MATS—The Mission Analysis and Trajectory Simulation Program

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THE Mission Analysis and Trajectory Simulation Program (MATS) is a general-purpose digital computer pragram written in FORTRAN IV.[1,2] It either has simulated or is potentially capable of simulating such diverse missions as Apollo, Mariner, Surveyor, Tiros, Comsat, Minuteman, and Sentinel. Key points of philosophy underlying the MATS design concept are: a phase-oriented sequencer controls the occurrence of events; the input parameters control the simulation; a bucket concept generalizes and minimizes data storage; and a modularized integrated systems approach permits planned evolution.

The phase concept provides the mechanism whereby occurrence of events can be sequenced logically as in real-time situations. A phase is defined as a time interval corresponding to one of a continuous sequence of flight segments. A phase may be of zero duration to simulate an instantaneous inflight or logical event. Phase changes are treated as trajectory discrete points at which variables that affect the vehicle, environment or simulation may be introduced or varied. Examples of phase-oriented trajectory parameters are engine ignition and cutoff, attitude maneuvers or steering algorithms, and environment modifications; phase-oriented simulation parameters include integration method and step-size control, output requests, logical phase manipulations, and iteration processes. The bucket concept minimizes the input storage requirements by identifying the data by phase, and storing it en masse; as each phase is initiated, the associated data are brought into active memory. The data are stored contiguously, so that no preassigned limits determine the type and volume active during any phase. Figure 1 schematically represents the program structure, which is based on a modular design concept.

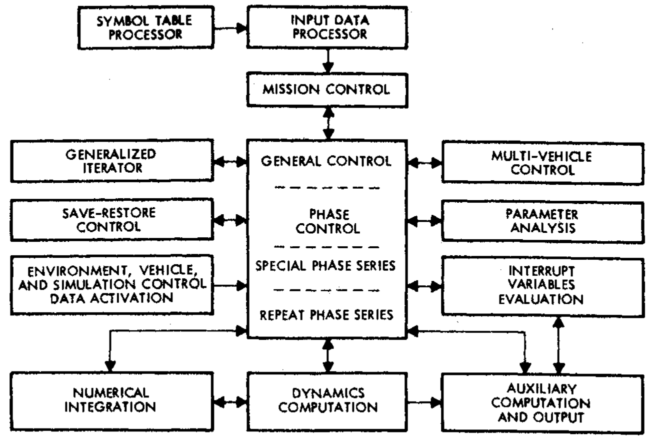

Fig. 1 Functional block diagram of MATS control hierarchy.

Trajectory and Vehicle Controls

Whole missions may be simulated in one computer run, or portions of the trajectory may be approximated or evaluated accurately to model the flight or the vehicle. Most options are phase-oriented, including the option to use either a point-mass three-degree-of-freedom (3DOF) simulation or a six-degree-of-freedom (6DOF) simulation; also available is a spherical-body approximation for atmospheric re-entry of freely falling bodies. Most modules are prefaced with a decision regarding updating at this calculation, during this phase, or during this simulation.

The integration coordinate system is Cartesian inertial and has its origin at the center of one of the bodies in the solar system with the X-Y plane parallel to the equatorial plane. The X-axis may extend through the zero meridian at time $T = 0$; this system is normally used for Earth ballistic and orbital missions where the perturbations of other solar bodies are neglected. Alternatively, the X-axis may be directed through the vernal equinox at the beginning of the Besselian solar year 1950.0; time is initialized from the input Julian date. These two orientations are commonly known as the Greenwich and the vernal equinox mean of 1950 coordinate systems. The vehicle attitude system is defined in terms of three sets of mutually orthogonal unit vectors or direction cosines with the origin at the vehicle center of gravity. For initiation of the first phase, the user may provide launch-pad geodetic survey data and firing azimuth from which the inertial position and velocity are computed; the attitude is aligned along the launch vertical with the pitch plane oriented parallel to the azimuth. Alternative options permit statement of the initial conditions in a variety of combinations. The attitude initiation options include the direction cosines input and several alignment and instantaneous reorientation capabilities.

External perturbations acting on the vehicle include atmospheric reaction, gravity of the central body, gravity of other bodies in the solar system, and solar radiation pressure. The user may select the model from the MATS standard options or he may define by input the model the simulation is to use. Two Earth atmosphere models are available, [the Air Research Development Command (ARDC) 1959 model and an analytic representation of the U. S. Standard Atmosphere, 1962], and either may be superseded by input tables. The gas laws permit computations of any fourth parameter from three input functions; otherwise, one of the standard models supplements insufficient tabular information. Winds may be included as tables.

Two models for the Earth gravitational acceleration are incorporated. The ellipsoidal model is a Legendre polynomial including only the J_2, J_3, and J_4 zonal harmonics. The Nth-order spherical harmonics model includes the coefficients for the zonal, sectorial, and tesseral harmonics for order up to 12; it provides the capability for the Department of Defense 1966 eighth-order model. Either of these simulations may be requested and/or modified by input.

When the moon is the central body, the seleno-potential function for the triaxial moon is computed, which includes consideration of the three principal moments of inertia. Accelerations due to other bodies in the solar system are computed from the inverse square law. The user selects those bodies whose influences are to be included. The ephemerides are provided from the Jet Propulsion Laboratories Ephemeris 3 or DE19 Series tapes. Acceleration due to solar radiation pressure and to Poynting-Robertson drag may be included optionally.

The vehicle characteristics may include weight and aerodynamic reference area, center-of-gravity and c.g. off-set tables in the pitch and yaw directions, center-of-pressure tables in the pitch and yaw planes, a drag coefficient table, and tabular normal or side-force coefficients. Weight may be initialized or adjusted at phase-change points. For solar radiation pressure, an exposed area may be given. For a 6DOF simulation, the moments and products of inertia tables may be supplied.

The locations of the one or more engines are input parameters. The propulsive forces are computed separately for each engine, so that each may be modeled appropriately.

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The simplified propulsion model includes tabular functions of thrust with optional atmospheric pressure correction and/or weight flow and/or specific impulse. Ablative weight and area losses are simulated with tabular functions. The Minuteman system with its complicated mass properties is available. The Atlas sixth- and twelfth-order influence coefficient models and a generalized linear coefficient model for delineating the steady-state performance of liquid-propellant rocket engines are in the process of validation; these models include propellant utilization systems.

The standard attitude control options available simulate open-loop unguided trajectories with several varieties of algorithms. In the rate steering options, angular rates give rise to the attitude vector direction cosine derivatives, which are integrated to determine the up-dated attitude orientation of the vehicle. These include a zero-lift pitch turn to maintain the pitch angle of attack at zero, a yaw turn to maintain the yaw angle of attack at zero, tabular functions for pitch, yaw, and roll rates, horizon scanner algorithms to maintain spacecraft orientation, and other miscellaneous angular controls. The analytic options instantaneously rotate the vehicle to requested orientations in pitch, yaw, and roll, relative to some reference attitude such as the launch vertical, the orbit plane, or the local vertical.

If the 6DOF option is selected, angular accelerations are integrated to yield angular rates from which are computed derivatives for the attitude vector integration. A calculus of variations method is implemented whereby the Euler-Lagrange multipliers are integrated and attitude is derived analytically. This method yields a time optimal trajectory (which optimizes payload weight for the constant weight utilization vehicles) by computing appropriate pitch and yaw steering profiles. The formulation includes terms to approximate the effects due to Earth oblateness (J_2) and aerodynamic drag and normal forces. A specialized version provides engine throttling capability. The variational equations, integrated along with the equations of motion of the spacecraft, provide first-order estimates of the effect resulting from a small change in the initial state vector. The differential correction procedure involves the determination of a matrix of partial derivatives of observations with respect to the initial state vector. These equations find application in interplanetary targeting and in the determination of mid-course corrections.

MATS does not incorporate any specific guidance or control system. It provides all appropriate interface connections for the simulation of the navigation unit and the control system—whether they be radio or inertial guidance. Communication interface exists for the interpretive computer simulation of the actual ground-based or onboard guidance computers.

Program Controls

Figure 2 is a flow diagram of MATS controls, some or all of which may be exercised. Phase-oriented inputs control the activation and functional purpose of each control.

Several methods of numerical integration are available to simulate appropriately that segment of the trajectory being calculated. Time is the independent variable and the integration increment is an input parameter. The methods include: 1) Runge-Kutta-Gill, fourth-order, fixed and variable step; 2) Adams-Moulton fourth-order, fixed and variable step, which uses Runge-Kutta as a starter and has the flexible capability of extrapolating with the predictor equation to intermediate non-normal points; 3) Cowell eighth-order, fixed and variable step, which uses Runge-Kutta as a starter; it is a modified Gauss-Jackson second-sum method used only during free flight to integrate directly second-order differential equations; and 4) improved Euler, a second-order Runge-Kutta, fixed and variable step; it is used primarily when the step size is constrained to be small to simulate high-frequency response guidance and control systems.

The table interpolation module incorporates constant, step, linear, quadratic, least oscillatory, and polynomial expansion types of interpolation with special table extremity handling options. The argument may be stored or equally spaced in either ascending or descending numerical order and may be any computed variable. Multivariate functions up to a level of four may be interpolated.

Phase control and interrupt control

Phases are typed as primary or secondary. A primary phase specifies its termination criteria. Secondary phases are subordinate to a primary and specify their initiation criteria; an option permits simultaneous consideration of phase initiations. Each phase may specify up to four initiation/termination criteria; all are evaluated by a linear extrapolation in time on the variable named by the user.

The phase control module determines the phase initiation or termination criteria, calculates the next computing increment, requests integration of the state vector, exercises the logic to terminate a phase and/or initiate a subsequent phase, and services the program interrupt requests for auxiliary computations, for output, and for return to a higher level control.

Various inputs may alter the normal ascending sequence and request phase control to skip forward or backward, to execute alternative sequences, or to repeat certain phases. The integration process under phase control logic may be interrupted for servicing various requests such as auxiliary computations, output, and concurrent integration of phases or vehicles. The interrupt logic examines the requests to ascertain whether the time has come to perform the service.

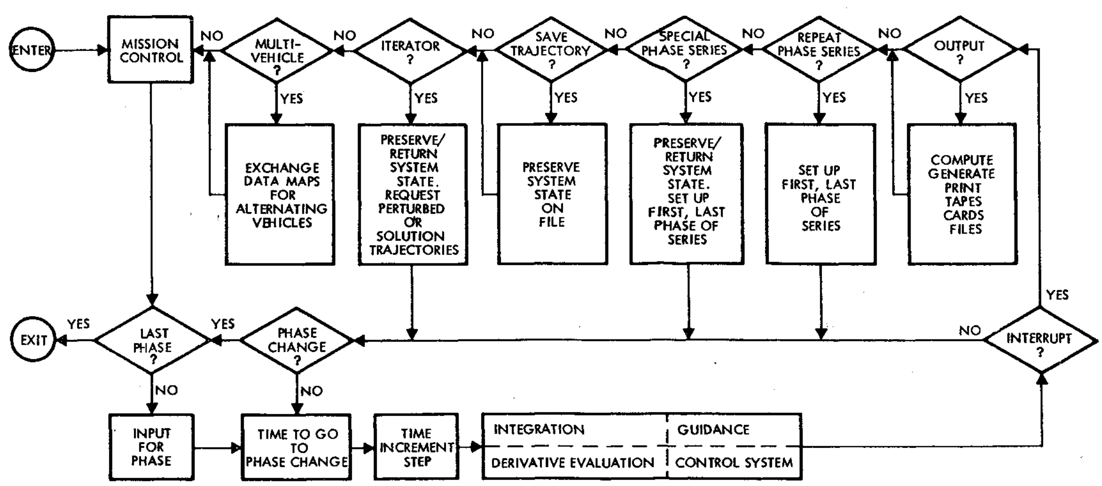

Fig. 2 Flow diagram of MATS controls.

When the auxiliary request is satisfied, trajectory integration proceeds; user inputs specify whether the interrupt influences the propagation of the state vector.

Phase series and alternative vehicle options

A special phase series is one to be executed as an adjunct to the inflight trajectory integration computations; an interrupt requests that the state vector and other pertinent data be preserved and that the trajectory simulation revert to a special sequence of phases. At the conclusion of this digression, the state vector is restored and integration of the actual trajectory proceeds. Examples of such adjunct series include following a jettisoned stage to impact, perturbing initial conditions to collect observations of final conditions for covariance matrix calculations, and examining side constraints on conditional behavior of systems parameters. The special phase series may be nested without undue restraints.

A repeat phase series is one to be executed in line with the inflight trajectory integration. It is used for convenience and economy in data input and storage for those collections of similar events that occur at various points along the trajectory. The state vector is propagated according to any influential parameters introduced by these phases. This control is exercised only at phase-change points and presently may be nested to a level of four. Examples include 1) an orbiting vehicle with a phase terminating on flight path angle of zero degrees to give apogee and perigee print points; to generate ten orbits one may repeat the phase twenty times; and 2) various ignitions of a propulsion system defined in one phase.

Each vehicle simulated has available all the capabilities of the program. Input identifies the vehicles and their associated phases. The user selects one vehicle as the reference; its state vector is advanced in time until an interrupt (which may be a function of time, altitude, or velocity, etc.) requests the alternative vehicle(s) to be updated. The reference vehicle data are preserved, and the remaining vehicle(s) are alternately mapped into active memory and integrated up to the time of interrupt. Such alternative vehicle integration may be used when a vehicle neither experiences the force field of another vehicle nor imposes its force field on another vehicle.

When dynamic coupling exists between vehicles, trajectory propagation proceeds in the simultaneous vehicle integration mode. This capability, currently in design, will permit transfer of information from within the integration-derivative evaluation algorithm to simulate accurately, for example, the plume effect of a vehicle exhaust system. The number of vehicles is virtually unlimited since the data for each vehicle may be stored on an external file.

The save-restore control provides an economic advantage to the user by permitting him to save the state vector and other pertinent data on file at specified points during the trajectory. On subsequent runs he may restart the flight at any of these points thus bypassing those segments of the trajectory which did not change.

Iterator

The iterator (a generalized Newton-Raphson method) requests integration of a nominal trajectory, generates a matrix of partial differential corrections by computing first-order differences from perturbed trajectories, and computes a least-squares solution estimate for the search variables. It requests trajectory integrations repeatedly until convergence of constraint variables to prescribed tolerances is achieved or until some maximum number of iterations is attempted. The search variables may be any input parameters, and the constraint variables may be any computed parameters. Since iterations may be established over any group of phases, the iterator provides "n-point" boundary value solutions for over- and under-determined as well as symmetric systems of nonlinear equations.

An improvement in the error variance causes that trajectory to be considered the nominal, and the iterator proceeds toward convergence in a constant slope sense. If the solution results in no improvement, the iterator recomputes the partials matrix from a new set of perturbed trajectories; divergence is thus logically impossible. Bounds and scale factors are inputs that the user may specify to accelerate convergence. The partials matrix may be printed; it may be input, in which case the first generation of perturbed trajectories is omitted.

To maximize or minimize a variable with respect to a single search parameter, the iterator approximates the function with a quadratic interpolation polynomial, solves for the appropriate extremum, and evaluates the function by integrating a subsequent trajectory. Convergence is declared when the change in the function from the previous value closest to the extremum is less than the specified tolerance. The iterations may be overlapping and/or nested; the number is virtually unlimited.

Input-output and symbol table processors

The display of parameters not required for the integration of the trajectory is requested by an interrupt. The auxiliary variables computed include geodetic position, velocity magnitudes, flight path angles, analytic impact predictions or orbital parameters, radar observations, etc. Two print formats are prebuilt and via input the user may supersede or append to either list any additional computed parameters. The design of this output processor permits quick-look information during integration with complete format generation following, or on a later run. Data tapes may be generated for error analysis, plotting purposes, or test range requirements. A header print summarizes the input data set in an easily readable format.

The input processor handles varying amounts of data through the bucket concept. The data may be input in any order and may be superseded. It is read contiguously into the bucket and organized by phase when trajectory execution is requested. On the CDC-6000 computer the bucket is located in an area where, if it fills to capacity, additional memory is requested. After the redundant data are eliminated and the organization by phase is completed, the memory is released. Since memory is an expensive item in the equipment configuration, considerable saving ensues from the bucket processing. The formats of the input parameters are symbolic with numeric identifiers for the phases and vehicles.

To facilitate symbolic input, MATS incorporates a sophisticated symbol table processor. By using a hashing technique it creates a unique numeric identifier for each recognizable parameter such that the various types of data are acknowledged and treated appropriately.

Concluding Remarks

The basic philosophy of MATS, that it be event-oriented and input-controlled, permits the program to be used for a wide variety of vehicles, missions, and projects. The integrated modularized systems approach facilitates program development, expansion, and evolution without major redesign or implementation effort.

The program comprises some 300 subroutines that occupy some 110,000 decimal words in 15 overlaid segments in addition to mission control and guidance modules. The component integration permits economic isolation of initiation-type functions and omission of redundant algorithms. The systems approach permits adaptability, generality, and successful design analysis on a broad scope.

Future plans involve quick-reaction-rapid-dynamics techniques; the possibility of linkup with an analog computer to simulate continuous functions more appropriately; and investigation of time-saving interactive communication devices, such as teletypewriters and the CDC-274 Digigraphics or the IBM-2250 Graphics consoles.

References

[1] Dethlefsen, D. G., ed., "The Mission Analysis and Trajectory Simulation Program Engineering Document," Feb. 1967, TRW Systems Group, Redondo Beach, Calif.

[2] Lanzano, B. C., ed., "The Mission Analysis and Trajectory Simulation Program Programmer's Handbook," and "The Mission Analysis and Trajectory Simulation Program User's Guide," both rev. Jan. 1970, TRW Systems Group, Redondo Beach, Calif.

Interaction of Gases with an Ablator and the Ablator Components

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THE interaction of gases with a "discontinuously filled elastomer" (a material consisting of a matrix in which colloidal sized particulate matter is dispersed) has both theoretical and applied significance. For example, a 15% vacuum-induced decrease in the thermal conductivity of an ablator has been reported[1] and re-exposure of the ablator to the atmosphere for 24 hr caused the thermal conductivity to revert to substantially its pre-exposure value. These results suggest that gas sorption-desorption may be partially reponsible for the observed changes in thermal conductivity. One purpose of the present work was to measure quantitatively the amounts of several gases sorbed by the same ablator used in the thermal conductivity studies.

The mechanism of sorption of each gas on the ablator is of intrest also. However, since the ablator is a composite material it is not possible from sorption measurements on the ablator itself to define unambiguously the sorption mechanism. A knowledge of which component the gas is interacting with is a necessary step in defining the mechanism. A second purpose of this Note is to present the results of sorption studies on the individual components of the ablator to elucidate the sorption mechanism.

Materials and Experimental Procedures

The ablator used was a filled silicone elastomer designated NASA E4A1 with the following composition: silicone elastomer (73 wt%), silica spheres (11 wt%), phenolic spheres (10 wt%), and silica fibers (4 wt%). The matrix was prepared at the NASA-Langley Research Center using GE silicone liquid (RTV-602). The silica spheres were Eccospheres SI manufactured by Emerson and Cuming, Inc.; these hollow microspheres had a particle size range of 30 to 125μ and a wall thickness of ~2μ. The hollow phenolic shperes (#BJO-0930) were Microballons manufactured by Union Carbide Corporation from Bakelite phenolic resin and had a particle size range of 5 to 127μ. The silica fibers (J-M: 110) were microquartz fibers of ~2μ diameter manufactured by Johns-Manville.

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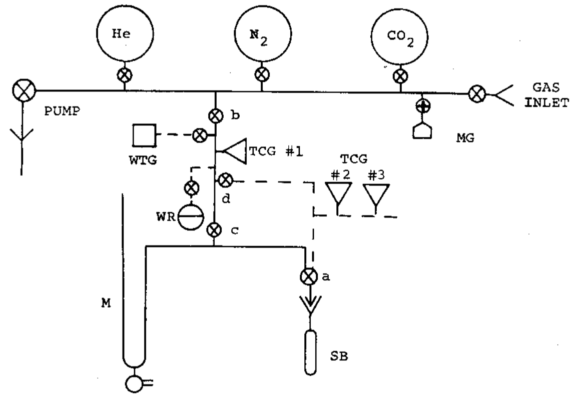

Fig. 1 Apparatus for the determination of gas sorption.

The sorption of various gases at room temperature by the ablator was measured in the constant-volume apparatus shown in Fig. 1. The test sample consisting of about 34 cubes (~5 mm on edge) of the ablator weighing 3.4555 g in sample bulb SB were evacuated in a liquid nitrogen trapped mercury diffusion pump system to $<1 \times 10^{-5}$ torr at room temperature and stopcock *a* closed. A volume of test gas was introduced via stopcocks *b* and *c*. Stopcock *c* was then closed, and the gas pressure was read on the Hg manometer *M*. Stopcock *a* was then opened, the gas was expanded into SB, and the pressure decay $p(t)$ was recorded until dp/dt was ~0.02 torr/min over a 30-min period. The sample was evacuated at room temperature to $<1 \times 10^{-5}$ torr as read on McLeod gauge MG after each gas exposure. Sorption measurements were made at 50°C by immersion of SB into a constant-temperature water bath.

The procedure for water sorption was modified as follows: water vapor was introduced from the water reservoir WR.

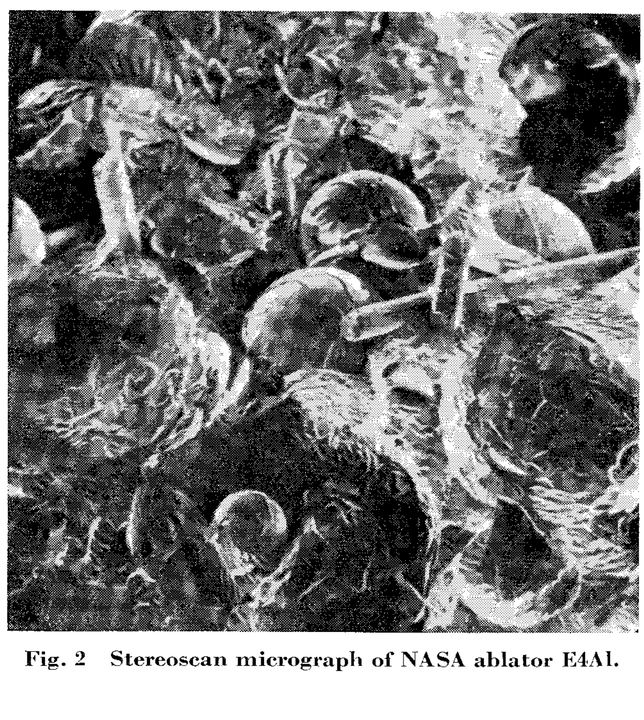

Fig. 2 Stereoscan micrograph of NASA ablator E4A1.