete range of input parameters as specified in RWM-202. Means will be provided to cause a sufficient number of signal loss situations to yield a reasonable confidence factor in the determination of the probability of re-acquisition (approximately 200 situations based upon the specified probability of 0.95).

b. Synchronization Recovery

Input parameters, as listed in para. 3.2.1.1.2 of RWM-SS-202, are:

- J/S ratio (dB)
- Vehicle velocity (m/sec)
- Vehicle acceleration (m/sec^2)
- Vehicle jerk (m/sec^3)

Output parameter is probability of synchronization.

The J/S ratio will be determined in the same manner as discussed in paragraph a, above, on Signal Re-Acquisition.

Vehicle velocity and acceleration are available from truth data on the pre-computed tape. Vehicle jerk is not available explicitly, but can be determined by differencing of successive acceleration outputs.

The user flight profile and jammer scenario will be planned to exercise the synchronization recovery performance of the GDM over the complete range of input parameters as specified in RWM-202. There will be a sufficient number of synchronization recovery situations generated by the GDM in the sequential mode, to yield a reasonable confidence factor in the determination of the probability of synchronization (approximately 1000 situations based upon the specified probability of 0.99).

c. Jamming Immunity

Input parameters, as listed in para. 3.2.1.1.3 of RWM-SS-202, are:

- J/S ratio (dB)
- Operating mode

Output parameters are:

- Maximum J/S for initial signal acquisition
- Maximum J/S for maintaining system lock
- Maximum J/S for maintaining system track
- Maximum J/S for synchronization recovery (associated with paragraph b, above, on Synchronization Recovery)
- Maximum J/S for maintaining carrier track

Determination of these output parameters requires the following GDM event markers, along with time tags:

- Signal acquisition
- Loss of system lock
- Loss of system track
- Synchronization recovery
- Loss of carrier track

For each GDM operating mode, the jamming scenario will be planned to start from some low J/S ratio (less than 34 dB) and to gradually increase the J/S ratio until all the GDM event markers indicate a failure to derive information from the signal. Each of these situations will be repeated a sufficient number of times (approximately 10) to demonstrate the repeatability of the results.

The actual J/S ratio at the event markers is determined in the same manner as discussed in paragraph a, above, on Signal Re-Acquisition.

d. Data Recovery

Input parameters, as listed in para. 3.2.1.1.4 of RWM-SS-202, are:

- J/S ratio (dB)
- Jammer type

Output parameter is bit error rate (BER).

For the various jammer types, the required J/S ratio will be set, and a real time bit-by-bit comparison will be made between the truth navigation data and the data as recovered by the GDM receiver. Bit errors will be counted over a 6 hour period. Since the bit rate is 50 per second, the 6 hour comparison period represents a total of 1,080,000 bits, which will yield a reasonable confidence factor on the BER requirement of less than 10^{-5}. This will require that the demodulated data output from the GDM receiver be available as an external interface.

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