REPORT SAMSO-TR-75-255, VOL I

B.S. 12

GENERALIZED TRAJECTORY SIMULATION

Volume I: Overview

TRAJECTORY ANALYSIS PROGRAMMING DEPARTMENT
Information Processing Division
Engineering Science Operations
The Aerospace Corporation
El Segundo, Calif. 90245

21 November 1975

Final Report

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

Prepared for
AIR FORCE ROCKET PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
Edwards Air Force Base, Calif. 93523

and THE AEROSPACE CORPORATION

SPACE AND MISSILE SYSTEMS ORGANIZATION
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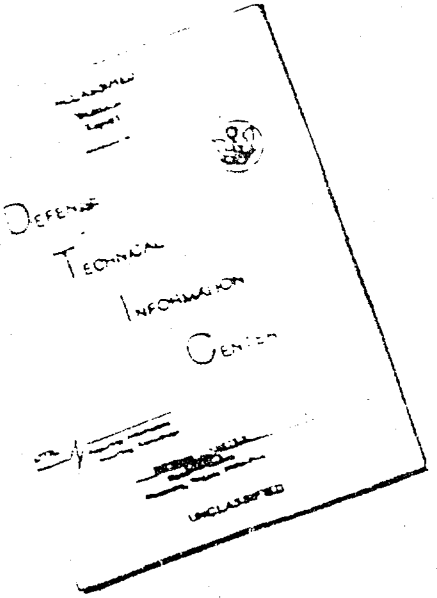
Los Angeles, Calif. 90009


UNCLASSIFIED
Defense
Technical
Information
Center
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This report was prepared by The Aerospace Corporation, El Segundo, California, under Contract F04701-75-C-0076 with the Space and Missile Systems Organization (AFSC), P.O. Box 92960, Worldway Postal Center, Los Angeles, California 90009. The work was sponsored by the Air Force Rocket Propulsion Laboratory (AFSC), Edwards AFB, California 93523, with Capt. Francis Lymburner as project officer. This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public including foreign nationals.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(18) 1. REPORT NUMBER (19)
SAMSO-TR-75-255 Vol I

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) The Generalized Trajectory Simulation System. Volume I: Overview,

5. TYPE OF REPORT & PERIOD COVERED
Final Report
1-1-75 to 8-31-75

6. PERFORMING ORG. REPORT NUMBER (14)
TR-0076(6666)-1 Vol I

7. AUTHOR(s)
Trajectory Analysis Programming Department
Information Processing Division
Engineering Science Operations

8. CONTRACT OR GRANT NUMBER(s) (15)
F04701-74-C-0075,
F04701-75-C-0070

9. PERFORMING ORGANIZATION NAME AND ADDRESS
The Aerospace Corporation
El Segundo, California 90245

(9) Final rept. 1 Jan 75 — 31 Aug 75.

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS (11)
Space and Missile Systems Organization
Air Force Systems Command
Los Angeles, Calif. 90045

12. REPORT DATE
21 Nov[redacted]75

13. NUMBER OF PAGES
45 (12) 46p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Air Force Rocket Propulsion Laboratory
Air Force Systems Command
Edwards Air Force Base, Calif. 93523

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DDC

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)

CDC 6000/7000	Remote Terminal Access	Launch Support
Modularized Program	Trajectory Analysis	Error Analysis
Software System	Flight Dynamics	Optimization
Physical Modeling	Boost Vehicle Simulation	Least Squares
Verification and Validation	Reentry Vehicle Simulation	Interpolation

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

The Generalized Trajectory Simulation (GTS) system provides a vehicle design and trajectory simulation capability. GTS is written in FORTRAN compatible with CDC 6000/7000 series computer systems. User-oriented input data specifications, computational efficiency, diverse program applicability, and convenient program modifications have been primary considerations in the design of the GTS system. The trajectory simulation capability can accommodate diverse types of vehicle configurations, flight

DD FORM 1473 FACSIMILE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

404 661

19 KEY WORDS (Continued)

Guidance and Targeting
Trajectory Simulation
Flight Mechanics
Powered Flight Simulation
Orbital Analysis
Performance Analysis
Dynamic Systems Simulation
Post Flight Reconstruction
Numerical Operators
Numerical Integration
Nonlinear Programming
Solid Rocket Motor Sizing
Vehicle Weight Estimation
Propellant Technology
Vehicle Sizing
Vehicle Design
Pre-processors
Symbolic Input Language

20 ABSTRACT (Continued)

profiles, and mission objectives. Additionally, the GTS system contains an extensive vehicle sizing capability and a state-of-the-art optimization capability. The computer memory requirement depends upon the application of the system. GTS applications on 6000 series computers typically require 125K to 160K octal words of memory. For the 7000 series computers, GTS applications typically require 120K to 160K octal words of small core memory (SCM) and 50K to 100K octal words of large core memory (LCM).

This volume provides the potential user an overview of the GTS system. Included is a summary of the major operational capabilities and the structural design of the GTS system.

PREFACE

This volume, the first of five volumes that describe the Generalized Trajectory Simulation (GTS) system, provides the potential user with an overview of GTS, including a summary of the major operational capabilities and structural design of the GTS system. The remaining volumes are:

> Volume II: GTS Usage Guide. This document serves as a general usage guide for GTS and includes a set of example problems, a comprehensive description of the Generalized Trajectory Language, and a discussion of the trajectory simulation control. In addition, a set of appendices contain a master reference list for all volumes and supplementary information to aid the user in defining his problem.
>
> Volume III: GTS Flight Dynamic Models. This publication deals with the GTS library of flight mechanics and flight dynamics models utilized for trajectory simulations.
>
> Volume IV: GTS Numerical Operators. This report concerns the GTS library of numerical operators, including integration, optimization, and interpolation operators.
>
> Volume V: GTS Weight Estimation Models for Sizing Applications. This volume documents the GTS library of weight estimation models utilized for sizing applications.

This report was prepared by D. S. Meder and J. L. Searcy.

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SECTION 1
INTRODUCTION

This document is the first of a set of five volumes that describe the Generalized Trajectory Simulation (GTS) system. The intent of the first volume is to provide the potential user with an overview of the capabilities and structural design of the GTS system. Successive volumes provide a more detailed description of the various components of the GTS system and a description of the input data required to execute the software. The remaining volumes of the documentation series are:

Volume II.	GTS Usage Guide
Volume III.	GTS Flight Dynamics Models
Volume IV.	GTS Numerical Operators
Volume V.	GTS Weight Estimation Models for Sizing Applications

The Generalized Trajectory Simulation (GTS) system comprises a linked set of digital computer programs used for many Aerospace Corporation boost, satellite, and reentry vehicle/mission simulation studies. GTS satisfies the requirements for trajectory simulations, vehicle sizing, and optimization capabilities beyond those available in other computational tools. Architecturally, the software system exploits the logical concept of complete separation of mathematical operations, physical modeling, and software control functions. The system software is completely programmed, with some minor exceptions, in a FORTRAN language compatible with CDC 6000/7000 series computers. Applications may be submitted to the system via the normal card reader input queue or, alternately, from remote terminals.

The primary design consideration for the GTS system has been the provision of an easy-to-use software tool that permits a variety of users, with diverse applications, to individually balance their requirements for completeness and accuracy with cost and time constraints. Consequently, user-oriented input data specification, computational efficiency, wide applicability, and straightforward software development and modification features have been primary objectives in the design of the program. These objectives have been accomplished, in part, by carefully separating the mathematical operators, the engineering models, and the executive program control functions. The logic governing the interconnection between program components is under input processing control. As a result of this design, the user's input data is processed and related to a directory of GTS subroutines so that the minimal software configuration required for the particular application is automatically loaded and executed.

The modular design of GTS provides an exceptionally convenient means by which modifications or extensions of the existing capabilities can be implemented, validation and verification of new models accomplished, and overall operating efficiency maintained at a high level. These features are of particular value in those applications which are exploratory in nature. The major components of the GTS system are given in Table 1.

1.1 GTS Operational Capabilities

The major functions and capabilities of the GTS system are summarized in this section to provide a convenient introductory reference. Each of the significant capabilities is briefly described in subsequent paragraphs of this section.

1.1.1 Trajectory Simulation

The GTS trajectory simulation capability provides a basic framework to define and control a diversity of vehicle and mission simulations. The user may define new physical models or select models from an existing large library of flight dynamic models. A complete description of the existing models is provided in Volume III. The GTS trajectory control feature allows a wide degree of flexibility for the specification of required flight profiles and mission objectives. General areas of application of the trajectory simulation capability are indicated in Table 2.

Table 1. Principal Components of the GTS System

- A SIMULATION LIBRARY OFFERING A LARGE SELECTION OF MATHEMATICAL OPERATORS AND PHYSICAL MODELS REQUIRED FOR THE ANALYSIS OF VEHICLE MISSION SYSTEMS
- THE GENERALIZED TRAJECTORY LANGUAGE PREPROCESSOR (GTL), WHICH SCANS AND INTERPRETS THE USER-ORIENTED INPUT DATA, EXTRACTS AND REFORMULATES MANY IMPLIED FUNCTIONS, AND GENERATES THE GTS MODEL DATA REQUIREMENTS FOR THE PARTICULAR PROBLEM
- A PREPROCESSOR PROGRAM WHICH CORRELATES THE MODEL-DATA REQUIREMENTS PRODUCED BY GTL WITH A DETAILED DIRECTORY OF THE PROGRAM'S SUBROUTINE INTERCONNECTIONS AND FROM THIS GENERATES THE REQUIRED PROGRAM CONFIGURATION FOR THE PARTICULAR PROBLEM
- GTS MASTER EXECUTIVE WHICH EXECUTES THE REQUIRED PROGRAM CONFIGURATION, USING THE APPROPRIATE PROCESSING CAPABILITIES TO SOLVE THE PARTICULAR PROBLEM

Table 2. Representative Trajectory Simulation Applications

- VEHICLE CAPABILITY ANALYSIS
- BOOSTER SELECTION
- MISSION REFERENCE TRAJECTORIES
- LAUNCH WINDOW STUDIES
- VEHICLE STABILITIES STUDIES
- LAUNCH SUPPORT
- GUIDANCE EQUATION DEVELOPMENT
- LIFTING BOOST VEHICLE ANALYSIS
- RECOVERABLE BOOSTER STAGING
- BALLISTIC AND MANEUVERING REENTRY VEHICLES
- AIRCRAFT TRAJECTORY SIMULATION
- ERROR ANALYSIS
- POSTFLIGHT RECONSTRUCTION
- SOFTWARE VALIDATION
- SOFTWARE VERIFICATION
- TUMBLING TURN ANALYSIS
- LOW THRUST ORBITAL MANEUVERS
- ABORT PROPULSION REQUIREMENTS
- DE-ORBIT PROPULSION REQUIREMENTS
- RENDEZVOUS MISSION STUDIES
- FLIGHT SAFETY SYSTEMS
- TERMINAL MANEUVER ANALYSIS
- ASCENT AND ORBITAL ABORT STUDIES
- FILTER RADAR TRACKING DATA
- SATELLITE SYSTEM ANALYSIS
- CONTROL SYSTEM STUDIES
- ORBITAL TRANSFER OPTIMIZATION
- ORBIT LIFETIME STUDIES
- DEBRIS DISPERSION STUDIES
- INTERPRETIVE COMPUTER SIMULATION (ICS)

1.1.2 Optimization

The GTS system includes a general purpose nonlinear constrained optimization capability that can be utilized independently or in conjunction with the trajectory simulation and vehicle sizing capabilities. The optimization capability is designed to optimize (i. e., maximize or minimize) an objective function, f(x), where x is a vector, subject to a set of nonlinear equality and inequality constraints. The operator is mechanized to utilize analytic partial derivatives, if available; otherwise numerical partial derivatives are computed. The optimization features of the GTS system are described, in detail, in Volume IV.

1.1.3 Vehicle Sizing Analysis

The GTS vehicle sizing models provide a vehicle sizing capability for space and missile vehicles that utilize solid propellant rocket motors. Liquid propelled vehicles can also be accommodated within the sizing procedure. They, however, require the development of specialized weight estimation models to represent particular characteristics of the desired liquid propellant system.

The sizing models estimate performance sensitive component weights to determine a vehicle configuration consistent with realistic geometry and mission constraints.

Intended applications include preliminary design studies, booster subsystem trade-off studies, and growth studies of existing systems including the analysis of advanced propellant technology or new launching concepts. The existing library of weight estimation models is completely documented, including information on their use and interface with other capabilities of the GTS system, in Volume V.

1.1.4 Generalized Trajectory Language (GTL)

The input to all of the operational capabilities of the GTS system is via a higher level symbolic input language especially designed to accommodate trajectory simulations, vehicle sizing, and optimization applications. GTL not only controls the input of data to the program, it also is used to select and build the actual software configuration that is loaded into the computer and executed.

GTL provides a free form, user-oriented input method that is straightforward to learn and use. This approach encourages concentration on the input requirements of the engineering application with little, or no, concern for the intricate details of the software. The input language also allows a user to include FORTRAN subroutines as a portion of the input data deck. These routines are processed at program execution time and utilized in a fashion similar to any other model within the GTS system. The GTL language is described in Volume II.

SECTION 2

GTS SYSTEM CHARACTERISTICS

A description of the characteristics of the major GTS system capabilities is presented in this section. A detailed description of these capabilities, including a discussion of the input data required to apply these capabilities to specific problems, is presented in the remaining volumes of the GTS documentation series.

2.1 Trajectory Applications

The trajectory simulation capability of the GTS system is applicable to a variety of vehicle configurations, mission trajectory profiles, and mission objectives, as indicated by Table 2. Moreover, the modular structure of the GTS system enables the user to satisfy his particular requirements for efficiency and completeness. The basis of the trajectory simulation capability is a set of flight dynamic models. The organization of these models typifies the modular design of GTS. This organization is discussed in the next section. An overview of the manner by which these individual models are incorporated into a trajectory simulation is then discussed.

2.1.1 Model Types and Models

The flight dynamics models are organized into functional units referred to as model types. Associated with each model type is a set of models. Each of the models associated with a specific model type simulates a particular function or element of the flight dynamics. For example, an atmosphere model simulates the atmosphere, or a weight model computes the vehicle weight. A complete list of the trajectory simulation model types and their corresponding simulation function is presented in Table 3. Clearly, there is no unique way to simulate these functions. Moreover, different applications require varying levels of complexity of the functions being simulated. Consequently, a variety of models are available within each model type. For example, there are currently 7 different atmospheric models available. That is, each model within a model type simulates the same engineering function but in a different or possibly more sophisticated

Table 3. Trajectory Simulation Model Types in GTS

MODEL TYPE MNEMONIC	FUNCTION
INIT	INITIALIZE VEHICLE POSITION AND VELOCITY
GRAV	SIMULATE ACCELERATION DUE TO THE ATTRACTION OF THE CENTRAL BODY
ATM	SIMULATE ATMOSPHERE
WIND	SIMULATE WINDS
WEIGHT	COMPUTE VEHICLE WEIGHTS
GUID	COMPUTE GUIDANCE COMMANDS, OR SIMULATE AIRBORNE COMPUTER
CONTROL	SIMULATE AUTOPILOT OR OPEN LOOP STEERING
ATTITUDE	COMPUTE BODY ATTITUDE
AEROF	COMPUTE AERODYNAMIC FORCES
AEROM	COMPUTE AERODYNAMIC MOMENTS
AERO	COMPUTE AERODYNAMIC FORCES AND MOMENTS
ACTUATOR	SIMULATE ACTUATORS
ENGINE	SIMULATE ENGINE
PROPF	COMPUTE PROPULSIVE FORCE VECTOR
PROPM	COMPUTE PROPULSIVE MOMENTS
TEOM	INTRODUCE THE TRANSLATIONAL EQUATIONS OF MOTION
REOM	INTRODUCE THE ROTATIONAL EQUATIONS OF MOTION
SENSOR	SIMULATE SENSORS; e.g., ACCELEROMETERS, GYROS, PLATFORMS, IMUs
DER	INTEGRATE AUXILIARY EQUATIONS OF INTEREST (e.g., velocity losses)
NONDER	COMPUTE AUXILIARY QUANTITIES OF INTEREST

manner. Thus, the user is able to select the model that realistically and efficiently represents his problem.

For a particular trajectory simulation, the software configuration that is actually executed includes only those model types and associated models which the user specified for that simulation. At user-specified events new data may be introduced into the simulation by changing the data associated with a given model, by changing the model associated with a given model type, or by introducing new model types and associated models.

2.1.2 Trajectory Profile Specification

Within the GTS system, trajectory simulations are performed by describing the desired trajectory profile as a series of phases separated by events. A trajectory is defined to be the entire vehicle state-time history of interest. A discrete time point along a trajectory is referred to as an event. The user may specify conditions which define events. These conditions usually refer to an instantaneous state of the vehicle as computed by the program. Examples of event criteria are:

(i) flight path angle equal to -15 degrees
(ii) vehicle altitude increasing and equal to 300000 feet
(iii) maximum value of dynamic pressure.

Several actions may result from the detection of an event. For example, new data may be introduced to the simulation which will alter the course of the trajectory, or information may be output which will leave the course of the trajectory unaltered.

A phase is defined to be a continuous portion of a trajectory between two successive event occurrences. Thus, a phase is always initiated and terminated by an event. Events are of particular interest to the user, since it is by the response to user-specified events that new data is introduced to the simulation or that the trajectory is terminated. Precise information concerning the types of events and the specification of event criteria is presented in Volume II.

2.2 Sizing Applications

The GTS system includes a set of weight estimation models which, combined with the GTS optimization and trajectory simulation features, form a generalized sizing capability for vehicles utilizing solid propellant rocket motors. Although ultimate component design is not precluded, the sizing capability is normally for preliminary design studies to estimate component weights which will determine a propulsion system configuration consistent with realistic vehicle geometry, performance, and mission constraints. Parametric weight scaling equations are utilized for sizing each major rocket component. The sizing capability does not require the specification of reference designs prior to generating results and provides for the inclusion of technology changes. Results are valid for propulsion system weights between 3,000 and 2,000,000 pounds.

The sizing capability utilizes a model type-model structure similar in nature to the trajectory simulation capability. It may be executed as a stand-alone application or in conjunction with the trajectory simulation. For example, the sizing capability may be executed to evaluate a vehicle geometry, weight, and propulsion quantities. Subsequently, at the user's option, vehicle parameters computed by the sizing application are available as input data for a trajectory simulation. The optimization process is invoked to satisfy the required vehicle geometry constraint.

Note that the aforementioned application of the optimization capability does not require any trajectory simulations. After the optimized vehicle configuration has been determined, a trajectory simulation utilizing the optimized vehicle may be requested.

A variation of the procedure just described is the application of the optimization operator to the satisfaction of coupled vehicle/trajectory constraints. In this instance, the objective might be the determination of a set of vehicle parameters that satisfy a set of vehicle geometry constraints and maximizes the range of the vehicle. For such an application, the sizing capability, the trajectory simulation capability and the optimization capability are all executed as a part of the same application. Additional information on the individual sizing models and examples of the use of the sizing capability are presented in Volume V.

2.3 Numerical Operators

The extensive GTS library of physical and engineering models is supplemented with a compatible set of numerical operators. These operators are distinguished from the physical and engineering models in that they provide methods for the solution of mathematical problems associated with scientific and engineering simulations. The three major categories of numerical operators available within the GTS system are; (1) integration operators, (2) optimization and search operators, and (3) interpolation operators. Analogous to the engineering operators, GTS provides a choice of operators in each category. Furthermore, the numerical operators are independent of the engineering models in the sense that any of the numerical operators may be specified in conjunction with any particular model configuration the user has selected. For example, any one of the available integration operators may be selected for a particular trajectory simulation. Similarly, any one of the available optimization algorithms may be executed as a part of the trajectory optimization capability or vehicle sizing capability. Consequently, the engineering analyst may choose the numerical algorithms which provide the desired balance between accuracy and efficiency for his particular problem. These numerical algorithms, along with the associated input data, are described in Volume IV.

2.3.1 Integration Techniques

While the integration techniques in GTS are general purpose, these techniques have been chosen with particular attention to their viability in solving sets of differential equations associated with trajectory simulations. Variations of mission profiles, accuracy requirements, and computational efficiency dictate that several techniques be available. These techniques are Runge-Kutta fixed step (fourth order), Adams-Moulton fixed step (m-th order, $1 \leq m \leq 8$), and Adams-Moulton variable step, (m-th order, $1 \leq m \leq 8$). The integration operators are not restricted to a pre-set number of differential equations. The number of differential equations is dependent upon the particular simulation, and typically varies from as few as six to over one hundred equations.

2.3.2 Optimization Capability

The GTS system contains two state-of-the-art nonlinear constrained parameter optimization operators. They are designed to solve the following problem. Determine the values of the n parameters, or independent variables, $x_1, x_2, \ldots, x_n$, such that the scalar function $f(x) = f(x_1, x_2, \ldots, x_n)$ is optimized (maximized or minimized), subject to equality constraints of the form

$$c_i(x) = 0 \quad , \quad i = 1, 2, \ldots, k$$

and inequality constraints of the form

$$c_i(x) \geq 0 \quad , \quad i = k+1, \ldots, m$$

Special cases of the above problem include constraint solving problems in which there is no objective function and the number of variables is greater than or equal to the number of constraints, and nonlinear least squares problems in which there is no objective function and the number of constraints is greater than the number of variables. Also, optimal control problems may be solved using the optimization techniques available in GTS.

These optimization and search techniques are fully incorporated into the GTS system. The complete library of physical models is available as part of the definition of an optimization problem. The input required to define optimization problems is compatible with the input required to define trajectory simulation and vehicle sizing problems. Thus, the definition of the optimization problem does not require a separate specification of the associated trajectory simulation or weight estimation problem. To illustrate, assume that a user has defined a trajectory simulation, and as a part of further analysis, he wishes to define an associated trajectory optimization problem. The only additional input required is a specification of which trajectory input quantities are to be the independent variables and which computed quantities are to be the objective function and/or constraints. In this regard, any input quantity may be an optimization variable. Thus, for example, an independent variable may be a tabular value, a model input value, or a quantity which is part of an event specification. Likewise, the user has complete freedom in choosing which quantities form the objective function and constraints.

Furthermore, the independence of the physical models and optimization provides the user the capability to formulate many diverse types of problems. As indicated, a variety of trajectory optimization problems may be formulated, such as boost trajectory problems, reentry problems, or orbital transfer problems. Likewise, vehicle sizing applications may be defined which do not require trajectory simulations, or vehicle sizing applications may be specified which require both the vehicle sizing and trajectory simulation capabilities. Finally, the operators may also be used to obtain the optimal solution to a large class of problems having similar mathematical characteristics to trajectory and vehicle sizing problems.

Some of the optimization algorithms utilize partial derivative information. If the information can be computed analytically, the optimization operator will effectively use this information. Otherwise, a scheme for obtaining numerical partials is implemented.

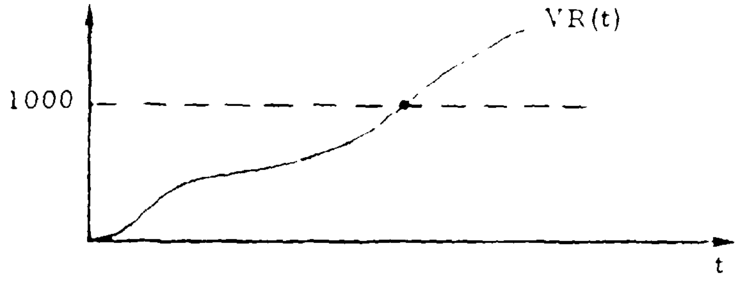
2.4 General Applicability of the GTS System

Many of the capabilities of the GTS system have applicability to areas other than trajectory simulation or vehicle design. The numerical operators, for instance, provide numerical methods for solving mathematical problems which may arise independent of any vehicle design or trajectory simulation considerations. For example, the integration operators provide a capability for the solution of any set of first order, initial value differential equations. Likewise, the optimization operators are designed to solve a general nonlinear parameter optimization problem. The flexibility of the GTS input characteristics permits these operators to be properly invoked to solve the particular problem of interest. This capability is illustrated in Volume II.

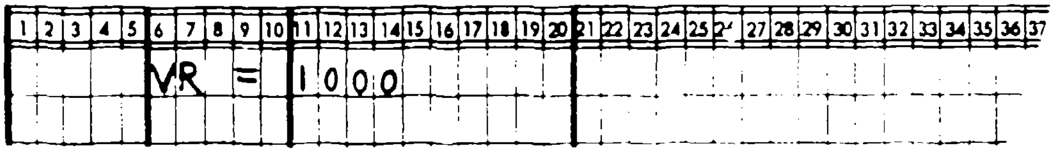
2.5 Generalized Trajectory Language (GTL)

GTL is a higher level input language included as an integral part of the GTS system. GTL interprets card images and formulates all the input into a form acceptable to the internal GTS input processor. GTL provides a user-oriented format that permits a user to define the application (trajectory, vehicle sizing, optimization, etc.), the individual models required, the associated numerical operators, and all of the required input data values in a free form mnemonic oriented fashion. A complete description of GTL is part of Volume II.

To illustrate GTL, consider the following examples of GTL data specification. Relative to the trajectory simulation capability, the following examples illustrate the specifications of events in GTL. Assume an event occurs when the criterion that the variable VR is equal to 1000 is satisfied.

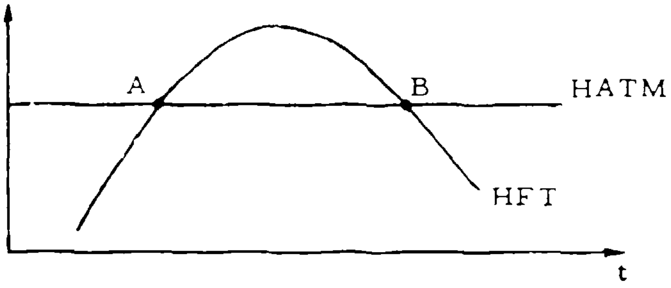


The GTL specification, that is the actual input that users must supply, for this event is



```
     VR = 1000
```

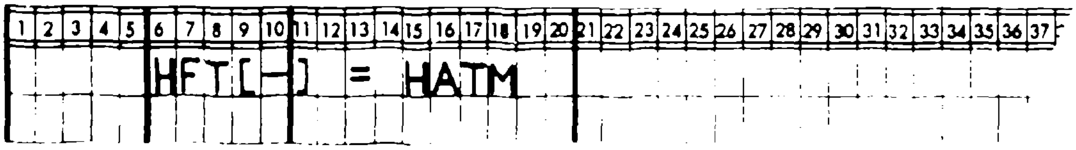
Next, assume an event occurs when the criterion that the variable HFT is equal to the variable HATM, and HFT is increasing (point A on the graph).



The GTL specification for this event is

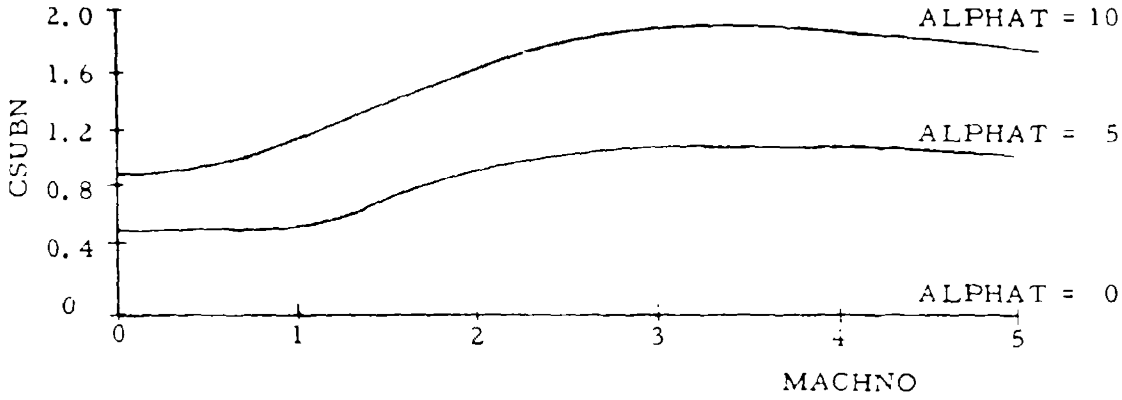
```
     HFT[+] = HATM
```

Alternatively, if an event is to occur when HFT is equal to HATM and HFT is decreasing (point B on the graph), then the GTL specification of this event is

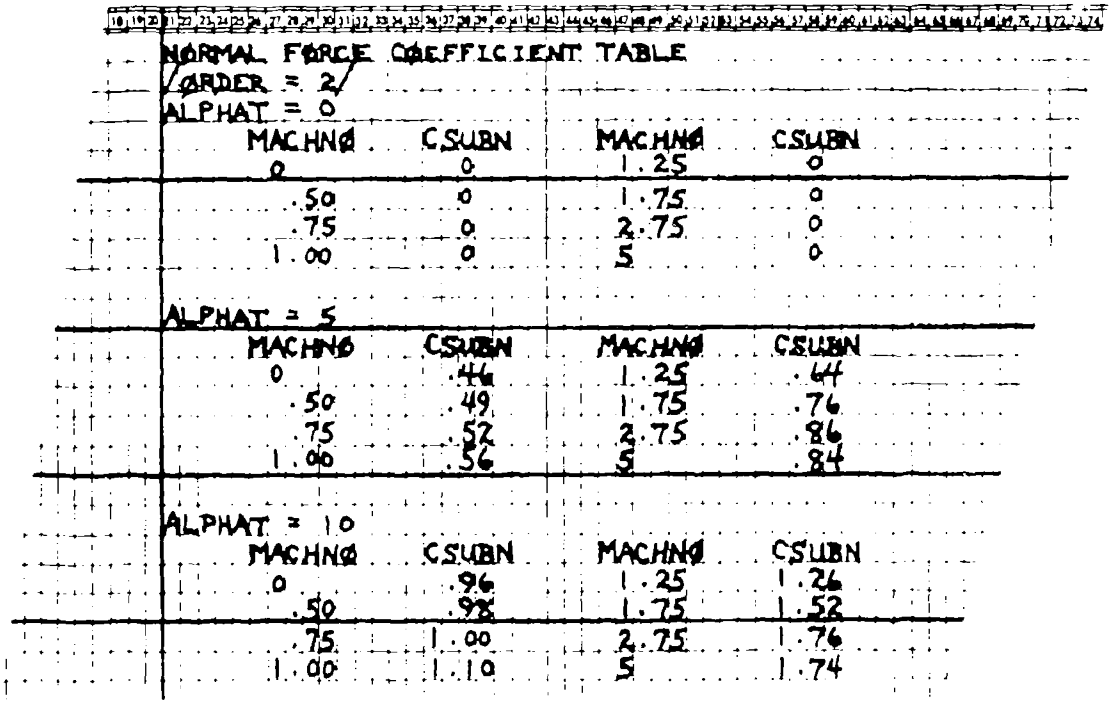


```
     HFT[-] = HATM
```

A common method for specifying functional relationships in GTS is via tabular data. GTL provides a convenient format for tabular input. As an illustration, assume that the quantity CSUBN is a function of two independent variables, ALPHAT and MACHNO, as represented in the following graph.



The corresponding GTL tabular input, assuming quadratic interpolation, is the following.



```
NORMAL FORCE COEFFICIENT TABLE
/ORDER = 2/
ALPHAT = 0
       MACHNO    CSUBN       MACHNO    CSUBN
        0          0          1.25       0
         .50       0          1.75       0
         .75       0          2.75       0
        1.00       0          5          0

ALPHAT = 5
       MACHNO    CSUBN       MACHNO    CSUBN
        0         .46         1.25      .64
         .50      .49         1.75      .76
         .75      .52         2.75      .86
        1.00      .56         5         .84

ALPHAT = 10
       MACHNO    CSUBN       MACHNO    CSUBN
        0         .96         1.25      1.26
         .50      .98         1.75      1.52
         .75     1.00         2.75      1.76
        1.00     1.10         5         1.74
```

In order to provide a convenient method for executing the optimization capability, GTL includes an optimization input format. The format provides the user with an easy-to-use mechanism for specifying optimization input data. For example, the choice of the optimization operator is specified by a statement of the form

```
/THE OPTIMIZATION OPERATOR IS UOPTIM/
```

A constraint that the variable VR, evaluated at event PO50, be greater than or equal to 1000 is specified by

```
(VR.AT.PO50 ≥ 1000.)
```

A constraint that the variable GDLV be equal to GDLPD plus 30. is specified by

```
(GDLV = GDLPD + 30.)
```

An additional GTL capability allows user coded FORTRAN routines to be included in the GTL input data. These routines are automatically inserted into the GTS simulation. Thus, the user can request that unique auxiliary computations be made or that minor modifications to existing GTS models be made without modifying the existing GTS models.

2.6 Input/Output Capabilities

The GTS system allows the user to specify his input data and receive his output data in various forms and formats. The primary means of specifying input data is by means of punched cards. However, the user may access input data which resides on a disk file or magnetic tape. Special purpose input data, such as radar tracking data, may be input to a problem. The system requires the user to describe the format of the input data. That is, the number of words per data frame or the relative locations of the particular data items of interest are specified to the system via GTL input.

GTS has the capability of producing several types of output all under the control of the user. Included are printed output in a standard format, printed output and/or case summary print which is formatted by the user, binary data files for subsequent use in other software tools, and graphical output processors.

The standard output print (block print) follows the model types of GTL input data. That is, the printed data is formed into distinct blocks where each block is associated with a particular model type (e.g., AEROF, CONTROL). A data item may be a floating point number, an integer number, a logical value, or an alpha-numeric character string. The user may request that blocks be edited to reduce the output or that data items which are not included in a standard print block be printed in a supplementary data block. A block print key is printed at the beginning of each case.

User-defined output is handled by a special output operator. Any GTS variable or user-defined variable name is an acceptable output quantity. Multiple executions of the output operator are permissible, and each call may reference a different format statement and list of variables. In addition, if logical tests are required to determine what to print or when to print, a subroutine may be written and input with the GTL input data to perform these functions.

Plots are obtained by writing the output data to be plotted on files using the special output model. The plotting capabilities are executed as post-processors and are accessed by means of GTL input. Also available is a world map plotting capability. The user may also request that any or all input data tables (interpolation or step tables) be plotted.

2.7 Trajectory Simulation Example

As an illustration of the use of the GTS system, consider the simulation of the three degree-of-freedom trajectory for a satellite in orbit. The data specified to define the orbit and establish the initial position of the vehicle are:

apogee altitude = 3000 nautical miles
perigee altitude = 1000 nautical miles
inclination of orbit = 20°
argument of perigee = 85°
true anomaly = 260°
satellite longitude = -119°

A spherical non-rotating earth model is used in this example. The integration method is 8th order, variable step, Adams-Moulton. The initial integration interval is 8 seconds. Trajectory data is to be printed at apogee and perigee (i.e., whenever the inertial flight path angle is zero).

The initial configuration of the orbit is shown in Figure 1. The data as it appears on a GTS coding form is shown in Figure 2. A computer generated listing of the CTL input and trajectory output is also included. Additional examples which illustrate the capabilities of the GTS system are detailed in Volume II.

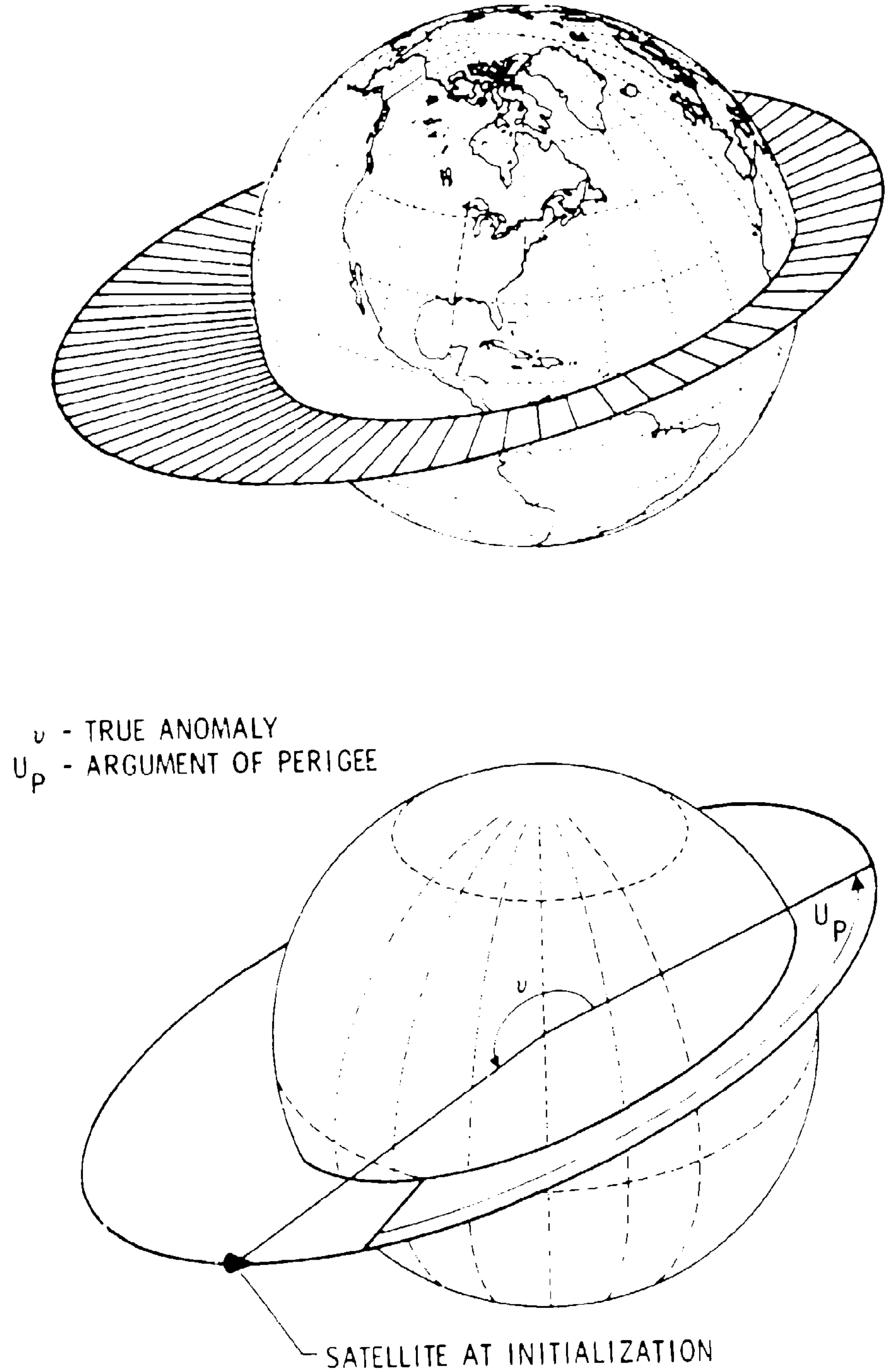
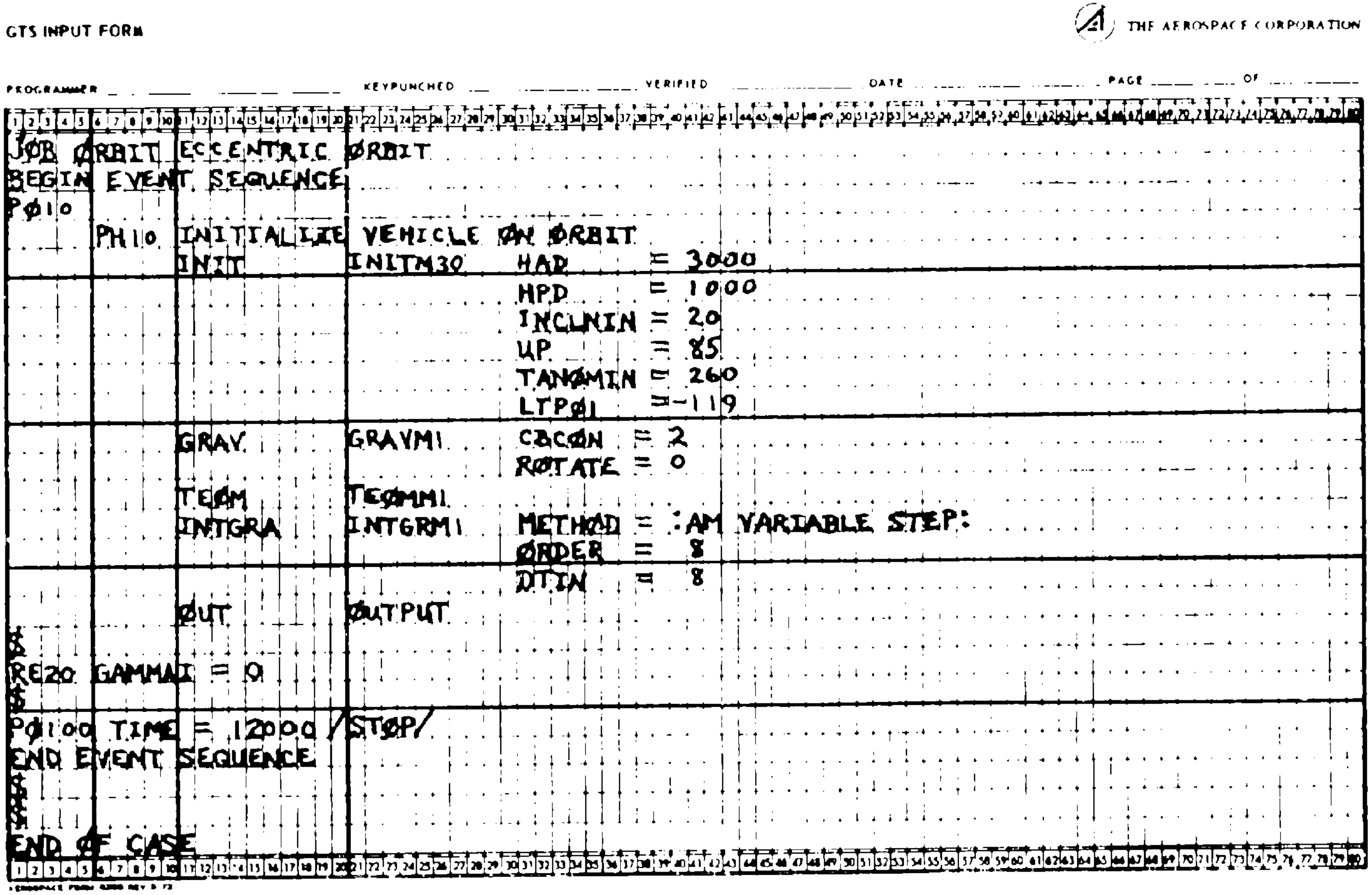


Fig. 1. Orbit Configuration



GTS INPUT FORM

THE AEROSPACE CORPORATION

PROGRAMMER ____ KEYPUNCHED ____ VERIFIED ____ DATE ____ PAGE ____ OF ____

```
JØB ØRBIT ECCENTRIC ØRBIT
BEGIN EVENT SEQUENCE
PØ10
     PH10 INITIALIZE VEHICLE ØN ØRBIT
          INIT      INITM30   HAD     = 3000
                              HPD     = 1000
                              INCLNIN = 20
                              UP      = 85
                              TANØMIN = 260
                              LTPØ1   =-119
          GRAV      GRAVM1    CBCØN   = 2
                              RØTATE  = 0
          TEØM      TEØMM1
          INTGRA    INTGRM1   METHØD  = :AM VARIABLE STEP:
                              ØRDER   = 8
                              DTIN    = 8
          ØUT       ØUTPUT
$
RE20 GAMMAI = 0
$
PØ100 TIME = 12000 /STØP/
END EVENT SEQUENCE
$
$
END ØF CASE
```

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Fig. 2. GTL Input Data

```
ENVIRONMENTAL DATA                                        ATMOSPHERE
       CENTRAL BODY                                                    NO WINDS
NON-ROTATING        SPHERICAL              NO ATMOSPHERE

EQUATORIAL RADIUS        POLAR RADIUS              ROTATION RATE          GRAV. CONSTANT           PRESSURE AT SEA LEVEL
   .20902900E+08            .20902900E+08           0.                       .14076539E+17            0.



                                                    BLOCK PRINT KEY
                                                    ---------------

                                                                                                          W
                                                              1   GDLV                 LV                 DW
TIME                 HFT                 GCLV                 2   ETATOT                                  AZR
DTNOM                H                   RV                   3   VR                   GAMMAR
VI                   GAMMAI              AZI
                                                              4   DXECI                DYECI              DZECI
XECI                 YECI                ZECI                 5   SDDXECI              SDDYECI            SDDZECI
DDXECI               DDYECI              DDZECI               7   ILV
GECI(1)              GECI(2)             GECI(3)             11   RANGIIP              CRNGRF             DRNGRF
RANGRLS              RANGRIP             RANGILS
                                                             30   KE/PE                                   SMAORB
ORBIT TYPE                               SOVRLEA             31   PERIOD               OLNODE             MUNODE
INCNODE              ECC                 DOMEGAP             32   TNODE                LNODE              RA
INCLV                TRANOMV             OMEGAV              33   GDLVA                LVA                RP
HA                   VAPOG               OMEGAA              34   GDLVP                LVP
HP                   VPERG               OMEGAP              35   TPERG                MUPERG
                     TAPOG               MUAPOG
```

The preceding BLOCK PRINT KEY displays print key lines which contain mnemonic program symbols. The print key lines are identified by line numbers. These line numbers are used to relate the lines of printed output in the BLOCK PRINT with the print key lines contained within the BLOCK PRINT KEY.

Brief definitions of the output quantities are presented below. The output quantities are identified by their mnemonic program symbol, and are ordered by line number.

LINE 1

TIME	Current time within the dynamic system
HFT	Altitude of the vehicle (feet)
GCLV	Geocentric latitude of the vehicle
GDLV	Geodetic latitude of the vehicle
LV	Longitude of the vehicle
W	Total vehicle weight

LINE 2

DTNOM	Nominal integration step size
H	Altitude of the vehicle (nautical miles)
RV	Radial distance from center of earth to vehicle
ETATOT	Total load factor
- - - - -	
DW	Total weight flow-rate from vehicle

LINE 3

VI	Magnitude of the inertial velocity vector
GAMMAI	Inertial flight path angle
AZI	Inertial azimuth
VR	Magnitude of the earth relative velocity vector
GAMMAR	Earth relative flight path angle
AZR	Earth relative azimuth

LINE 4

XECI	The ECI X coordinate of vehicle position
YECI	The ECI Y coordinate of vehicle position
ZECI	The ECI Z coordinate of vehicle position
DXECI	Time derivative of XECI
DYECI	Time derivative of YECI
DZECI	Time derivative of ZECI

LINE 5

DDXECI	Time derivative of DXECI
DDYECI	Time derivative of DYECI
DDZECI	Time derivative of DZECI
SDDXECI	The ECI X component of sensed acceleration
SDDYECI	The ECI Y component of sensed acceleration
SDDZECI	The ECI Z component of sensed acceleration

LINE 7

GECI(1)	The ECI X component of gravitational acceleration
GECI(2)	The ECI Y component of gravitational acceleration
GECI(3)	The ECI Z component of gravitational acceleration
ILV	Inertial longitude of the vehicle
- - - - -	
- - - - -	

LINE 11

RANGRLS	Relative range from launch site to current position
RANGRIP	Relative range from initial position to current position
RANGILS	Inertial range from launch site to current position
RANGIIP	Inertial range from initial position to current position
- - - - -	
- - - - -	

LINE 30

ORBIT TYPE	Type of orbit
SOVRCEA	Ratio of semilatus-rectum to equatorial radius
KE/PE	Ratio of kinetic energy to potential energy
- - - - -	
- - - - -	

LINE 31

INCNODE	Orbit inclination at next ascending node
ECC	Orbit eccentricity
DOMEGAP	Inertial motion of apsides
PERIOD	Orbit period
DLNODE	Inertial motion of ascending node
SMAORB	Orbit semimajor axis

LINE 32

INCLV	Local orbit inclination
TRANOMV	True anomaly
OMEGAV	Argument of latitude of current position
TNODE	Time of next ascending node
LNODE	Relative longitude of next ascending node
MUNODE	Inertial range angle from present position to next ascending node

LINE 33

HA	Altitude of next apogee
VAPOG	Inertial velocity at next apogee
OMEGAA	Argument of latitude of next apogee
GDLVA	Geodetic latitude at next apogee
LVA	Relative longitude at next apogee
RA	Radial distance from the center of the earth to the next apogee

LINE 34

HP	Altitude at next perigee
VPERG	Inertial velocity at next perigee
OMEGAP	Argument of latitude of next perigee
GDLVP	Geodetic latitude at next perigee
LVP	Relative longitude at next perigee
RP	Radial distance from the center of the earth to the next perigee

LINE 35

- - - - -	
TAPOG	Time of next apogee
MUAPOG	Inertial range angle from present position to next apogee
TPERG	Time of next perigee
MUPERG	Inertial range angle from present position to next perigee
- - - - -	

```
                                        BLOCK PRINT

-----------------------------------------------------------------------------------------------------

 BEGIN NEW PHASE -- INITIALIZE VEHICLE ON ORBIT                                      (PH1)    )
 ---------------

--------------------------------------- TIME =      0.0000000  ---------------------------------------

          0         12088402.9     -5.07854582     1  -5.07854582     -119.000000             0
  8.00000000        1989.49525      32991302.9     2            0                             0
  20676.0280       -10.5916336      70.6299448     3   20676.0280     -10.5916336     70.6299448

 -15931711.1       -28741567.7     -2920433.91     4   18315.3498     -6506.44030     7050.69694
  6.24539504        11.2669909      1.14484021     5            0               0             0
  6.24539504        11.2669909      1.14484021     7  -119.000000
  7132.52375       .244266599E-10   7132.52375    11   .244266599E-10           0             0

 ORBIT TYPE    -    ELLIPTIC        1.52793315    30   .500965479
  20.0000000        .183817620               0    31   167.740910               0     33055131.0
  20.0000000        260.000000      345.000000    32   404.961399     -104.867277     15.0000000
  3000.00000        17134.8266      625.000000    33  -19.9206644      159.813619     39131246.5
  1000.000000       24852.9129      445.000000    34   19.9206644     -20.1863806     26979015.5
                    7237.08983      280.000000    35   2204.86252      100.000000

-----------------------------------------------------------------------------------------------------

--- EVENT ---------------- EVENT ---------------- EVENT ---------------- EVENT ---------------- EVENT ---

-----------------------------------------------------------------------------------------------------

 ESC = RE20            (RE20    )      TYPE =  0
 THIS EVENT OCCURRED BY SATISFACTION OF THE CONDITION  -- GAMMAI     =  -.354419266643E-07

--------------------------------------- TIME =  2204.8526213  ---------------------------------------

  2204.85262        6076111.33      19.9206487     1   19.9206487     -20.1869054             0
  120.000000        999.999315      26979011.3     2            0                             0
  24852.8508       -.354419267E-07  88.1828883     3   24852.8508     -.354419267E-07 88.1828883

  23806625.9       -8752955.95      9192245.48     4   8319.98651      23407.1157     740.912066
 -17.0653677        6.27440495     -6.58930204     5            0               0             0
 -17.0653677        6.27440495     -6.58930204     7  -20.1869054
  1683.91162        5999.97038      1683.91162    11   5999.97038               0             0

 ORBIT TYPE    -    ELLIPTIC        1.52792504    30   .591905759
  20.0000000        .183811518               0    31   167.738990               0     33054878.8
  20.0000000        360.000000      84.9995064    32   10469.3055     -104.867277     275.000494
  2999.91767        17135.0001      264.999507    33  -19.9206487      159.813095     39130746.2
  999.999315        24852.8508      84.9995066    34   19.9206487     -20.1869051     26979011.3
                    7237.07234      180.000000    35   2204.85263      .228258995E-06
```

```
-----------------------------------------------------------------------------------------------------------------
--- EVENT ------------------ EVENT ------------------ EVENT ------------------ EVENT ------------------ EVENT ---
-----------------------------------------------------------------------------------------------------------------

ESC = RE20            (RE20    )      TYPE = -0
THIS EVENT OCCURRED BY SATISFACTION OF THE CONDITION   -- GAMPAI        =    .175118667205E-06
------------------------------------------- TIME =  7237.0243697 ------------------------------------------------

   7237.02437        18227959.0      -19.9206500       1  -19.9206500      159.813137                  0
   256.000000        2999.91978       39130759.0       2            0                                  0
   17134.9958       .175118667E-06    91.8170971       3   17134.9958      .175118667E-06    91.8170971

  -34529493.3        12695391.5      -13332570.3       4  -5736.27033     -16138.2261       -510.823633
   8.11206238       -2.98254616       3.13223947       5            0               0                  0
   8.11206238       -2.98254616       3.13223947       7   159.813137
   9116.09010        4800.02720       9116.09010      11   4800.02720               0                  0

  ORBIT TYPE    -    ELLIPTIC         1.52792526      30   .408094166
   20.0000000        .183811668                0      31   167.739041               0         33054885.4
   20.0000000        179.999999       264.999547      32   10469.3080     -104.867277        95.0004533
   2999.91978        17134.9958       264.999547      33  -19.9206500      159.813138        39130759.0
   999.999395        24852.8521       444.999547      34   19.9206500     -20.1868617        26979011.8
                     7237.02440      .777586894E-06   35   12269.1956      180.000001

-----------------------------------------------------------------------------------------------------------------
--- EVENT ------------------ EVENT ------------------ EVENT ------------------ EVENT ------------------ EVENT ---
------------------------------------------- TIME = 12000.0000000 ------------------------------------------------

   12000.0000        6204201.28       18.8485017       1   18.8485017     -35.1631912                  0
   256.000000        1021.08321       27107101.3       2            0                                  0
   24753.3483       -2.18542513       83.1866051       3   24753.3483     -2.18542513        83.1866051

   20972133.2       -14774043.9       8757408.06       4   12639.3222      21139.1594        2472.19124
  -14.8214012        10.4410949      -6.18902510       5            0               0                  0
  -14.8214012        10.4410949      -6.18902510       7  -35.1631912
   2358.88722        5150.17782       2358.88722      11   5150.17782               0                  0

  ORBIT TYPE    -    ELLIPTIC         1.52791653      30   .589963436
   20.0000000        .183795471                0      31   167.736052               0         33054492.8
   20.0000000        345.839946       70.8362970      32   20533.4766     -104.867277        289.163703
   2999.75517        17135.3048       264.996351      33  -19.9205486      159.809740        39129758.0
   1000.03476        24852.5831       84.9963512      34   19.9205486     -29.1982597        26979226.7
                     17301.2180       194.160054      35   12269.1365      14.1600542

-----------------------------------------------------------------------------------------------------------------

ESC = P0100           (P0100   )      TYPE = -0
THIS EVENT OCCURRED BY SATISFACTION OF THE CONDITION   -- TIME          =    .120000000000E+05
-----------------------------------------------------------------------------------------------------------------
```

```
*******************************************
*          AEROSPACE CORPORATION          *
*  GENERALIZED TRAJECTORY SIMULATION SYSTEM *
*******************************************

                 INPUT DATA
                 ----------


ORBIT    2    JOB ORBIT   ECCENTRIC ORBIT
ORBIT    3    BEGIN EVENT SEQUENCE
ORBIT    4    P010
ORBIT    5         PH10 INITIALIZE VEHICLE ON ORBIT
ORBIT    6              INIT      INITM30   HAO      = 3000
ORBIT    7                                  HPD      = 1000
ORBIT    8                                  INCLNIN  = 20
ORBIT    9                                  UP       = 85
ORBIT   10                                  TANOMIN  = 260
ORBIT   11                                  LTP01    =-119
ORBIT   12              GRAV      GRAVM1    CBCON    = 2
ORBIT   13                                  ROTATE   = 0
ORBIT   14              TECH      TEOMM1
ORBIT   15              INTGRA    INTGRM1   METHOD   = 'AM VARIABLE STEP'
ORBIT   16                                  ORDER    = 8
ORBIT   17                                  DTIN     = 4
ORBIT   18              OUT       OUTPUT
ORBIT   19    $
ORBIT   20    RF20 GAMMAI = 0
ORBIT   21    $
ORBIT   22    P0100 TIME = 12000 /STOP/
ORBIT   23    END EVENT SEQUENCE
ORBIT   24    $
ORBIT   25    $
ORBIT   26    END OF CASE
```

2.8 Remote Terminal Execution of GTS

All of the capabilities of the GTS system are available for remote terminal use in conjunction with the CDC supplied INTERCOM feature. The actual methods of operation will depend on the hardware characteristics of the terminal to be used.

The output from the job may be obtained by several different methods. The user may request the print file to be directed to his terminal where he may either list the entire file or make use of INTERCOM editing procedures to print items of particular interest. If the user has a line printer available, he may list the output by that means. Alternately, the output can be directed to the central site printer.

Figure 3 shows a portion of the input required to execute the GTS system from a remote terminal via the INTERCOM system. The INTERCOM system directs the flow of information and data between a central computer and a number of remote terminals and is compatible with CDC 6000/7000 computers. For this example the trajectory simulation that was defined in section 2.7 is executed.

The reader can easily recognize the correlation of the data given in Figure 3 and the data given in Figure 2. The additional symbols and commands are specific to the INTERCOM system and are explained in the INTERCOM User's Guide available from Control Data Corporation.

The following statements are remote terminal inputs to GTS.

```
510=JOB ORBIT  ECCENTRIC ORBIT
520=BEGIN EVENT SEQUENCE
530=P010
540=     PH10 INITIALIZE VEHICLE ON ORBIT
550=          INIT     INITM30   HAD     = 3000
560=                             HPD     = 1000
570=                             INCLNIN = 20
580=                             OP      = 85
590=                             TANOMIN = 260
600=                             ETPO1   =-119
610=          GRAV     GRAVM1    CBCON  = 2
620=                             ROTATE = 0
630=          TEOM     TEOMM1
640=          INTGRA   INTGRM1   METHOD = :AM VARIABLE STEP:
650=                             ORDER  = 8
660=                             DTIN   = 8
670=          OUT      OUTPUT
680=$
690=RE20 GAMMAI = 0
700=$
710=P0100 TIME = 12000 /STOP/
720=END EVENT SEQUENCE
730=$
740=$
750=END OF CASE
..
```

The following statements are INTERCOM commands used to send the above inputs to the central computer.

```
..save,orbit,n

..batch,orbit,input
```

Fig. 3. Remote Terminal Input

SECTION 3

GTS SYSTEM ARCHITECTURE

The GTS system consists of a compatible set of processors, operators, and models that can be flexibly selected to prepare a minimum software configuration customized to the requirements of a particular application. The primary functional capabilities (trajectory, vehicle sizing, optimization) can be invoked in any logical hierarchal fashion. Each of these capabilities invokes and loads only the models and operators required to accomplish its purpose. All of the models and operators are interfaced through a sophisticated data structure and corresponding set of data operators. This feature permits independently developed models to be properly interfaced, via the data structure, into a coherent simulation. Consequently, the system support structure also facilitates the extension or altering of simulations by adding, deleting, or changing model subroutines. In conjunction with GTL, the system will load and execute, in a stand-alone fashion, any individual engineering model subroutine using input defined parameters and providing corresponding outputs. This feature provides a powerful tool for the modular validation and verification of large-scale simulations.

The complete system has been automated to eliminate bothersome and time-consuming operational overhead. The required processors are invoked, in the proper sequence, on the command of CDC control cards that are automatically generated for the user by a control card generator. This allows the user to concentrate on the application and not on the physical operation of the software.

The component members of the GTS system architecture are indicated in the following paragraphs of this section along with a brief description of their function.

3.1 Control Card Generator

The control card generator constructs proper sets of CDC control cards to execute the GTS system for a variety of applications. Options are available to invoke features of a maintenance system, provide for modifications and additions to the library of operators and models and to select, load, and execute a simulation.

3.2 GTL Processor

The GTL processor scans the GTL input data to construct files of parameter and variable data required by a given application plus determining the functional processors, associated models, and program structure required for the application. The program structure information is passed to a subsequent pre-processor that selects the required program elements from a library and constructs a tailorized version of GTS. The parameter and variable information is saved on temporary files for use in the application as it is required.

3.3 GTS Pre-processor

This program module accepts files of program structure information compiled by the GTL processor. This pre-processor utilizes this information to select the required program models from the GTS system library. These models and all implicitly required supporting subroutines are structured into a computer program specific to the given application. The computer program is further processed by the CDC system loader and made available for execution. This procedure eliminates many of the problems normally associated with the ever-expanding computer memory requirements. The size and number of operators and subroutine models contained in the GTS library is allowed to grow in an open-ended fashion. This growth does not result in an ever increasing requirement for computer memory.

3.4 GTS Executives and Model Library

The primary executive operators of the GTS system were identified in Section 1.1. These functional operators (trajectory, vehicle sizing, optimization) are supported by an extensive library of numerical operators (integration, interpolation, etc.), data operators, and physical and engineering model subroutines. Libraries are maintained in FORTRAN source language and relocatable binary format for CDC 6000/7000 series computers.

3.5 GTS Post-Processors

A series of post-processing elements are available to the user of the GTS system. Communication with these processors is via the use of disk or tape files generated during the execution of a GTS simulation. The primary post-processors provide a variety of graphical output capabilities. These graphical features provide the ability to plot any GTS variable versus any other variable. Features are also available to display information on pre-printed or computer generated world map backgrounds.