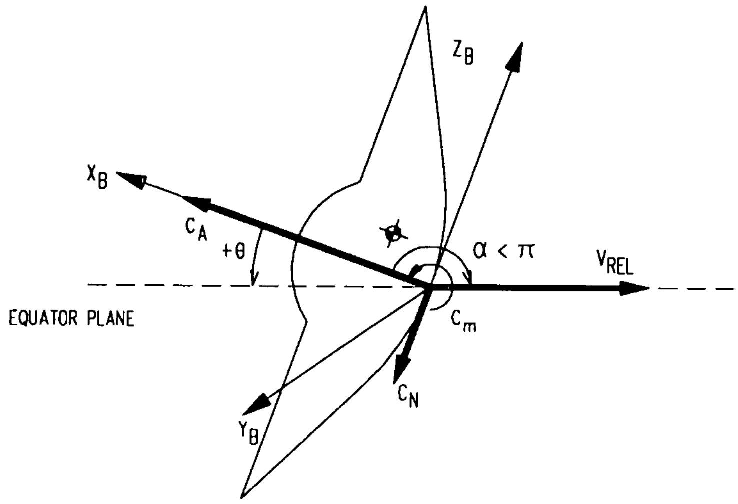
Report LR-726

START User Manual

Version 2.1

July 1993

Ir. E. Mooij



TU Delft
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Title: START user manual: version 2.1
Author(s): E. Mooij
Abstract: This user manual describes the Simulation Tool for Atmospheric Re-entry Trajectories Version 2.1. The software is capable of doing six-degrees-of-freedom re-entry simulations, starting with a deorbit-burn manoeuvre in orbit. After the atmospheric entry, the descent under a parachute can be simulated as well. Central bodies included, are: Earth, the Moon, Mars and Titan. The program has been equipped with a menu-oriented user interface, giving full access to the input data.
Keyword(s): deorbit-burn manoeuvre, re-entry simulation, parachute descent, software, user manual, START

Issue	1	2	3	4
Date	31-10-91	07-07-93		
Prepared	E. Mooij	E. Mooij		
Verified	---------	A.G.M. Marée		
Approved	---------	H.J.D. Piersma		

CHANGE RECORD

Issue No.	Rev. No.	Date	Pages Changed/ Added/ Deleted	Topics Introduced
01	01	31-10-91		Manual for Start Version 1.0
02	01	21-06-93	All	Complete update to Start Version 2.1
	02	07-07-93		Comments processed

START

a Six Degrees of Freedom Simulation Tool

for

Atmospheric Re-entry Trajectories

Version 2.1 - April 1993

Programmed by: E. Mooij (TUD/LR/A2R)

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Notations.

Roman

a	semi-major axis	m
a	speed of sound	m/s
a	dimension of spin vane	m
b	dimension of spin vane	m
C_D	drag force coefficient	-
C_l	rolling moment coefficient	-
C_L	lift force coefficient	-
C_m	pitching moment coefficient	-
C_n	yawing moment coefficient	-
C_S	side force coefficient	-
C_X	axial force coefficient	-
C_Z	normal force coefficient	-
d	aerodynamic reference length	m
dt	simulation step	s
D	drag force	N
D_0	nominal diameter	m
e	eccentricity	-
e	elipticity	-
F_G	gravitational force	N
g_0	reference gravitational acceleration at surface	m/s^2
g_load	occurring dimensionless deceleration (deceleration/g_0)	-
h	height (geometric altitude)	m
h_{hg}	initial altitude for horizontal gust	m
i	inclination	rad
I	inertia tensor	kg m^2
L	roll moment	Nm
L	lift force	N
L_{riser}	riser-line length	m
L_s	suspension-line length	m
L/D	lift-to-drag ratio	-
m	mass	kg
m_a	added mass	kg
M	pitch moment	Nm
M	Mach number	-
M_{sw}	swivel moment	Nm
n_p	number of parachutes	-
n_{sv}	number of spin vanes	-
N	yaw moment	Nm
p	atmospheric pressure	N/m^2
p	angular roll rate w.r.t. the I-frame	rad/s
p_{ref}	reference pressure	N/m^2
q	angular pitch rate w.r.t. the I-frame	rad/s

q_{dyn}	dynamic pressure	N/m^2
r	angular yaw rate w.r.t. the I-frame	rad/s
r	distance to the Centre of Mass of the central body	m
r_{sv}	mean local radius descent module for spin vanes	m
R_e	radius at equator	m
S	side force	N
S	aerodynamic reference area	m^2
S_0	nominal reference area	m^2
t	time	s
t_{hg}	thickness of horizontal gust	m
T_{kin}	kinetic temperature	K
u	cartesian velocity in *X*-direction	m/s
v	cartesian velocity in *Y*-direction	m/s
V	relative flow velocity	m/s
$V_{hg,max}$	maximum velocity for horizontal gust	m/s
V_{ss}	steady state wind velocity	m/s
$V_{ss,max}$	maximum steady state wind velocity	m/s
$V_{ss,s}$	steady state wind velocity at surface	m/s
w	cartesian velocity in *Z*-direction	m/s
x	cartesian *x*-position	m
x_{att}	X-coordinate attachment	m
x_{sv}	X-coordinate spin vane	m
y	cartesian *y*-position	m
z	cartesian *z*-position	m

Greek

α	angle of attack	rad
α_T	total angle of attack	rad
$\dot{\alpha}$	time derivative of α	rad/s
β	angle of sideslip	rad
$\dot{\beta}$	time derivative of β	rad/s
γ	flight-path angle	rad
δ	planetocentric latitude	rad
η_{sv}	efficiency (scale) factor of spin vanes	
θ	pitch angle	rad
θ	true anomaly	rad
θ_{sv}	attitude angle spin vane	rad
λ	longitude	rad
μ	gravitation parameter	m^3/s^2
ρ	atmospheric density	kg/m^3
σ	bank angle	rad
τ	planetocentric longitude	rad
ϕ	roll angle	rad
χ	heading	rad

ψ	yaw angle	rad
ω	argument of pericentre	rad
Ω	longitude of the ascending node	rad

Indices

a	airspeed based
g	groundspeed based
p	parachute
r	(re-)entry vehicle
sv	spin vane
x	*X*-direction

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1. Introduction.

This user manual describes the re-entry simulation software package START (an acronym for Simulation Tool for Atmospheric Re-entry Trajectories). The development of START Version 1.0 began as a part of a thesis study for Aerospace Engineer of Delft University of Technology, Faculty of Aerospace Engineering. The thesis study was performed at ESTEC, Noordwijk (The Netherlands), and covered a period of 10 months (January - October 1991). This development has been extensively described by Mooij (1991a and 1991c). The program was used to do a first mission analysis of the ESA Huygens Probe (Mooij, 1991b).

START Version 2.0 was the outcome of a seven months part-time activity for the Huygens Project Team at ESTEC, and started in January 1992 (Mooij, 1992). An additional contract for ESTEC, dealing with the implementation of the deorbit-burn manoeuvre, finally led to the current version of START (Mooij, 1993a).

This manual will concentrate on how to use the software; no technical description of re-entry flight dynamics nor a discussion on how START was developed, is given. For this, the interested reader is referred to the above mentioned references. Before discussing the capabilities of START, we will give a short overview of START and some general remarks on the User Interface (UI). A full documented listing of the program is published as an Appendix to this user manual (Mooij, 1993b). However, this document is not available to the general public.

2. General description of START.

2.1. Overview of features.

START can be defined to be a 6-dof open-loop re-entry trajectory simulation tool. Open-loop means here, that there are no guidance and control capabilities. The equations of motion, which can be divided into equations of translational motion (position and velocity) and equations of rotational motion (attitude and angular motion), are based on the following state variables: r, τ and δ for the position; V, γ and χ for the velocity; p, q and r (the rotational rate of the body w.r.t. to the inertial planetocentric frame) for the angular motion; and α (angle of attack), β (angle of sideslip) and σ (bank angle) for the attitude of the re-entry vehicle w.r.t. the oncoming flow. As an alternative definition of the attitude, the so-called quaternions have been implemented.

As is indicated in Fig. 2.1, the actual flight dynamics code, the core of the program, is embedded in a UI. It provides the user with a friendly tool to edit all the input data necessary for the trajectory analysis and to start the simulation itself. In other words, all possible actions can only be activated by means of this UI.

The input data can be divided into four blocks, in Fig. 2.1 indicated with trapezoids. The first block is related with the re-entry vehicle. A vehicle can be described as a number of mass elements, each with its own mass, CoM and inertia tensor. This way of entering the vehicle enables a user to 'build' a re-entry vehicle on basis of fundamental geometrical shapes with readily available inertia tensors. The global inertia tensor will be computed during the simulation. Besides, this concept of mass elements can also be used for configuration changes by just deleting one (or more) of the mass elements.

A major part of the vehicle data consists of the aerodynamic database. Each of the (six) force and moment coefficients can be written as a Taylor series, as a function of a number of independent variables, for instance:

$$CF = CF_0 + CF_{X1} \cdot X1 + CF_{X2} \cdot X2 + \ldots + CF_{X1,X2} \cdot X1 \cdot X2 + \ldots$$

The variables Xi are called derivation variables (e.g., α, β, one of the three angular rates); the order of derivation can be 0, 1 or 2. Besides, each of the coefficients CF.. can be entered as a table (max. 10x10), as a function of 0, 1 or 2 table variables (e.g., α, β, q_{dyn}, M). This way of entering aerodynamic data is very flexible. And, by storing the data in a separate file, the aerodynamic data can be updated after each configuration change, by simply reading in an aerodynamic database file. The aerodynamic forces and moments consist of the drag, side and lift forces D, S, and L, and the rolling, pitching and yawing moments L, M and N, respectively.

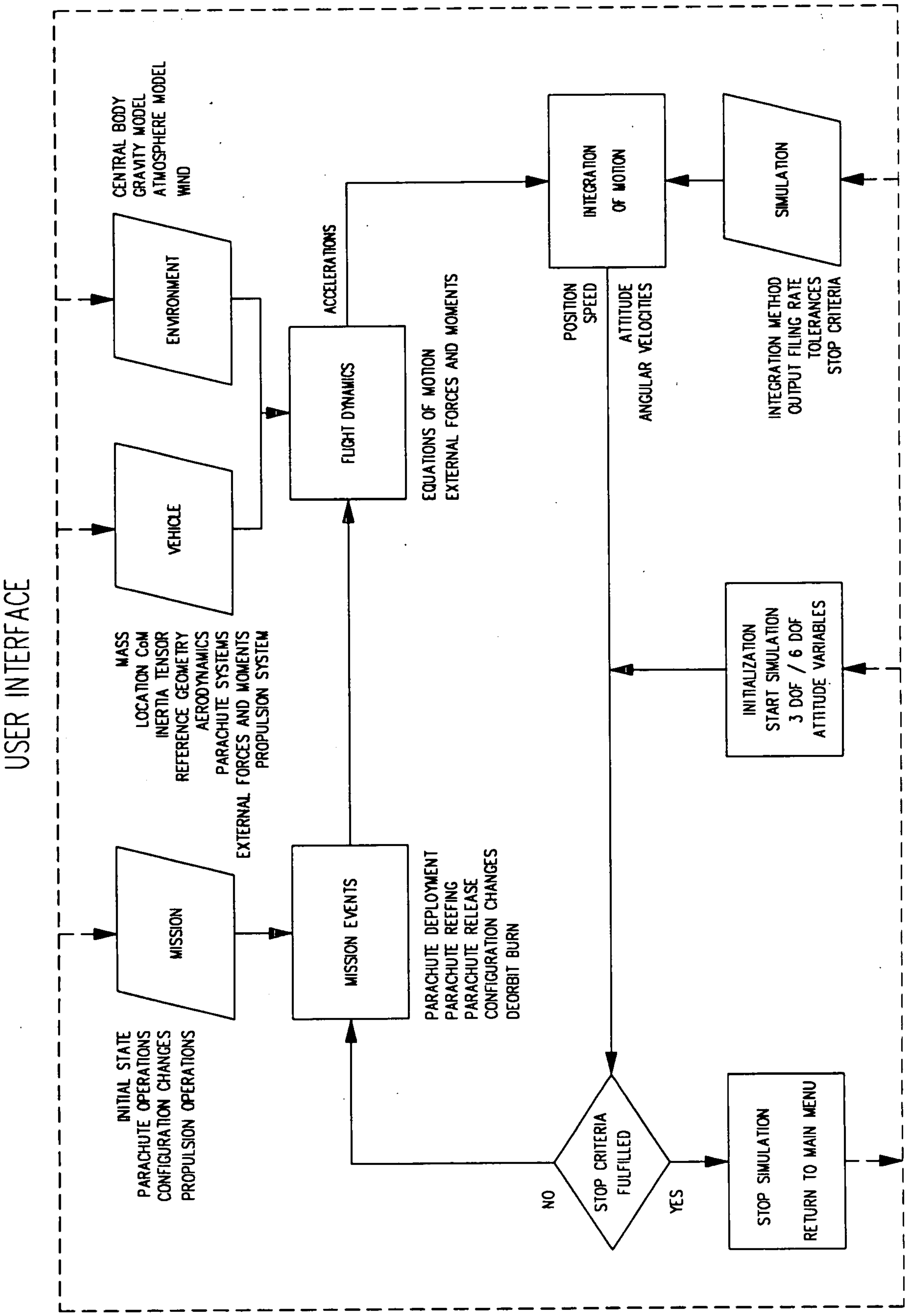


Fig. 2.1 - Schematic layout of START.

As a parachute model, a 3D, 6-dof model has been implemented. Both the parachute and the re-entry vehicle are thought to be rigid bodies (no mass points), connected by a rigid bar. This rigid-bar connection prevents the two bodies to rotate w.r.t. each other. However, the two bodies can spin w.r.t. each other, along this hypothetical bar, because a (non-ideal) swivel has been implemented in the connection between parachute and re-entry vehicle. Non-ideal means here, that the swivel causes a friction moment that counteracts the spinning motion. The air in and under the parachute is taken into account as added mass. The shape of the canopy is defined to be a hemisphere. The model may also include reefing (i.e., step-wise opening) of the parachute. Three parachute systems can be defined.

To create additional external moments, a simplified spin-vane model has been implemented. Each vane is considered to be a rectangular flat plate. The lift and drag contribution for one vane is computed, based on flat-plate theory. These forces result in a rolling moment that drives the re-entry vehicle. The contribution of all the vanes is taken into account by multiplying the computed rolling moment by the number of vanes. This implies, that the flow direction for each vane is assumed to be identical, so no transverse winds can be studied, for instance.

The definition of the propulsion system is currently restricted to an engine, which can only be used for a deorbit-burn manoeuvre. Engine properties are given by the (constant) thrust and specific impulse. The thrust force is supposed to act on the CoM of the spacecraft.

The second block deals with the environment. In the first place, a central body can be selected. This can either be the Earth, the Moon, Mars or Titan. Depending on the central body is the choice of the gravity model (central field plus harmonics up to J_4) and that of the atmospheric model. For the Earth, there are three available models: US Standard atmosphere 1962 (US62), US76 and a simple tabulated model based on US76 (up to 90 km) and CIRA86 (above 90 km). The Martian atmosphere is also tabulated and based on Viking-1 data. For the Titan atmosphere, the tabulated minimum, nominal and maximum Lellouch-Hunten model of October 1987 are used.

A major part of the environmental data consists of the wind database. Presently, the wind model may exist of a steady-state wind and horizontal wind gusts. The steady-state wind can be defined as two components, either a zonal and a meridional component, or a modulus and direction component. The components can be entered in tabular form, being a function of two independent variables at the most (i.e., the atmospheric pressure, the height and the latitude, with a maximum of 40 entries per variable). It is also possible to define a zonal component only, being a (simple) function of the planetary rotation. In addition, the so-called Flasar wind model has been implemented for Titan. This is an engineering model, defining a zonal steady-state wind as a function of altitude (atmospheric pressure) and latitude.

A total of 10 horizontal wind gusts can be specified. Main parameters are the initial altitude, the thickness, the maximum velocity and the direction of each gust. Two shapes have been predefined.

The mission block enables the user to define the mission of the re-entry vehicle. Data correspond to the initial state of the vehicle (for position and velocity, both spherical, cartesian and orbital parameters can be specified), parachute deployment, reefing and release, (other) configuration changes and thrust operations. The latter are restricted to the deorbit-burn manoeuvre. This manoeuvre can be either impulsive (an immediate change in velocity and direction, without using a thrust force) or based on the operation of the deorbit-burn engine (including fuel-mass consumption).

The fourth block, simulation, contains data for executing the actual simulation, i.e., the choice of the integrator (fourth-order fixed-step Runge-Kutta, seventh-order variable-step Runge-Kutta-Fehlberg, variable-order variable-step Adams-Bashforth, Adams-Moulton, second-, third- and fourth-order, fixed-step Adams-Bashforth), the maximum integration step size, the output filing rate for both the quicklook data (information for user during the simulation) and the plot data, the tolerances of the state variables (used by the variable step size integrators) and the stop criteria (e.g., t, h, M).

Input data can be stored in a data file and retrieved when necessary. The aerodynamic data, the parachute systems and the wind model can be stored and retrieved separately.

The actual simulation can be performed in two modes, namely 3 and 6 dof. In the first mode, the re-entry vehicle is considered to be a mass point and only translations can be analyzed (little CPU-time is used). In the second mode, the vehicle is thought of as a rigid body and both translations and rotations can be examined. For the attitude of the body, both aerodynamic angles (α,β,σ) and quaternions can be selected.

Each time step, the equations of motion are integrated to give position and speed (3 dof) and attitude and angular velocities (6 dof). Mission events can be executed whenever a predefined flight condition occurs. Computations proceed until a stop criterium is met. In that case, control is returned to the UI.

2.2. The User Interface.

All features of START can be accessed via a menu-oriented UI. These features are grouped together in sub-menus, e.g., loading, editing, and saving input data. A sub-menu can be entered by simply entering the corresponding number. By selecting a sub-menu choice, we can either go further down in the menu structure, or return to the previous or main menu. To achieve this, each sub-menu always has the following two options:

```
-9- Return to previous menu
-0- Return to main menu
```

Entering either option [9] or [0], the user can leave the current sub-menu.

The major part of the menu structure deals with inputting and editing data. Some general marks apply to this editing.

In this manual, we use squared brackets [] to indicate that the character(s) between brackets must be entered. The Enter-key is indicated by [Enter]. Sometimes, it occurs that we have to answer a question with *yes* or *no*. The keys [y] and [n] are reserved for this. However, also [Y] and [N] are valid entries. In this manual, we use the latter notation, but both upper- and lower-case keys can be used. As we have already seen above, entering a menu option is indicated by [1], [2], etc.

In almost all cases, a default value of the input data is shown, which can be accepted, by pressing the Enter-key, or changed, by typing the required value and then pressing the Enter key. The default values are indicated by

```
... default =  ....
```

In all cases, the units of the related variables are shown. Angles and angular rates are always entered in degrees and degrees per second. Radians are not used for input.

3. Execution of START.

START is primarily an interactive program, which means that with the aid of the extensive UI all input data can be modified before simulating. However, the simulations can put a heavy computational burden on the system, depending on the type of simulation and the kind of computer system one is using. For this reason, a so-called batch mode has been included in START. In this mode, it is possible to overrule the UI and directly begin a simulation, as will be explained in the next Section. The interactive mode is discussed in Section 3.2.

3.1. Batch mode.

After execution of START, an introduction screen is shown, giving information about the program and version number. Besides, the following question is printed:

```
BATCH datafile name (ENTER for none):
```

By specifying a file name, the batch mode is invoked. Simply spoken, this means that START can be executed in a batch job[1]. A batch job is a file, containing all commands which are needed to successfully execute an arbitrary computer program. This batch job is submitted to a batch queue and executed in the background, with a lower priority than users which are working interactively. In this way, the computer system is spared and local users are not bothered by long waiting times. Any output generated by the program is usually written to a specified .LOG file and can be referenced when the batch job is finished.

In the case of executing START in batch mode, we need to specify some data, for a successful execution of a simulation. These data are stored in the BATCH datafile. The layout of this file is as follows:

```
input-file name                                {any valid file name}
quicklook-file name                            {any valid file name}
plot-file name                                 {any valid file name}
simulation mode                                {1 = 3 dof, 2 = 6 dof}
kinematic attitude variables     {1 = (α,β,σ), 2 = quaternions}
```

Nota bene: the user is referred to Chapters 4 and 8 for more specific details on the above data entries.

As an example, we will define the BATCH datafile BATCH.DAT:

```
input.dat
output.dat
output.plt
2
```

[1] Executing programs in batch mode is computer dependent and will not be discussed in this manual. For any specific details the user is referred to the User and Reference Guides of his computer system.

1

The batch job is started by submitting the following batch file to a batch queue:

```
$ start[2]
BATCH.DAT
```

When START is executed, the following line (i.e., BATCH.DAT) is read when START needs its first input (when the user is asked for a BATCH datafile). When the file does not exist, program execution is immediately terminated. If the file exists, it is read and checked for any invalid data entries. If all data are correct, execution is continued, thereby *suppressing any output to the screen*. The simulation stops whenever a stop criterium has been met (see Chapter 8).

Warning: any existing output file (output.dat and output.plt in the above example) will be overwritten!

3.2. Interactive mode: the Main Menu.

The batch mode of START can be ignored if we do not enter a BATCH datafile name. We begin again with the introduction screen and the question:

```
BATCH datafile name (ENTER for none):
```

By pressing [Enter], this screen makes place for the Main Menu as shown below, from which we can access all features of START.

-1- Load input data
-2- View input data
-3- Edit input data
-4- Save input data
-5- Start simulation
-6- Quit the program

By entering one of the numbers [1] to [6], we will enter the second layer of the menu structure, as indicated in Fig. 3.1. In the following Chapters, each of the options of the Main Menu will be discussed.

[2] The command line, as has to be specified on a VAX, has been given here as an example.

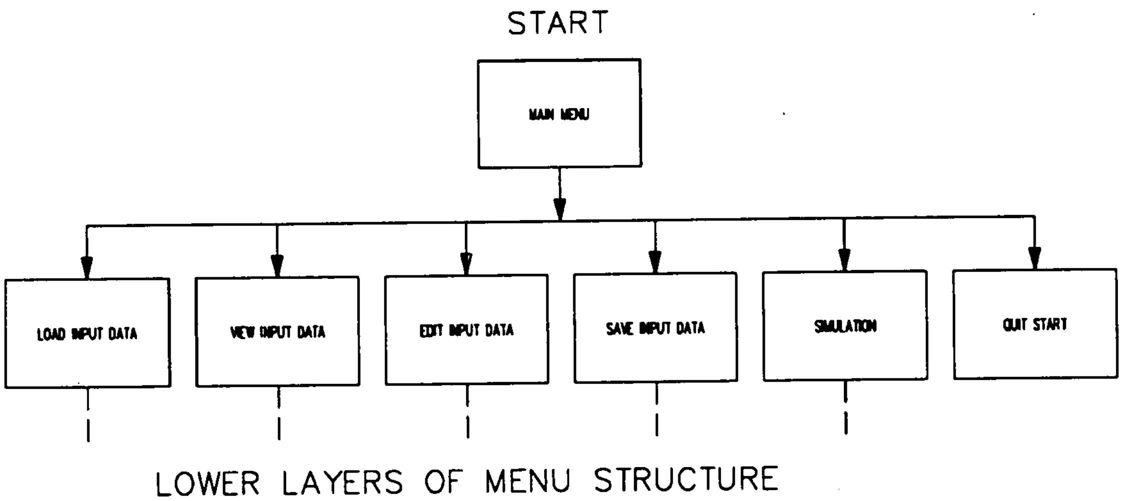


Fig. 3.1 - The Main Menu.

4. Load input data.

By choosing the option **Load input data**, the default input filename and a File Menu, as shown below, appear on the screen. The default file name can be 'INPUT.DAT' (program default) or the last user-specified name.

-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu

By entering [1], the program will use the default input filename, as is shown on the screen. Nota bene: the program will not check whether the current input dataset has already been saved. This responsibility is left to the user. Loading a new set of input data will overwrite the current input data.

If the input file is not found, an error message is given. After accepting the error message (by pressing [Enter]), the message disappears and we arrive at the situation as we did when first entering the File Menu. When the input file is found, the input data are read in. A message on the screen tells the user that the input data are currently being loaded. If, due to any reason, an error is encountered during the read process, this process is aborted and an error message is given. Accepting the error message will result in a return to the File Menu. The input data in memory may be distorted due to the read error, so therefore the input dataset is automatically reset to the Apollo configuration as shown in Appendix A. After successfully retrieving the input data, we return to the Main Menu.

Choosing option 2 enables the user to change the input filename. When changing the filename, one can also specify the drive and/or a (sub-)directory. Pressing [Enter] will terminate the input. If no name has been given - a so-called *blank* filename has been entered - the default name will be assumed. Operations proceed as has been discussed before.

We can leave the File Menu, *without* loading new input data, by entering [9] or [0]. In that case, the input data, as stored in memory, remain unaffected.

In Fig. 4.1 on the following page, the related (sub)-menus are schematically shown.

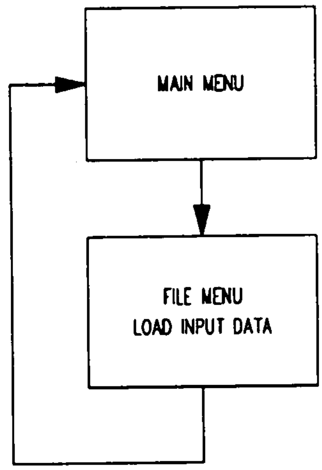


Fig. 4.1 - The File Menu for loading the input data.

5. View input data.

With the option **View input data** one can browse the input data to see the current values of the data which will be used when performing a simulation. The input data will be shown on the screen in exactly the same way and order as they are stored in the input file (Appendix A). An example of a screen with input data is shown in Fig. 5.1.

```
                  * * * * * VIEW INPUT DATA * * * * *

                  ******************************
                  **      MASS PROPERTIES     **
                  ******************************

Number of mass elements                                          1

**********> Data for mass element # 1

Mass at epoch (kg)                                  0.4976000000D+04

X-coordinate CoM (m)                               -0.2570000000D+01
Y-coordinate CoM (m)                                0.0000000000D+00
Z-coordinate CoM (m)                                0.1370000000D+00

Ixx (kg m^2)                                        0.5617605456D+04
Iyy (kg m^2)                                        0.4454623056D+04
Izz (kg m^2)                                        0.4454801760D+04
Ixy (kg m^2)                                        0.0000000000D+00
Ixz (kg m^2)                                        0.1751999840D+04
Iyz (kg m^2)                                        0.0000000000D+00

                  Next screen <Y/N>? <Default = Y>
```

Fig. 5.1 - A screen with input data, as can be seen with the option **View input data**.

At any time the user can decide either to see the next screen or to return to the Main Menu. For the next screen, the user can enter [Y] or simply press [Enter], because the default setting is [Y]. Entering [N] results in the return to Main Menu. The same will happen when the last screen of input data has been shown.

6. Edit input data.

6.1. The Edit Menu.

Editing the current set of input data is possible, by choosing option 3 of the Main Menu. The Edit Menu, which is given below (see also Fig. 6.1), shows that the input data can be divided into four separate modules. Each of these data blocks will be described in the four following Sections. Options 9 and 0 of the Edit Menu result in an immediate return to the Main Menu.

-1- Vehicle
-2- Environment
-3- Mission
-4- Simulation
-9- Return to previous menu
-0- Return to main menu

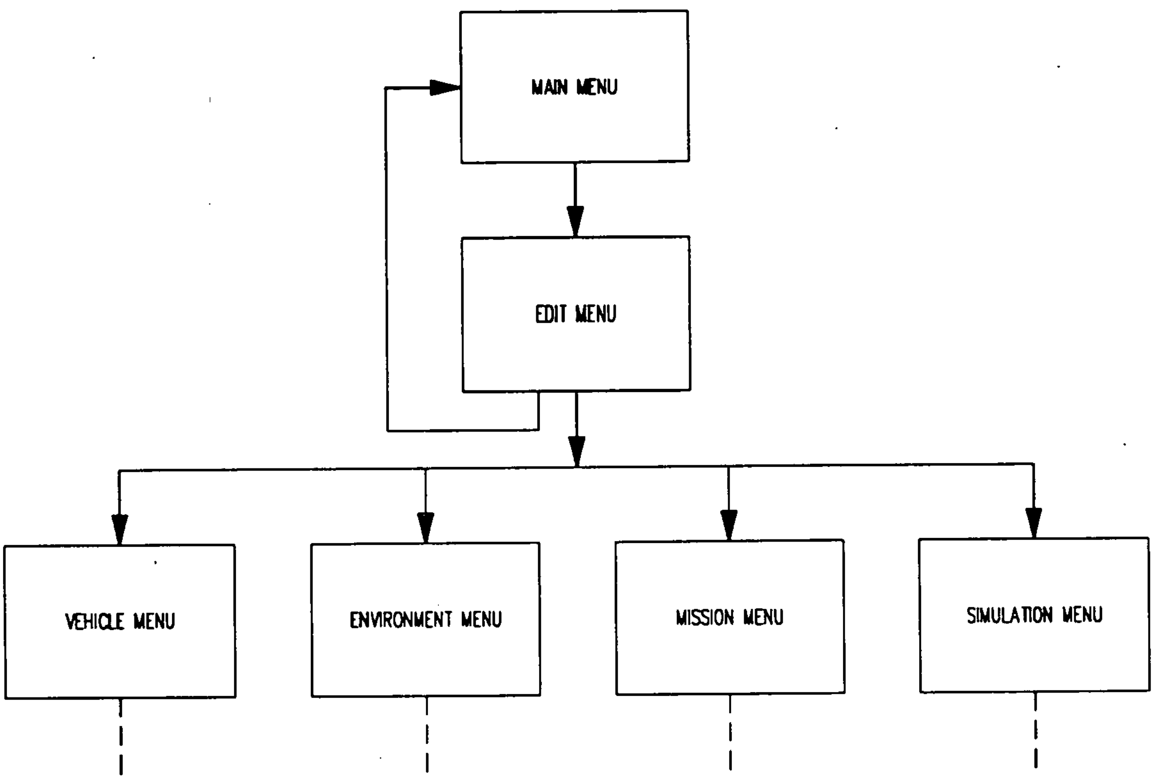


Fig. 6.1 - The Edit Menu.

6.2. Editing re-entry vehicle related data.

6.2.1. The Vehicle Menu.

The input data dealing with the re-entry vehicle can be divided into five categories. The first category of input data consists of the mass properties of the spacecraft, i.e., the mass, the location of the Centre of Mass (CoM) and the inertia properties. The second category deals with the aerodynamic properties of the re-entry vehicle. In this data block, the reference geometry to compute aerodynamic forces and moments is placed. The third category describes a major subsystem of the re-entry vehicle, namely the parachute system. In the fourth category we find external forces and moments, which may act on the re-entry vehicle next to aerodynamic, gravitational and propulsive forces. The fifth category, finally, characterizes the propulsion system.

This subdivision can also be found in the Vehicle Menu, as depicted below. However, the inertia properties and the reference geometry have been given a separate menu entry for practical purposes and with respect to future extensions of the program. The menu entry marked with an asterix cannot be chosen, despite the fact that it has been implemented in the user interface. This topic, thermodynamics, is part of future extensions.

-1- Mass properties
-2- Inertia tensor
-3- Reference geometry
-4- Aerodynamics
-5- Parachute system
-6- External forces and moments
-7- Propulsion system
-8- (*) Thermodynamics
-9- Return to previous menu
-0- Return to main menu

Options 9 and 0 can be chosen, when the user wants to return to either the previous menu, i.e., the Edit Menu, or the Main Menu. The relation of the several layers of the menu structure can be found in Fig. 6.2 on the following page.

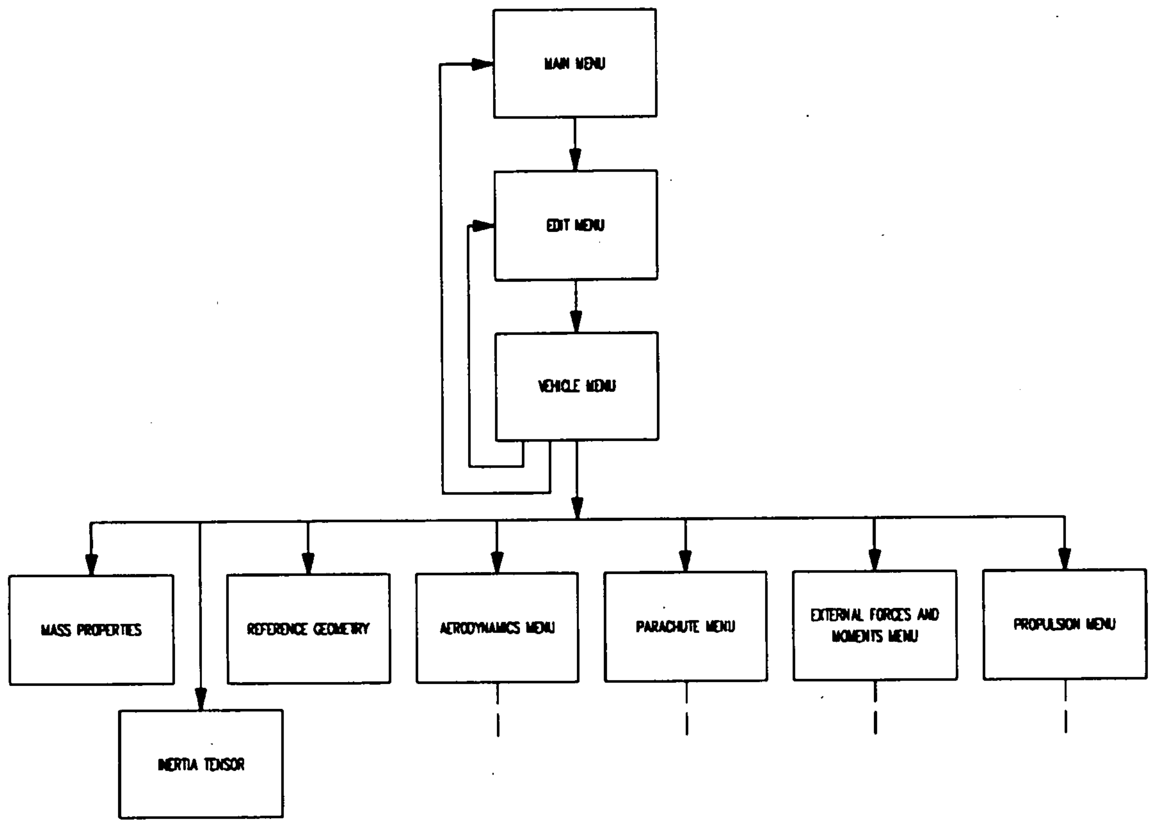


Fig. 6.2 - The Vehicle Menu.

6.2.2. Mass properties.

The re-entry vehicle can be thought to consist of a number of distinct elements, from now on called mass elements, which, when linked together, correspond with a solid body having the same mass properties as the re-entry vehicle as a whole. In this way, the re-entry vehicle can be modelled with basic geometrical shapes (spheres, cones, boxes, etc.) of which the mass properties are known or easy to calculate.

In order to define a number of mass elements, with a fixed distance between each other, it is necessary to define a reference frame in which the coordinates of the mass elements can be expressed. This reference frame has its origin in the so-called aerodynamic reference point, the point with respect to which the aerodynamic force and moment coefficients are defined. The direction of the axes is arbitrarily, as long as this definition will be used consistently. From now on, if we speak about a reference frame, the above mentioned frame is meant.

Entering [1] from the Vehicle Menu (option **Mass properties**), first allows from the user to enter the number of mass elements. Up to a maximum number of 10 mass elements can be defined. If any configuration change (see Section 6.4.4) has previously been defined, and the number of mass elements is decreased, the number of configuration changes will be reset to zero, because they are directly linked with mass element numbers. Nota bene: the variables related with the configuration changes keep their values in that case, so the user can easily redefine the configuration changes.

Per mass element, the user must give the mass m at epoch (time of re-entry) in kg and the location of the CoM, X_{cm}, Y_{cm} and Z_{cm} in m, expressed in coordinates of the reference frame. The mass must be greater than zero, while the CoM can have either positive or negative coordinates.

If only one mass element has been defined, we will return to the Vehicle Menu after having entered the last value (the Z-coordinate of the CoM). In case the number of mass elements is greater than one, the user is asked to continue with the next mass element. Entering [Y] asks for the mass and location of the CoM of the next mass element, while entering [N] results in a return to the Vehicle Menu.

6.2.3. Inertia tensor.

For computations of the angular rates of the re-entry vehicle, the so-called inertia tensor $\boldsymbol{I}$ is used. It is defined as

$$\boldsymbol{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix}$$

As can be seen from the above definition, $\boldsymbol{I}$ is symmetrical. Therefore, only 6 out of the 9 inertia elements have to be defined, namely

I_{xx}, I_{yy} and I_{zz}, the moments of inertia in kg m^2

and

I_{xy}, I_{xz} and I_{yz}, the products of inertia in kg m^2

Using the concept of mass elements, gives rise to the values of the moments and products of inertia for each of the mass elements. Because it is not convenient to define the inertia elements with respect to the reference frame, so-called local frames are introduced. A local frame has its origin in the CoM of a mass element and has the same orientation as the (global) reference frame. This means that the X-, Y- and Z-axis of the local frame are collinear with the corresponding axes of the global reference frame and positive in the same direction. In other words, the local frames are not rotated with respect to the global reference frame.

Per mass element, the moments and products of inertia are defined with respect to the appropriate local frame.

Entering [2] from the Vehicle Menu (option **Inertia tensor**) enables the user to edit the inertia elements. Successively, the user can alter

I_{xx}, I_{yy} and I_{zz}; by definition these values must be greater than 0

and

I_{xy}, I_{xz} and I_{yz}; values can be either positive or negative

Nota bene: if a mass element is rotational symmetric, all the products of inertia are equal to zero.

If only one mass element has been defined, we will return to the Vehicle Menu after entering the last value (i.e., I_{yz}). In case of more than one mass element, the user can choose between editing the inertia tensor of the next mass element and returning to the Vehicle Menu. Having edited the last mass element will also result in a return to the Vehicle Menu.

6.2.4. Reference geometry.

The reference geometry is defined for the complete re-entry vehicle, and consists of the reference length and area for which the aerodynamic coefficients are defined and the reference length on which the Reynolds number is based. Usually, the two reference lengths are the same.

After entering [3] from the Vehicle Menu (option **Reference geometry**), the user can successively change

the reference length d (m) for the aerodynamic coefficients

the reference area S (m^2) for the aerodynamic coefficients

the reference length L_{ref} (m) for the Reynolds number

It is obvious, that each of the values entered must be greater than zero. After entering the value for L_{ref}, we return to the Vehicle Menu.

6.2.5. Aerodynamics.

6.2.5.1. The Aerodynamics Menu.

The major part of the input data consists of the aerodynamic properties of the re-entry vehicle. These data are an integral part of the input file. However, it is also possible to store the aerodynamic data in a separate file, the so-called aerodynamic database. This way of storing enables the user to select a different aerodynamic database when there is a configuration change, which may affect the aerodynamic properties (e.g., the jettisoning of an aerodynamic decelerator). We will discuss this in more detail in Section 6.4.4.

The aerodynamic coefficients and related data can be entered and edited by choosing option 4, **Aerodynamics**, from the Vehicle Menu. The resulting Aerodynamics Menu, as shown below, enables the user to load or save an aerodynamic database, to enter aerodynamic coefficients and to define the way of table extrapolation, which has to be used during the simulation. As is obvious from the menu, there are two ways of defining the aerodynamic coefficients.

-1- Load aerodynamic database
-2- Edit coefficients for axisymmetric body
-3- Edit coefficients for non-axisymmetric body
-4- Extrapolation method
-5- Save aerodynamic database
-9- Return to previous menu
-0- Return to main menu

The first way (option 2, **Coefficients for axisymmetric body**) makes use of the fact that the re-entry vehicle is an axisymmetric body. This means that the aerodynamic representation of the re-entry vehicle is restricted to only three (independent) aerodynamic coefficients, related with symmetrical motion, namely

C_D : the drag coefficient
C_L : the lift coefficient
C_m : the pitching moment coefficient[3]

The second way of aerodynamic modelling (option 3, **Coefficients for non-axisymmetric body**) enables the user to fully define the aerodynamic properties of the re-entry vehicle. Six independent coefficients can be entered, namely

C_D : the drag coefficient
C_S : the side force coefficient
C_L : the lift coefficient

C_l : the rolling moment coefficient
C_m : the pitching moment coefficient
C_n : the yawing moment coefficient

As we will see in Section 6.2.5.3, the aerodynamic coefficients can be entered as tables, as a

[3] The force coefficients are defined with respect to the *Aerodynamic Frame* and the moment coefficients with respect to the *Body Frame*.

function of flight parameters. For flight conditions outside the table range, the actual coefficients can be computed according to different schemes. Choosing option 4 (**Extrapolation method**) from the Aerodynamics Menu enables the user to define one of these schemes.

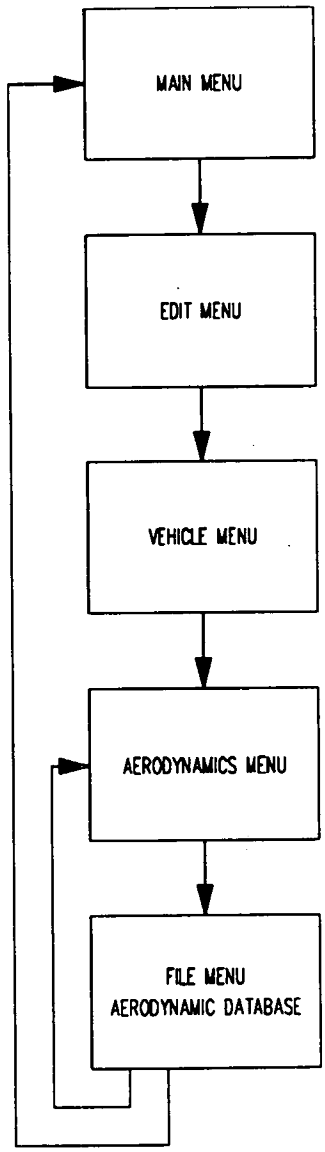


Fig. 6.3 - The Aerodynamics Menu.

Entering [9] results in a return to the Vehicle Menu, see also Fig. 6.3, and [0] in a return to the Main Menu. Before the actual return to one of these two menus, a check is made whether there is no inconsistency in the definition of the aerodynamic coefficients. In short, the inconsistency can be described as follows. The aerodynamic coefficients cannot be based on both the angle of attack α and the total angle of attack α_T at the same time. And, because α_T has been introduced to be used in combination with an axisymmetrical body only, it cannot be defined for a non-axisymmetrical body. As long as this inconsistency has not been solved, one cannot leave the Aerodynamics Menu and an error message is given when one tries. We will come back to this inconsistency, when we are dealing with the (non-)axisymmetrical body.

6.2.5.2. Loading and saving an aerodynamic database.

When either option 1 (**Load aerodynamic database**) or 5 (**Save aerodynamic database**) is chosen from the Aerodynamics Menu, the default name of the aerodynamic database and the following File Menu are shown on the screen:

-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu

The default name of the aerodynamic database can be 'AERO.DAT', which is the program default, or the last user-specified name.

The File Menu introduced above is the same as presented in Chapter 4 (**Load input data**). The discussion given in there also holds for this File Menu w.r.t. loading the aerodynamic database. It is briefly repeated here.

The default database name can be either accepted (option 1) or changed (option 2). Entering a 'blank' name (option 2) also implies the use of the default filename. When the indicated database is not found, an error message is given. We can enter another filename (option 2) or decide to leave the File Menu (options 9 and 0). Also an I/O-error during the read process results in an error message and a return to the File Menu. By choosing option 9, we can go up one level in the menu structure, which means in this case that we arrive at the Vehicle Menu again (see Fig. 6.4). Entering [0] results in a return to the top level of the menu structure, the Main Menu. When the aerodynamic database has been successfully loaded, the Aerodynamics Menu appears on the screen.

Saving an aerodynamic database is not much different. The user can either accept the default database name, as shown above the File Menu, by entering [1], or change the filename by entering [2]. In both cases, a check is made whether the given file already exists. A warning is given if this is true, and the user can decide to overwrite the existing file or to return to the File Menu, to change the filename. When the database has been successfully saved, control is returned to the Aerodynamics Menu. An I/O error during the write process results in aborting the process and a return to the File Menu. An error during the write process will not affect the data stored in memory, of course.

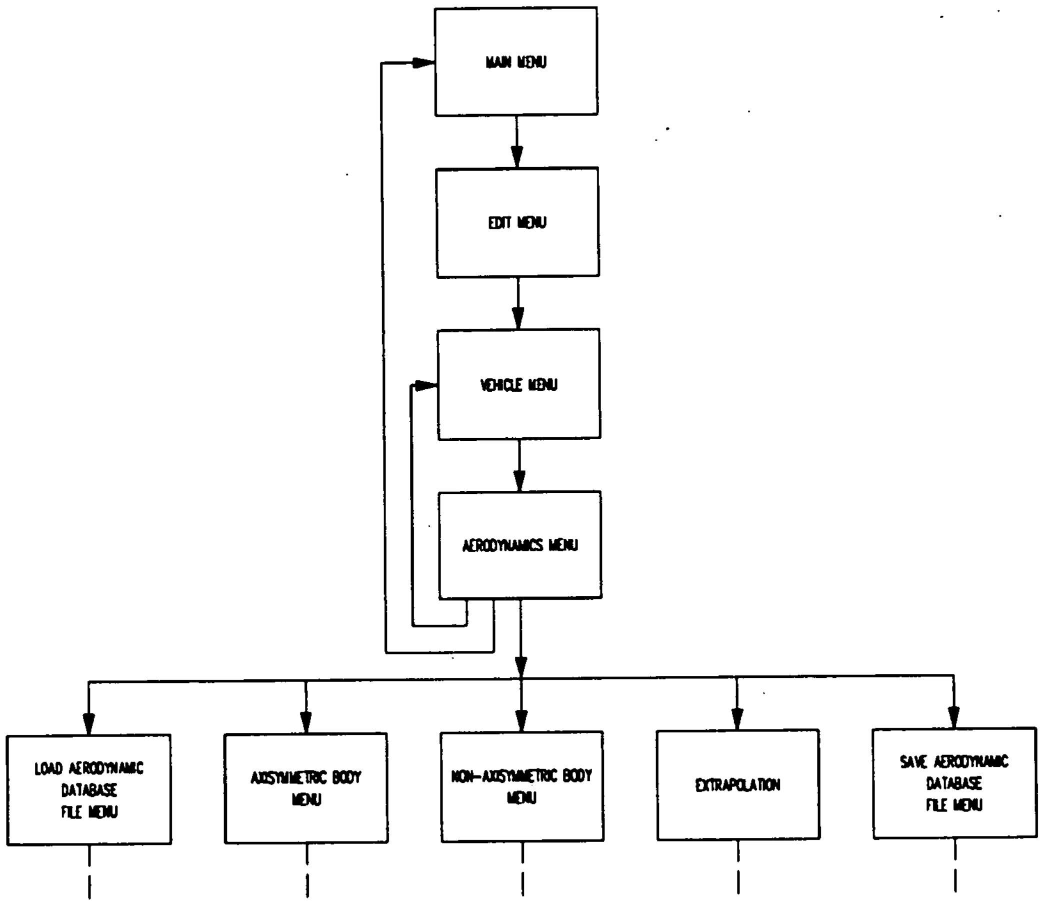


Fig. 6.4 - File Menu for loading or saving the aerodynamic database.

6.2.5.3. Edit coefficients for axisymmetric body.

Before we discuss the Axisymmetric Body Menu, we will shortly describe how aerodynamic coefficients are modelled. As has been stated in Section 2.1, the aerodynamic coefficients are expanded in a Taylor series. A coefficient can have the following form

$$CF = CF_0 + CF_{X1} \cdot X1 + CF_{X2} \cdot X2 + \dots + CF_{X1,X2} \cdot X1 \cdot X2 + \dots$$

Each of the terms CF_0, CF_{X1}, ... are the coefficient *components*. $X1$, $X2$, ... are the *multiplication terms* (also called derivation variables). Each of the coefficient components can be a function of so-called table variables, so that the aerodynamic coefficient can be dependent on flight conditions. If the number of table variables equals zero, then the coefficient component has a constant value.

Entering [2] from the Aerodynamics Menu, **Edit coefficients for axisymmetric body**, gives the Axisymmetric Body Menu, as shown below, on the screen (the related menu structure is shown in Fig. 6.5).

-1- Drag-force coefficient CD
-2- Lift-force coefficient CL
-3- Pitch-moment coefficient Cm
-9- Return to previous menu
-0- Return to main menu

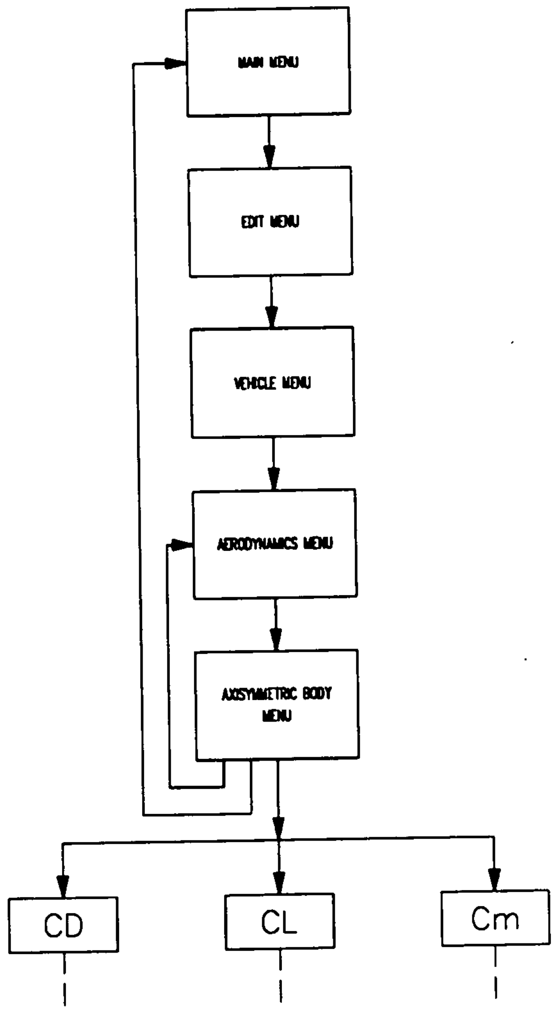


Fig. 6.5 - The Axisymmetric Body Menu.

As has been mentioned before, only three aerodynamic coefficients have to be defined to fully describe the re-entry vehicle. However, there are some restrictions. It must be noted that with this way of modelling, the rolling moment coefficient C_l is always equal to zero. When the user wants to enter a rolling moment coefficient, which is unequal to zero, he has to use option 3 of the Aerodynamics Menu, **Edit coefficients for non-axisymmetric body**. In order to take the remaining asymmetrical force and moment into account (side force and yawing moment), the three symmetric coefficients must be defined as a function of the *total* angle of attack, α_T, instead of the angle of attack α. In that case, the aerodynamic coefficients are so-called *total* coefficients, combining the dependency on angle of attack and angle of sideslip. Using α_T, C_S and C_L are derived from the total lift-force coefficient and C_m and C_n from the total pitching moment coefficient[4]. C_D can directly be obtained from the total drag coefficient.

There is one flight condition, where this way of modelling cannot be used. If $\alpha_T = \pi$, there is a singularity in the equations computing the aerodynamic coefficients. This flight condition corresponds with a ballistic ($\alpha = \pi$ and $\beta = 0°$) or close to ballistic ($\alpha \approx \pi$ and $\beta \approx 0°$) entry. The user has to be aware of the flight conditions encountered during the simulation, in order to use α_T-modelling.

Returning to the Axisymmetric Body Menu, we see five menu entries, three for editing coefficients and the usual two to return to the previous menu or the Main Menu.

Because editing each of the coefficients is done in the same manner, we will restrict the discussion to only one coefficient. Entering [1], [2] or [3] enables us to enter or change coefficient components. When the selected coefficient has not yet been defined - the number of coefficient components is zero - the user is asked whether he wants to enter a coefficient. Entering [Y] results in a number of data he has to enter, after [N] we return to the Axisymmetric Body Menu. On the other hand, if the selected aerodynamic coefficient has already been defined (the number of components is not equal to zero), the related data of the first coefficient component are shown on the screen, together with a menu from which we can start some actions.

Let us suppose the number of components was zero. In this case we immediately begin with entering the necessary data. The first number we must enter is the order of derivation. This value can be either 0, 1 or 2. Depending on this input are the next input data. When the order of derivation is 1 or 2, we must also enter the derivation variable(s). For this reason, the following table is printed on the screen:

```
-0- none
-1- alpha (degrees)
-2- beta (degrees)
-3- alpha_dot * d / V
-4- beta_dot * d / V
-5- p * d / V
-6- q * d / V
-7- r * d / V
```

4 If aerodynamic damping is included in the total pitching-moment coefficient, then this damping is dependent on the angular pitch rate. This implies, that a rotation about the *Y*-axis (pitch) is used to damp a rotation about the *Z*-axis (yaw). It may be clear, that despite the fact that we are dealing with an axisymmetrical body, this is not altogether realistic.

with below this table, the default value for the first derivation variable and the possibility to enter the new value. We can enter any value between [1] and [7]. Nota bene: the first entry, i.e., -0- none, has been added to show as default value when we have changed the order of derivation from 0 to 1 or 2. Since *none* for a derivation variable has no meaning (it would lower the order of derivation), [0] cannot be entered. The only way to change the order of derivation is directly, when we have to enter the order.

After entering the first variable of derivation, we have to enter the second one as well (if the order is 2)[5]. After the derivation variables, the number of table variables must be entered. Table variables are the independent variables of which a component can be a function. The number of table variables can be either 0, 1 or 2. When this number is 0, it means that the component has a constant value, independent of flight conditions. This constant value of the component must be entered next.

A number of 1 or 2, however, means that the value of the component may change during the flight. The following table appears on the screen

```
-0- none
-1- angle of attack (deg)
-2- angle of sideslip (deg)
-3- total angle of attack (deg)
-4- dynamic pressure
-5- Mach number
-6- Reynolds number
```

with below this table the default value for the first table variable. Here, the same principle as with the derivation variables has been applied. Only variables [1] to [6] can be chosen; [0] has been added to serve as default value, when necessary. In case there are two table variables, we must also enter a value for the second one (or pressing [Enter], if we want to accept the default value, as long as it is not 0).

Next, we can change the number of table entries for the table variable(s). Any value between 1 and 10 can be entered (0 would mean that definition of this table variable has been useless, so therefore it has been excluded).

[5] In principle, we assume a linear Taylor series. The fact that the order of derivation can be 2, which means a second derivative, is used to be able to define cross-derivatives (which stand for non-linear terms, but only a first derivative with respect to one variable). If the order is 2, and we choose for both derivation variables the same variable, this means that we have a second derivative with respect to this one derivation variable. In a Taylor series, the corresponding multiplication term would be $X1^2/2$, with $X1$ as the derivation variable. However, in START two *different* table variables are assumed, so therefore the multiplication term is *not* divided by 2, if we define two identical derivation variables. In the case, that defining such a second derivative is necessary, the user must divide the coefficient component itself by two before entering.

The next set of input data deal with the entries for the table variable(s) (NOT the entries for the coefficient component; these have to be entered later). For each entry, a default value appears on the screen, which we can either accept (by pressing [Enter]) or change. Nota bene: α, β and α_T must be entered in degrees, not in radians.

It is important to know, that the entries of the table variables can be in arbitrary order. After having entered the component entries, the table is sorted, i.e., the smallest table variable (and corresponding row or column with component entries) comes first and the other will be in ascending order. This sorting is done for interpolation purposes.

Depending on the number of table variables, and the number of entries per table variable, is the number of entries for the actual coefficient component. For a component, depending on two table variables with 10 entries each (the maximum number), the user has to input 100 values for the coefficient component. Entering a component depending on two table variables, means that the component is represented by a matrix. The values of the component are entered column-wise, in that case.

When we enter the values for the component, the values of the table variables for the current entry are shown on the screen. In this way, the chances to erroneously enter component values have significantly decreased.

Having entered the last entry of the coefficient component, the most important parameters are shown on the so-called overview screen. From this screen it is possible to change any parameter. We will discuss this in more detail after the following example.

Example.

Suppose we want to enter the damping term C_{m_q} of the pitching moment coefficient, defined as

$$C_m = C_{m_0} + C_{m_q} \frac{qd}{V}$$

with

q = angular pitch-rate with respect to rotating planetocentric frame (rad/s)

d = aerodynamic reference length (m)

V = relative flow velocity (m/s)

We assume that the first component, C_{m_0}, has already been entered and that we are about to enter the order of derivation of the second component, C_{m_q}.

The order of derivation is equal to 1. After entering [1], we see the table with derivation variables on the screen, the default value of this variable and the question to enter the value of the derivation variable (again: by pressing [Enter], we can accept the default value). Suppose the default value is not the correct one. In that case we enter [6], for $q * d / V$.

The next input data deal with the table variables. In our example, the damping term is given as a tabulated function of Mach number and total angle of attack, as indicated in Fig. 6.6.

	$\alpha_{T,1}$	$\alpha_{T,2}$	$\alpha_{T,3}$	$\alpha_{T,4}$	$\alpha_{T,5}$
M_1	$C(M_1,\alpha_{T,1})$	$C(M_1,\alpha_{T,2})$	$C(M_1,\alpha_{T,3})$	$C(M_1,\alpha_{T,4})$	$C(M_1,\alpha_{T,5})$
M_2	$C(M_2,\alpha_{T,1})$	$C(M_2,\alpha_{T,2})$	$C(M_2,\alpha_{T,3})$	$C(M_2,\alpha_{T,4})$	$C(M_2,\alpha_{T,5})$
M_3	$C(M_3,\alpha_{T,1})$	$C(M_3,\alpha_{T,2})$	$C(M_3,\alpha_{T,3})$	$C(M_3,\alpha_{T,4})$	$C(M_3,\alpha_{T,5})$
M_4	$C(M_4,\alpha_{T,1})$	$C(M_4,\alpha_{T,2})$	$C(M_4,\alpha_{T,3})$	$C(M_4,\alpha_{T,4})$	$C(M_4,\alpha_{T,5})$
M_5	$C(M_5,\alpha_{T,1})$	$C(M_5,\alpha_{T,2})$	$C(M_5,\alpha_{T,3})$	$C(M_5,\alpha_{T,4})$	$C(M_5,\alpha_{T,5})$

Fig. 6.6 - Example of an input table for the aerodynamic coefficient component C as a function of the two independent variables M and α_T.

For the number of table variables, we enter [2]. The next four questions we answer with

```
Table variable #1, default = 0, i.e. none
Input new value (Enter to proceed): [5]

Table variable #2, default = 0, i.e. none
Input new value (Enter to proceed): [3]

The number of entries for variable #1, default = 1
Input new value (Enter to proceed): [5]

The number of entries for variable #2, default = 1
Input new value (Enter to proceed): [5]
```

Nota bene: the default values given here, are just examples. They may differ per program session.

Next, we enter the values for the two table variables, first M_1 to M_5 and then $\alpha_{T,1}$ to $\alpha_{T,5}$. Finally, we must enter the 25 component entries per column. So we start with $C(M_1,\alpha_{T,1})$ to $C(M_5,\alpha_{T,1})$, then $C(M_1,\alpha_{T,2})$ to $C(M_5,\alpha_{T,2})$, etc. Having entered the last entry, i.e., $C(M_5,\alpha_{T,5})$, the overview screen of Fig. 6.7 appears.

```
                * * * * * EDIT INPUT DATA * * * * *

                     ****************************
                     **    AXISYMMETRIC BODY   **
                     ****************************

                       Pitching moment equation
   Component #2 of 2

   Order of derivation       : 1
   Ref. var. of deriv. #1    : q * d / V
   Ref. var. of deriv. #2    : none

   Number of table variables : 2
   Table variable #1         : Mach number
   Number of entries var. #1 :  5
   Table variable #2         : total angle of attack (deg)
   Number of entries var. #2 :  5

   -1- Change any parameter.     -9- Return to previous menu.
   -2- Add component.
   -3- Delete component.

                 Enter the number of your choice:
```

Fig. 6.7 - Overview screen for an aerodynamic-coefficient component.

We can now return to our discussion of entering and changing coefficients. The above screen is also shown, when we choose from the Axisymmetric Body Menu one of the three coefficients, and they have already been defined previously. Depending on the number of coefficient components is the Coefficient Menu. If the aerodynamic coefficient consist of only one component, we see the menu as shown below.

```
-1- Change any parameter.          -9- Return to previous menu.
-2- Add component.
-3- Delete component.
```

Choosing option 1, **Change any parameter**, we arrive at the same set of questions as discussed before. It is now possible to fully redefine the component. Of course, the current (default) values are shown for each variable.

With the second option, **Add component**, we can define a new component, which belongs to the current coefficient. Suppose we have defined the lift coefficient with one component, C_{L_0}, and we want to add a first derivative, C_{L_α}, so that the total expression for the lift coefficient will be

$$C_L = C_{L_0} + C_{L_\alpha} \cdot \alpha$$

then we can use this option. The number of components, which can be added is depending on the coefficient. For each of the coefficients, a maximum number of components has been defined. These are

C_D : 2 components

C_L : 5 components

C_m : 8 components

Adding a component, while the maximum number has already been used, results in an error message.

After adding a component, we return to the overview screen from which we entered the **Add component** option. This means, that for a coefficient with three components already defined, entering [2] (adding the fourth component) from the overview screen of the first component, we will return to the overview screen of the first component and not to the screen for this last entered component. Of course, it is possible to view this overview screen. We will come to that later.

With option 3, **Delete component**, we can remove the current component, i.e., the one currently shown on the screen. Due to the radical nature of this action, the user is asked for confirmation. Entering [Y] results in the actual deletion, while [N] will not affect the component definition. In that case we return to the overview screen. After deleting the current component, we return to the overview screen, where the next component (if any) is shown, or the previous one (if we deleted the last one). In case we deleted the only one component, we will return to the Axisymmetric Body Menu.

With option 9, **Return to previous menu**, we can return to the Axisymmetric Body Menu, as indicated in Fig. 6.5.

Up to now, we assumed that only one component had been defined. However, it is of course also possible that a coefficient consists of more components. In that case, it must be possible, when we have seen (or edited) the first component, to see the next one. For this reason, we see in the case of more components, a slightly different menu.

-1- Change any parameter.	-4- Show next component.
-2- Add component.	-9- Return to previous menu.
-3- Delete component.	

This menu will be shown on the overview screen, as long as there are more components to show. It is NOT possible to go back to a component. In that case, we have to return to the previous menu, and select the same coefficient, so that we begin with component 1 again. The use of this menu is identical to the one described above. The only difference is that the option **Show next component** has been added.

6.2.5.4. Edit coefficients for non-axisymmetric body.

Choosing option 2 from the Aerodynamics Menu, **Edit coefficients for non-axisymmetric body**, we can fully define the aerodynamic properties of the re-entry vehicle. We have three force and three moment coefficients at our disposal now, as can be seen in the Non-axisymmetric Body Menu below.

-1- Drag-force coefficient CD
-2- Side-force coefficient CS
-3- Lift-force coefficient CL
-4- Roll-moment coefficient Cl
-5- Pitch-moment coefficient Cm
-6- Yaw-moment coefficient Cn
-7- Return to previous menu
-8- Return to main menu

The discussion given in the previous Section about the coefficients for an axisymmetric body is without change also applicable to the coefficients for a non-axisymmetric body. We therefore refer to that Section. The maximum number of coefficient components, which can be defined, are:

C_D : 2 components

C_S : 5 components

C_L : 5 components

C_l : 5 components

C_m : 8 components

C_n : 8 components

With options 9 and 0 we can return to the upper layers of the menu structure, as is also shown in Fig. 6.8.

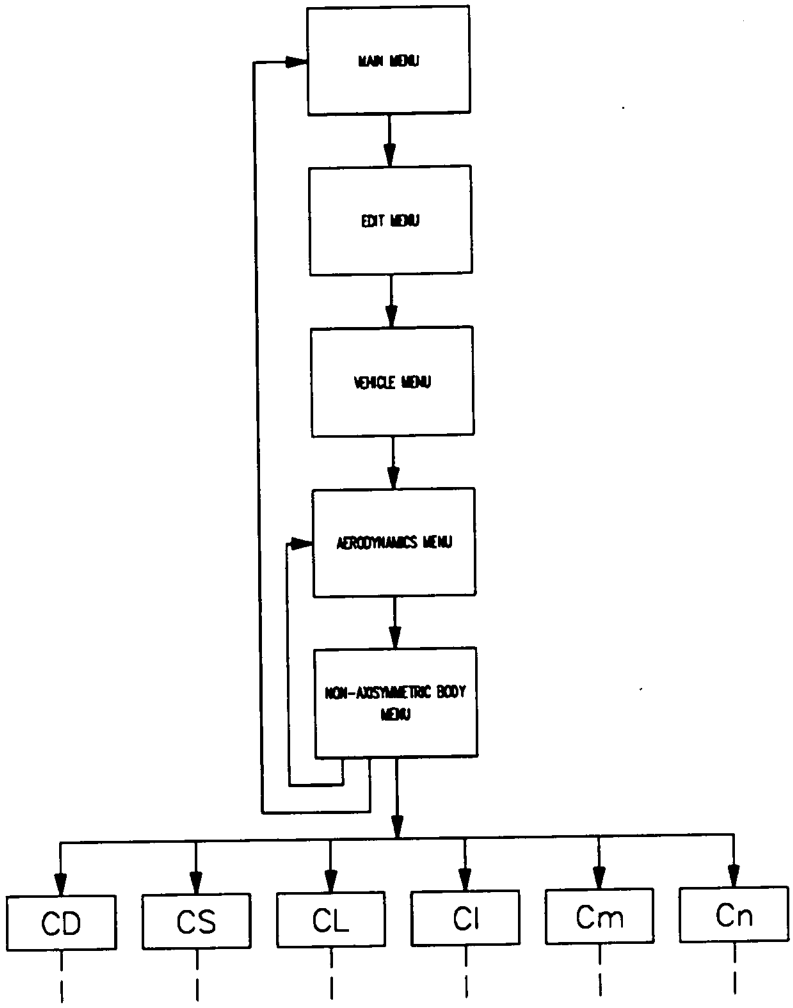


Fig. 6.8 - The Non-axisymmetric Body Menu.

6.2.5.5. Extrapolation method.

As we saw in the previous two Sections, the aerodynamic coefficients can be represented by tabulated functions of flight parameters. Depending on the actual flight condition, the correct value of the aerodynamic coefficient is computed by means of linear interpolation. When the flight conditions are such, that the actual values of the table variables are outside the table range, special care has to be taken.

We can define the way of extrapolation for those cases outside the table range. We enter [4], **Extrapolation method**, from the Aerodynamics Menu. Then, the default choice for extrapolation is shown, together with the Extrapolation Menu, as presented below:

-1- Coefficient not defined
-2- Use boundary value
-3- Extrapolation
-9- Return to previous menu
-0- Return to main menu

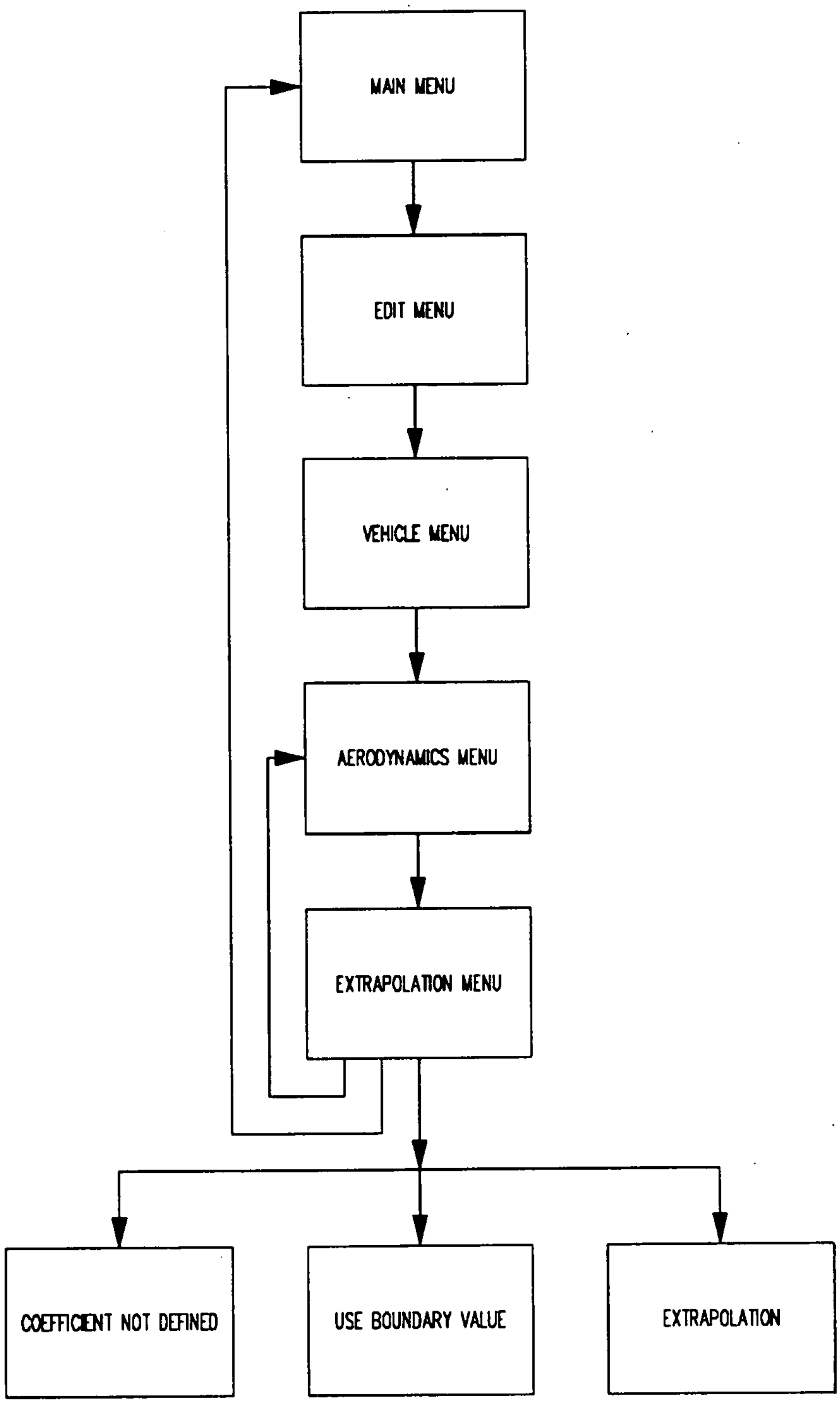


Fig. 6.9 - The Extrapolation Menu.

The first three entries give the possibilities for extrapolation. **Coefficient not defined** means, that when the flight conditions are such that they are outside the table range, the aerodynamic coefficient is not defined. This results in an error message during the simulation, which is aborted consequently.

Option 2, **Use boundary value** means the following. Suppose table variable #1 is the Mach number, with 5 entries, such that

$$M_1 < M_2 < M_3 < M_4 < M_5$$

If the actual Mach number, M, is smaller than M_1, this latter value is used. Also when $M > M_5$, the coefficient value for M_5 is used.

With **Extrapolation** (option 3), the coefficients are computed by means of linear extrapolation. It must be noted, that when the difference between actual values and boundary values of the table are large, the coefficient values may be too large or too small. The user must decide on basis of table range and occurring flight conditions whether this option can be used.

After selecting an extrapolation method, we return to the Aerodynamics Menu. Entering [9] or [0] results in a return to the Aerodynamics or Main Menu, respectively (Fig. 6.9).

6.2.6. The parachute system.

The following characteristics underlie the parachute model. The parachute/payload system is considered to be one single body. The equations of motion describe the translation *of* the global CoM of the system and the rotation *around* this CoM. The equations of translational motion are based on cartesian coordinates, in order to overcome the singularity for spherical coordinates when a vertical motion is studied. To describe the attitude of the system, quaternions are used. The effect of wind is taken into account.

Both the parachute and the re-entry vehicle are thought to be rigid bodies (no mass points), connected by a rigid bar. This rigid-bar connection prevents the two bodies to rotate w.r.t. each other. However, the two bodies can have a relative spin rate w.r.t. each other, because a (non-ideal) swivel has been implemented in the connection between parachute and re-entry vehicle. Non-ideal means in this case, that the swivel causes a friction moment which counteracts the spin rate.

The air in and under the parachute is taken into account as added mass. The shape of the canopy is taken as a hemisphere.

To minimize the CPU-time usage, the parachute/payload system is considered to be rotational symmetric. In that case, the inverse of the inertia tensor does not have to be computed every time step, since there exist an analytic form of the Euler equations for a rotational symmetric body. Nota bene: the inertia properties of the system change continuously because of the added mass, which is dependent on the atmospheric density and therefore on height.

6.2.6.1. The Parachute Menu.

Entering [5] from the Vehicle Menu, **Parachute System**, gives the following Parachute Menu on the screen (see also Fig. 6.10).

```
-1- Load parachute systems
-2- Parachute model (2D/3D)
-3- Number of parachute systems
-4- Edit a parachute system
-5- Save parachute systems
-9- Return to previous menu
-0- Return to main menu
```

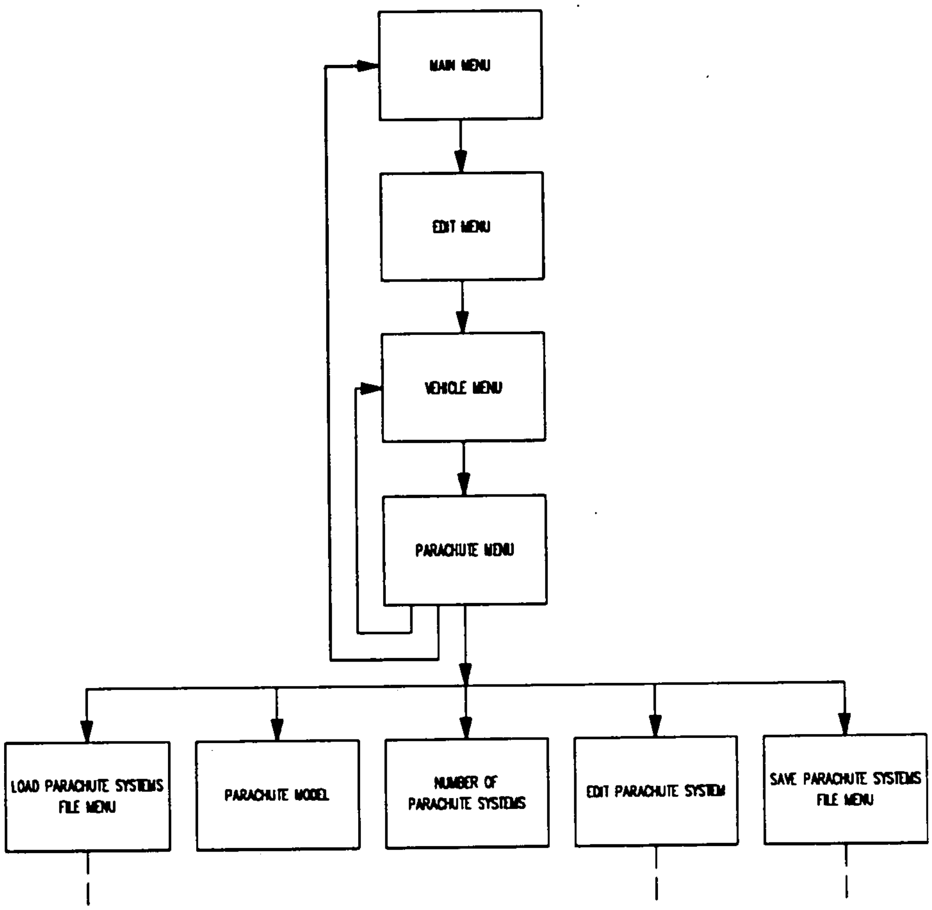


Fig. 6.10 - The Parachute Menu.

As can be seen from the first and fifth entry of this menu (**Load parachute systems** and **Save parachute systems**, respectively), all parachute-related data are treated as a separate entity, a so-called parachute database. This makes it easy to use an already defined parachute system with other vehicles.

The parachute model defined in START Version 1.0 is a 2D, 3 dof one. Both the entry vehicle and the parachute are represented by mass points, connected by a rigid bar. The model is relatively fast and gives qualitatively good results, as long as the influence of wind is not considered. The current model is a 3D, 6 dof parachute model, where the entry vehicle and the parachute are treated as (symmetrical) rigid bodies, still connected by a rigid bar. The model gives more accurate results (especially when the influence of wind is studied), but is computationally more intense. In the current version of the software, only the new model can be used, but for the future it is foreseen that the old model will be reimplemented as an alternative model. For this reason, menu entry 2 (**Parachute model (2D/3D)** has already been implemented.

A parachute system can be edited (option 4, **Edit parachute system**), once at least one (up to a maximum of three) parachute system has been defined with option 3, **Number of parachute systems**. Entering [9] or [0], results in a return to the Vehicle Menu or Main Menu, respectively (Fig. 6.10).

In the following Sections, each of the menu options will be discussed in more detail.

6.2.6.2. Load and save parachute systems.

Choosing option 1, **Load parachute systems**, or option 5, **Save parachute systems**, gives the name of the currently defined parachute database, and the following (familiar) File Menu.

```
-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu
```

The parachute-database filename can be 'PARA.DAT' (program default) or the last user-specified name.

Loading or saving the parachute database is executed in the same manner as has been described in Chapter 4 or Section 6.2.5.2. For the sake of convenience, we will briefly repeat the procedure. We begin with loading a database.

We can either accept the default database name by entering [1] or change the name by entering [2]. Entering a 'blank' name (option 2) also implies the use of the default filename. When the indicated database is not found, an error message is given. We can enter another filename (option 2) or decide to leave the File Menu (options 9 and 0). Also an I/O-error during the read process results in an error message and a return to the File Menu. The parachute data, which may have been distorted by the I/O error are reset to the default values. This means that no parachute systems are assumed.

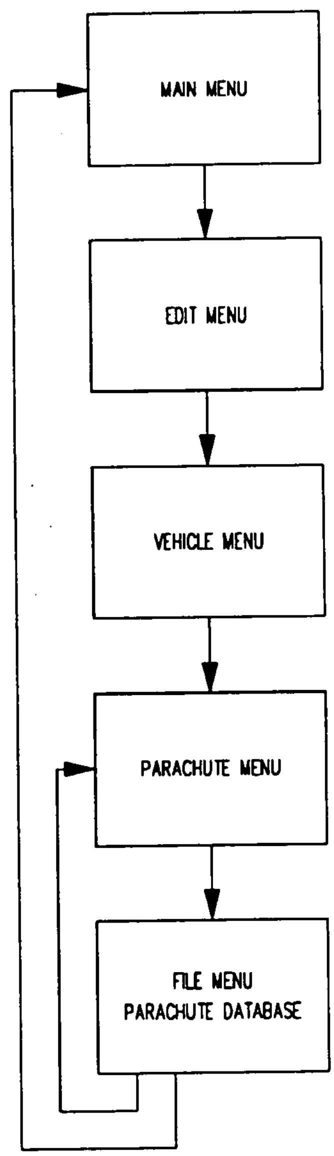


Fig. 6.11 - File Menu for loading and saving the parachute database.

By choosing option 9, we can go up one level in the menu structure, which means in this case that we arrive at the Parachute Menu again (see Fig. 6.11). Entering [0] results in a return to the top level of the menu structure, the Main Menu. When the parachute database has been successfully loaded, the Parachute Menu appears on the screen.

When we are saving a parachute database, we can specify the filename in exactly the same way as mentioned above. Once a valid name has been entered, a check is made whether the given database already exists. A warning is given if this is true, and the user can decide to overwrite the existing file or to return to the File Menu, to change the filename. When the database has been successfully saved, control is returned to the Parachute Menu. An I/O error during the write process results in aborting the process and a return to the File Menu. An error during the write process will not affect the data stored in memory.

6.2.6.3. Number of parachute systems.

Choosing option 3, **Number of parachute systems**, from the Parachute Menu it is possible to define the number of parachute systems. The maximum number of parachute systems is three. It is important to know, that if more than one system have been defined, all systems are taken into account when the mass properties of the complete entry vehicle are determined. Defining three parachute systems does not mean that we can only use one system during the mission; in fact, all three systems can be deployed, although it should be noted that a second parachute system can only be activated when the first one has been released.

Some remarks

- Decreasing the number of parachute systems does not erase the actual parachute data. However, they are not taken into account any more while simulating a mission. Increasing the number again, would show that the data are unaffected. This option is convenient, when one want to see the influence on the mass properties of the complete entry configuration. By decreasing the number with one, we can study the effect of the last defined parachute system.
- When the parachute systems are stored in an input file or a parachute database, only those parachute systems are stored, which have been defined by the number of parachute systems (starting with system 1, 2, and finally 3, if applicable).
- By decreasing the number of parachute systems, always the last defined system is removed first. It is not possible to copy the third system, for instance, to the first system. When parachute systems use the same aerodynamic database, these data have to be entered for each system. They cannot be copied either.

6.2.6.4. Edit a parachute system.

To **Edit a parachute system** (option 4 from the Parachute Menu), at least one parachute system must be defined. In case no parachute systems are defined, an error message is given, which tells the user that it is not possible to edit a parachute system. Accepting the error message (by pressing [Enter]), we return to the Parachute Menu. There, we can use option 3 (**Number of parachute systems**) to define the number of parachute systems.

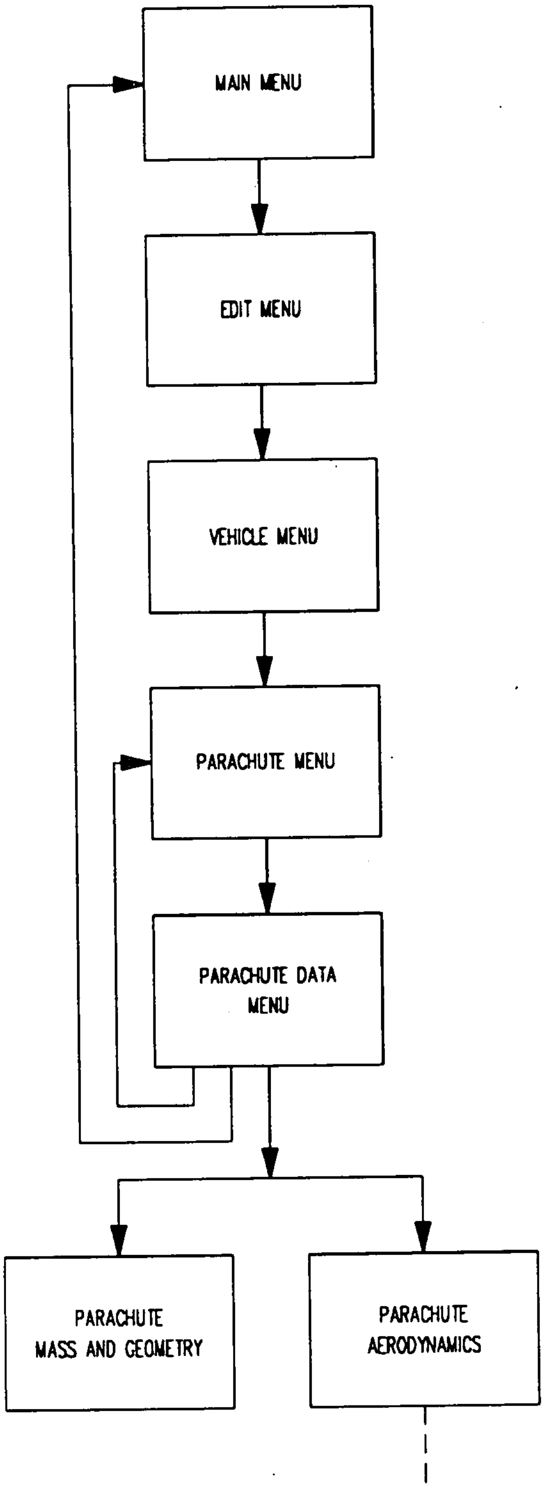


Fig. 6.12 - The Parachute Data Menu.

If we have defined a certain number of parachute systems, we can edit one. This is indicated by the Parachute Data Menu, as shown on the next page (see also Fig. 6.12):

-1- Mass and geometry
-2- Aerodynamics
-9- Return to previous menu
-0- Return to main menu

Choosing either option 1, **Mass and geometry**, or option 2, **Aerodynamics**, the user is first asked to enter the number of the parachute system, which he wants to edit. This number must be between 1 and the maximum number of defined parachute systems (this maximum number is indicated on the screen). Entering an invalid number results in a restatement of the question. Once a valid number has been entered, one can proceed with entering either mass and geometry or aerodynamic data, as will be explained below.

Mass and geometry

A schematic overview of the mass and geometry of the parachute system is shown in Fig. 6.13.

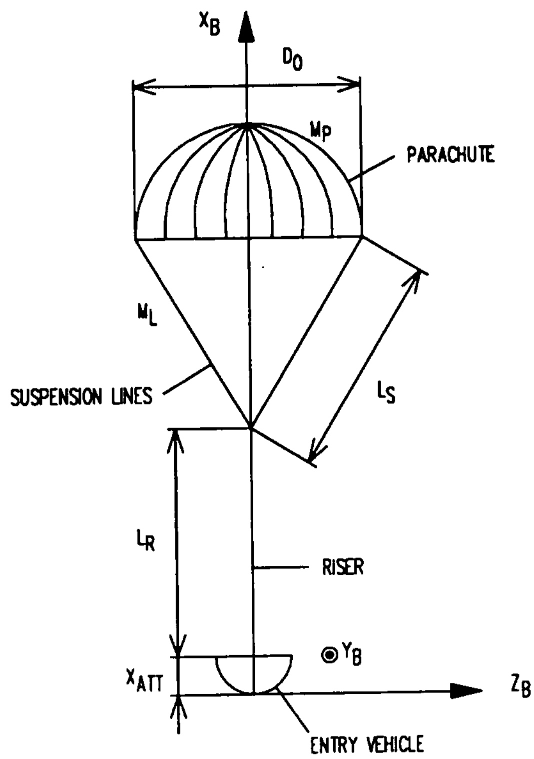


Fig. 6.13 - Parachute mass and geometry. The parachute system, as shown here, consists of only one parachute. The origin of the reference (body) frame is assumed to be coincident with the nose of the entry vehicle.

The first variable is the number of parachutes (of the currently defined parachute system). Depending on this number is the following parameter. If the parachute system consists of more than one parachute, a so-called cluster coefficient must be entered, with a value between 0 and 1. This cluster coefficient represents the performance loss of the parachute system due to clustering of the parachutes. A value of 0.9, for instance, means that the decelerating effect of the parachute system is only 90% of the nominal value.

The next variable is the parachute mass ($m_P > 0$ kg). Nota bene: the mass of a single parachute is meant, although the system may consist of more than one parachute. We assume that each of the parachutes has the same mass. Following the parachute mass, the mass of the suspension lines must be entered. Again, this mass is related to a single parachute.

Following the mass properties, the next three parameters define the geometry of the parachute. Successively, we must give the values for the nominal parachute diameter ($D_0 > 0$ m), the suspension-line length ($L_s > 0$ m) and the riser-line length ($L_{riser} > 0$ m).

As has been mentioned before, in the connection between the parachute and the re-entry vehicle, a swivel has been implemented. This does not imply that the swivel has to be included in the model. The user is asked whether a swivel is connected to the riser. Answering [N], means that the parachute and re-entry vehicle will roll with the same rate. It also means that the inertia properties of both the parachute and the vehicle are taken into account when the angular rates are computed. The parachute system truly is a single body, in this case.

On the other hand, when the user decides to connect a swivel to the riser by answering [Y], the rolling motion of the vehicle is decoupled from the one of the parachute. To be more precise, the parachute is considered not to roll at all (i.e., no roll rate w.r.t. inertial space). The computed roll rate is the one of the re-entry vehicle only.

The swivel can be non-ideal, meaning that the rolling motion of the re-entry vehicle causes a friction moment. Of course, this moment is always counteracting the rolling motion. To include the friction moment, a so-called friction coefficient has to be specified. The unit of this (positive) coefficient is 'meter'. Entering '0', results in an ideal swivel with no friction.

The connection of the riser to the vehicle is called the attachment point. Since we consider the parachute system to be a rotational symmetric body, only the *x*-coordinate of the attachment point has to be specified. This value concludes the input set of the parachute in deployed state.

The following data the user has to provide, deal with the mass properties of the parachute system in packed condition. We must give the location of the CoM of the packed parachute system, i.e., X_{cm}, Y_{cm} and Z_{cm} (in m) and the values of the inertia tensor, I_{xx}, I_{yy} and I_{zz} (the moments of inertia in kg m^2) and I_{xy}, I_{xz} and I_{yz} (the products of inertia in kg m^2). Nota bene: because it is possible that these data are not known, it is possible to enter '0' for the moments of inertia to exclude them. One must take note, that the location of the CoM of the parachute system must be equal to the global CoM of the re-entry vehicle, or there will be additional moments of inertia due to the shift of the CoM. After entering the last value, we return to the Parachute Data Menu.

Aerodynamics

After selecting the menu entry **Aerodynamics** (option 2) from the Parachute Data Menu, the user first has to specify which parachute system he wants to edit. After entering a valid number, the following sub menu, the Parachute Aerodynamics Menu, appears on the screen.

-1- Aerodynamic coefficients
-2- Extrapolation method
-9- Return to previous menu
-0- Return to main menu

We see similar menu entries as before, when we were discussing the aerodynamic properties of the re-entry vehicle: we can either edit aerodynamic coefficients or choose the extrapolation method for flight conditions outside the table range.

Although the parachute system is an axisymmetric body, which means that we could have restricted the number of aerodynamic coefficients to three (the 'total' aerodynamic coefficients, see also Section 6.2.5.3), this approach is not followed here for two reasons. In the first place, defining 'total' aerodynamic coefficients implies that the roll coefficient is always zero. Since it must be possible to study roll damping, the user must have full access to the aerodynamic coefficients. In the second place, and this is much more important, parachute descent usually takes place at a 'zero-angle-of-attack' (in our case $\alpha = 180°$) and for this value of α, the equations for transforming the 'total' coefficients hold a singularity.

After choosing option 1, **Aerodynamic coefficients**, we arrive at the following Coefficient Menu.

-1- Drag-force coefficient CD
-2- Side-force coefficient CS
-3- Lift-force coefficient CL
-4- Roll-moment coefficient Cl
-5- Pitch-moment coefficient Cm
-6- Yaw-moment coefficient Cn
-9- Return to previous menu
-0- Return to main menu

Entering and editing these coefficients is done in exactly the same way, as for the coefficients of the re-entry vehicle. Therefore, we refer to Sections 6.2.5.3 and 6.2.5.4. However, there is one difference for defining coefficients of the parachute system. The number of coefficient components is in all cases restricted to only two.

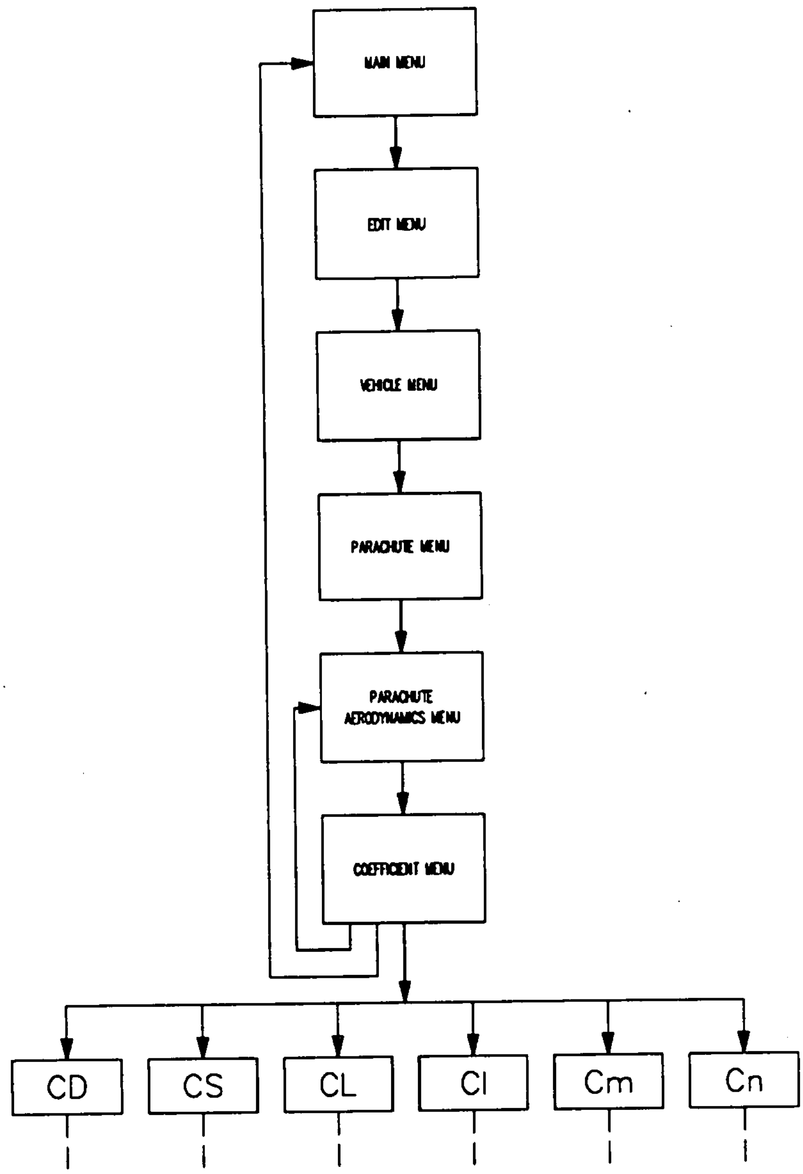


Fig. 6.14 - The Coefficient Menu, for editing the aerodynamic coefficients of the parachute system.

In Fig. 6.14, the related menu structure is given.

For flight conditions outside the table range, we must specify the extrapolation method. This method is valid for each of the parachute systems defined. Option 2 of the Parachute aerodynamics Menu, **Extrapolation**, enables the user to specify the extrapolation method (Fig. 6.15). We refer to Section 6.2.5.5 for more details.

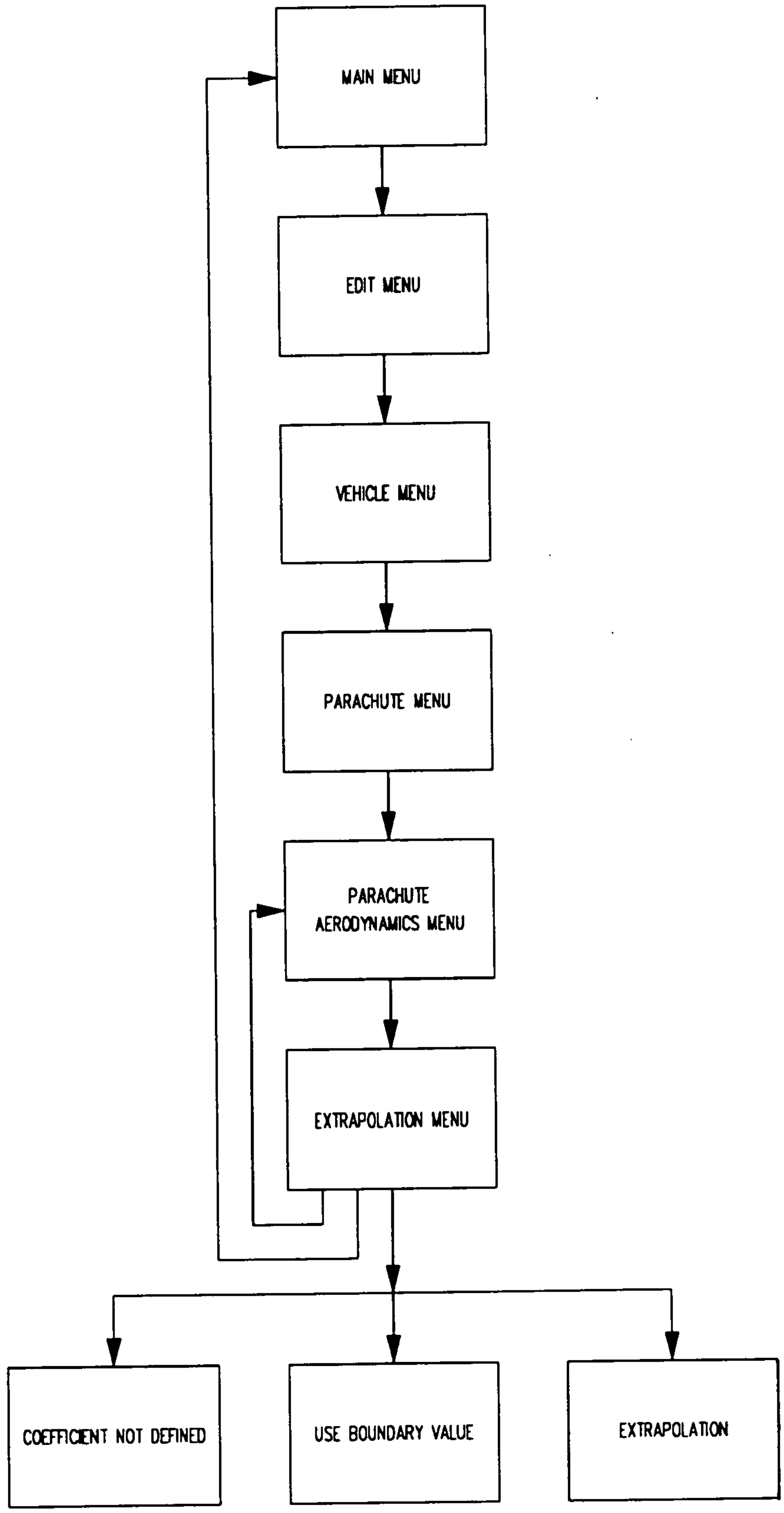


Fig. 6.15 - The Extrapolation Menu for the aerodynamic coefficients of the parachute system.

6.2.7. External forces and moments.

6.2.7.1. The External Forces and Moments Menu.

After entering [6] from the Vehicle Menu, option **External forces and moments,** the following External Forces and Moments Menu is shown on the screen. At this moment, the menu has only one entry, apart from the two entries to leave the menu (see also Fig. 6.16). In the next Section, we will discuss this entry, **Spin vanes.**

-1- Spin vanes
-9- Return to previous menu
-0- Return to main menu

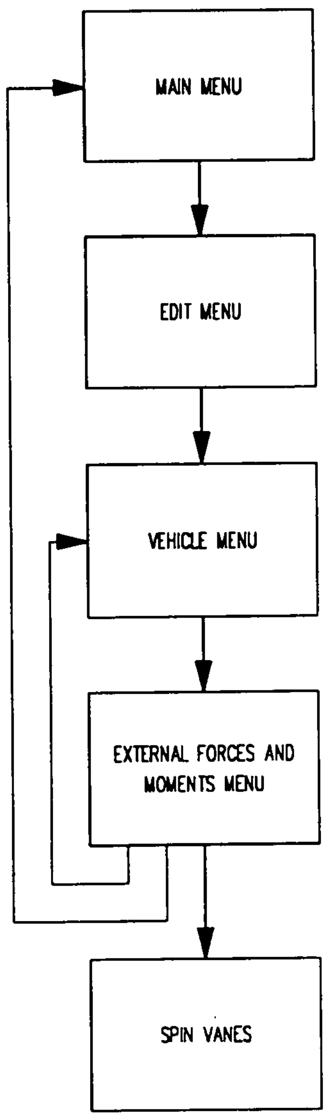


Fig. 6.16 - The External Forces and Moments Menu.

6.2.7.2. Spin vanes.

Option 1 from the External Forces and Moments Menu, **Spin vanes**, enables the user to select spin vanes and edit the related data. The spin vanes are small aerofoils, symmetrically mounted all around the vehicle. These spin vanes cause an additional external rolling moment. The following aspects underlay the (simplified) spin-vane model (Fig. 6.17).

Each vane is considered to be a rectangular flat plate. The lift and drag contribution for one vane is computed, based on flat-plate theory. These forces result in a rolling moment that drives the descent module. The contribution of all the vanes is taken into account by multiplying the computed rolling moment by the number of vanes. This implies, that the flow direction for each vane is assumed to be identical, so, for instance, no transverse winds can be studied.

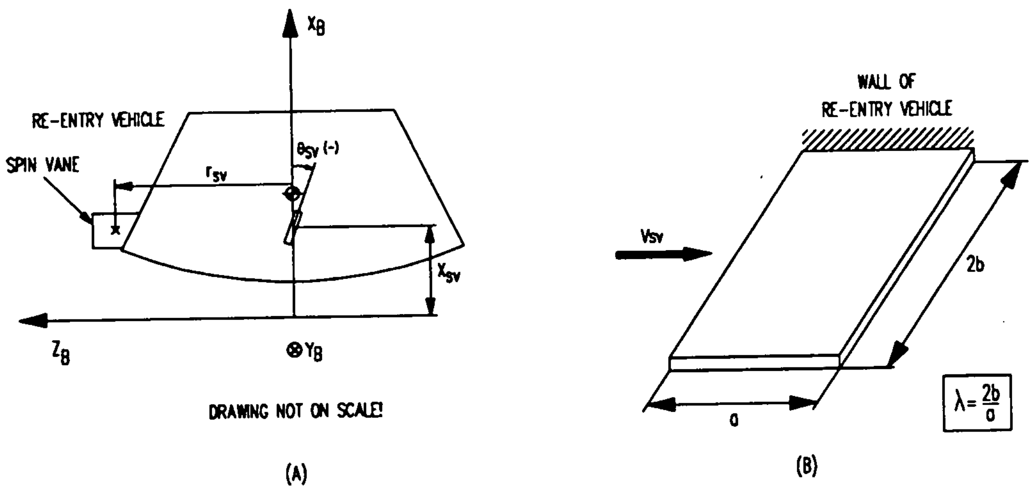


Fig. 6.17 - The spin-vane geometry: (A) The location of the spin vane is given by the radial distance r_{sv} and the X-coordinate x_{sv} in the reference body frame (index B). The offset angle of the spin vane w.r.t. the on-coming flow is indicated by θ_{sv}. (B) The spin vane as a flat plate; a is the reference length of the vane for computing the aerodynamic forces. Together with the aspect ratio λ the reference area can be computed.

Limitations of the developed model are the following:

- flow disturbances due to interactions between the re-entry-vehicle wall and the vanes are not considered,
- partial visibility of a vane due to shielding of the re-entry vehicle and a deviation in flow direction is not taken into account,
- the flow direction for each vane is different, unless we consider a vertical descent with no wind. For realistic computations, wind should be taken into account and therefore, the forces acting on each vane should be computed separately.

For the spin-vane model, the following set of input data has to be provided. Nota bene: the default values indicated here, may be different from the ones shown on the screen.

```
Number of spin vanes (max. 99), default = 24
Input new value (Enter to proceed):

Aspect ratio of spin vane,      default =  0.2000000000D+01
Input new value (Enter to proceed):

Reference length (m),           default =  0.3250000000D-01
Input new value (Enter to proceed):
```

After this value, the screen clears and a second set appears.

```
X-distance of spin vane (m),     default =  0.2700000000D+00
Input new value (Enter to proceed):

Radial distance spin vane (m),   default =  0.6240000000D+00
Input new value (Enter to proceed):

Attitude angle spin vanes (deg), default = -0.2000000000D+01
Input new value (Enter to proceed):

Scale factor (> 0),              default =  0.1000000000D+01
Input new value (Enter to proceed):
```

Remarks

- The X_B-axis of the reference frame is positive pointing backwards. When the vehicle is rolling to the right, the roll rate is negative. For increasing the roll rate, i.e., to make it more negative, the attitude angle of the spin vane has to be negative.
- With the scale (or efficiency) factor, the user can indicate whether the spin vanes are mounted in a region with increased (or decreased) dynamic pressure. When the dynamic pressure is, for instance, 20% higher where the spin vanes are located, the scale factor is 1.2. No change in efficiency results in a scale factor of 1, of course.

After entering the last value, the user returns to the External Forces and Moments Menu.

6.2.8. Propulsion system.

6.2.8.1. The Propulsion Menu.

Although at this moment only one engine can be selected and edited, a separate menu - the Propulsion Menu - has been reserved for editing the propulsion system of the re-entry vehicle. In the future it is foreseen that the menu will be extended with at least two other elements of the propulsion system.

Selecting option 7, **Propulsion system**, from the Vehicle Menu shows the following Propulsion Menu (see also Fig. 6.18). In this menu, the future extensions are indicated by an asterix. It is obvious that, apart from the general choices [9] and [0], only option [2], **Deorbit-burn engine**, is a valid one. In the next Section, we will discuss this engine in more detail.

-1- (*) Main propulsion system
-2- Deorbit-burn engine
-3- (*) Attitude control thrusters
-9- Return to previous menu
-0- Return to main menu

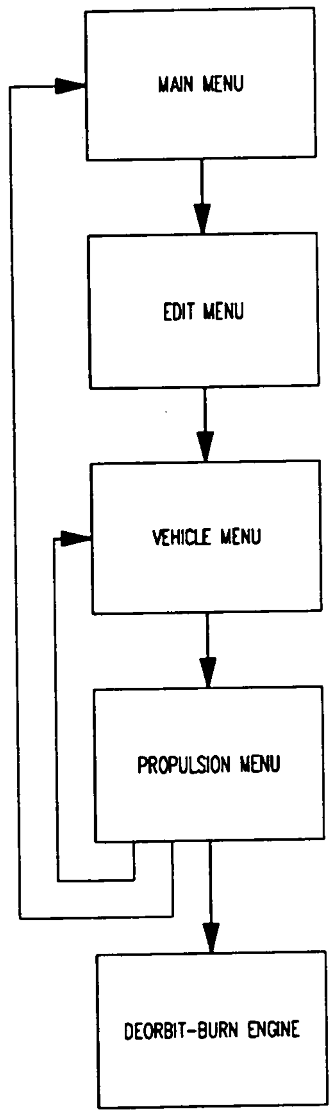


Fig. 6.18 - The Propulsion Menu.

6.2.8.2. The deorbit-burn engine.

The data of the (simplified) deorbit-burn engine can be edited, if we select option 2, **Deorbit-burn engine,** from the Propulsion Menu. Simplified in this case means, that the engine can only be used for 3-dof simulations, i.e., the location and direction of the engine are not included in the input data[6]. Besides, all engine data are considered to be constant.

The user is first asked, whether he wants to select the deorbit-burn engine. Answering [N], results in a return to the Propulsion Menu, while deselecting the engine. After replying [Y], the user is asked for two more data, i.e., the thrust in vacuum ($T > 0$ N) and the specific impulse in vacuum ($I_{sp} > 0$ s). After entering the value for I_{sp}, the user returns to the Propulsion Menu.

6.3. Modelling the environment.

6.3.1. The Environment Menu.

The second block of input data deals with the environment. If we choose option 2 of the Edit Menu, we get the following menu on the screen: the Environment Menu.

-1- Central body
-2- Gravitational model
-3- Atmosphere model
-4- Perturbations
-9- Return to previous menu
-0- Return to main menu

We see four menu entries dealing with the environment. These will be discussed in the following Sections. Entering [9] results in a return to the Edit Menu, while with [0] we arrive at the Main Menu. This is schematically shown in Fig. 6.19.

[6] For 6-dof simulations, it is necessary to know the exact orientation of the line along which the thrust is acting w.r.t. the global CoM, because the moment due to the force must be taken into account. For 3-dof simulations it is sufficient that the magnitude and direction of the thrust force are known.

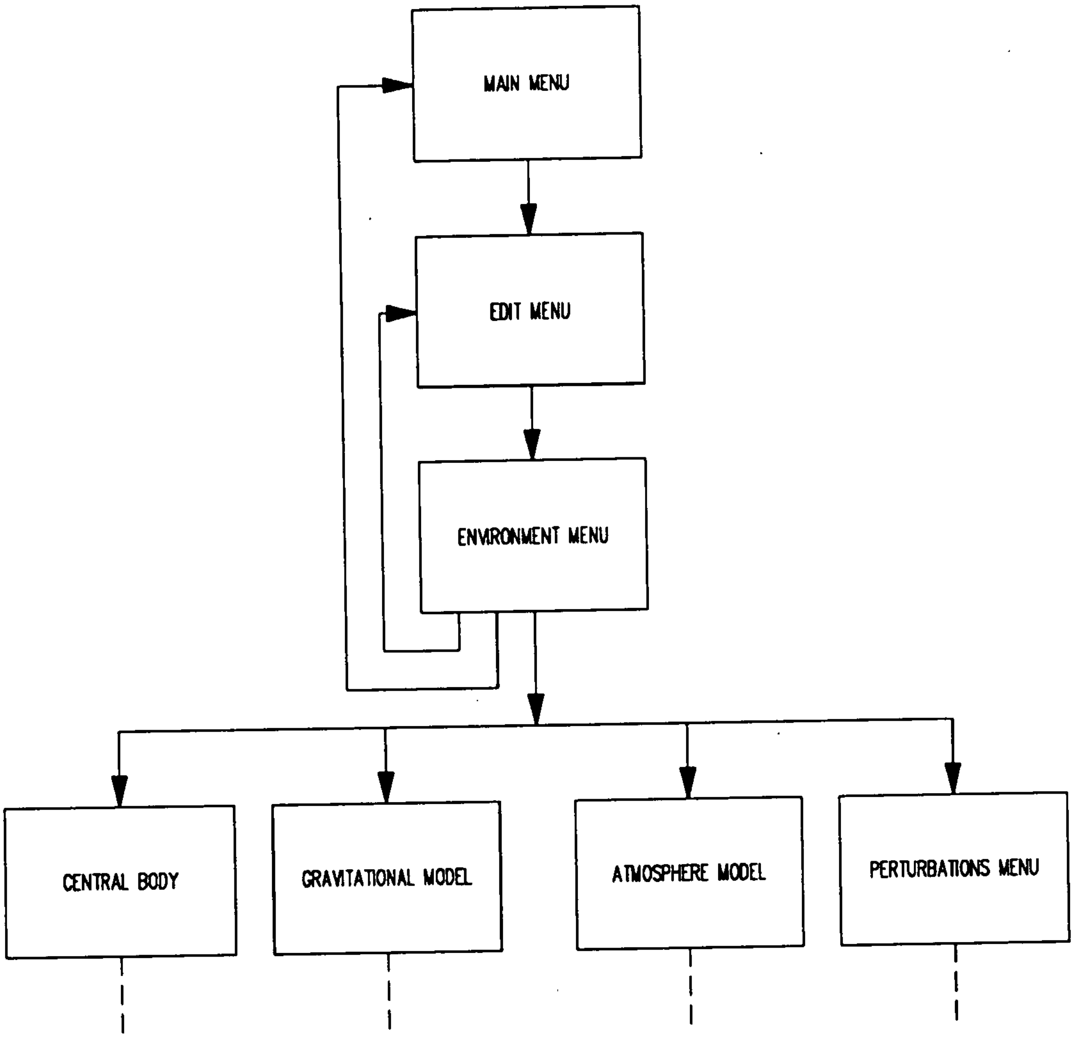


Fig. 6.19 - The Environment Menu.

6.3.2. Central body.

In START, it is possible to perform entry simulations to four different central bodies. Depending on the choice of the selected central body, are planet-related parameters, such as equatorial radius and the rotational rate of the planet. These parameters are invisible to the user. They are automatically adjusted, when we choose a different central body. We can do this by entering [1], **Central body**, from the Environment Menu. First, we see the default choice of the central body and a menu with the available central bodies.

-1- Earth
-2- Moon
-3- Mars
-4- Titan
-9- Return to previous menu
-0- Return to main menu

We can select one of the 4 central bodies by entering [1], [2], [3] or [4]. [9] and [0] will leave the current selected central body unaffected, and we return to the Environment Menu and Main Menu, respectively. After selecting a central body, we return to the Environment Menu.

The numerical values of the parameters, which are adjusted by changing the central body, are:

Earth

$e = 1/298.257$
$R_e = 6.378139 \cdot 10^6$ m
$\omega_{cb} = 7.292115 \cdot 10^{-5}$ rad/s

Moon

$e = 0$
$R_e = 1.7382 \cdot 10^6$ m
$\omega_{cb} = 2.6617 \cdot 10^{-6}$ rad/s

Mars

$e = 1/192$
$R_e = 3.402 \cdot 10^6$ m
$\omega_{cb} = 7.0882 \cdot 10^{-5}$ rad/s

Titan

$e = 0$
$R_e = 2.575 \cdot 10^6$ m
$\omega_{cb} = 4.548 \cdot 10^{-6}$ rad/s

with

e = elipticity

R_e = equatorial radius
ω_{cb} = rotational rate of the central body (along Z-axis of rotating planetocentric frame)

Linked with the choice of the central body is a default setting for the gravitational and atmosphere models. For each of the central bodies these are:

Earth

Gravitational model: central field with J_2, J_3 and J_4 included
Atmosphere model: Simple Earth (tabulated)

Moon

Gravitational model: central field with J_2 included
Atmosphere model: No atmosphere

Mars

Gravitational model: central field with J_2 included
Atmosphere model: Mars Viking-1

Titan

Gravitational model: central field
Atmosphere model: Nom. Lellouch-Hunten Oct. 87

6.3.3. Gravitational model.

Linked with the selected central body is the choice of the gravitational model. Entering [2] from the Environment Menu, the current selected central body with corresponding gravitational model is shown. The menu with the available models is depending on the central body. For each of the four central bodies, the menu will be presented.

For the Earth, we get the following menu on the screen.

-1- Central field
-2- J2 included
-3- J2 and J3 included
-4- J2, J3 and J4 included
-9- Return to previous menu
-0- Return to main menu

Here, the *J*-terms are the so-called harmonics, representing the inhomogeneity of the mass distribution. Each of the models can be selected by entering the corresponding number. [9] or [0] result in a return to the Environment Menu or the Main Menu, without affecting the currently selected model. After selecting a gravitational model, we return to the Environment Menu.

For the Moon and Mars, we can only choose from 2 models:

-1- Central field
-2- J2 included
-9- Return to previous menu
-0- Return to main menu

For Titan, we cannot choose. Only the central field model is available, which is automatically selected. This is displayed as a message on the screen, when we try to change the gravitational model. Pressing [Enter] results in a return to the Environment Menu, in that case.

The numerical values of the gravitational parameters are:

Earth.

$\mu = 3.9860047 \cdot 10^{14}$ m^3/s^2
$J_2 = 1.082627 \cdot 10^{-3}$
$J_3 = -2.536 \cdot 10^{-6}$
$J_4 = -1.623 \cdot 10^{-6}$

Moon.

$\mu = 4.90265 \cdot 10^{12}$ m^3/s^2
$J_2 = 2 \cdot 10^{-4}$
J_3 and J_4 are not defined

Mars.

$\mu = 4.317 \cdot 10^{13}\ m^3/s^2$
$J_2 = 1.9 \cdot 10^{-3}$
J_3 and J_4 are not defined

Titan.

$\mu = 8.9781 \cdot 10^{12}\ m^3/s^2$
J_2, J_3 and J_4 are not defined

with

μ = gravitational parameter
J_2, J_3 and J_4 = zonal harmonics

6.3.4. Atmosphere model.

Choosing option 3, **Atmosphere model**, from the Environment Menu enables the user to select (or deselect) an atmosphere model. The availability of models is again depending on the selected central body. After selecting an atmosphere model, we return to the Environment Menu.

First, the selected central body and atmosphere model are shown, plus a menu with possible choices. For the Earth, we get the following table.

-1- No atmosphere
-2- US Standard Atmosphere 1962
-3- US Standard Atmosphere 1976
-4- Tabulated CIRA86 (Kourou)
-9- Return to previous menu
-0- Return to main menu

Each of the models can be selected, by entering the corresponding number. The maximum altitudes for which the models are valid, are:

US Standard Atmosphere 1962: 700 km
US Standard Atmosphere 1976: 120 km
Tabulated CIRA86 (Kourou): 1000 km

Entering [9] leaves the current selected atmosphere model unaffected. We return to the Environment Menu, in that case.

If the central body is Mars, the following table is shown:

```
-1- No atmosphere
-2- Mars Viking-1
-9- Return to previous menu
-0- Return to main menu
```

The height limitation for Mars Viking-1 is 200 km.

For Titan, we get:

```
-1- No atmosphere
-2- Min. Lellouch-Hunten Oct. 87
-3- Nom. Lellouch-Hunten Oct. 87
-4- Max. Lellouch-Hunten Oct. 87
-9- Return to previous menu
-0- Return to main menu
```

The maximum altitude for which the three models are valid is for each one the same: 1250 km.

6.3.5. Perturbations.

6.3.5.1. The Perturbations Menu.

Entering [4], **Perturbations**, from the Environment Menu gives the Perturbations Menu, as shown below.

```
-1- (Tabulated) atmosphere perturbations
-2- Wind model
-3- (*) Third body
-9- Return to previous menu
-0- Return to main menu
```

Entering [9] or [0], results in a return to the Environment Menu or Main Menu, respectively (see also Fig. 6.20).

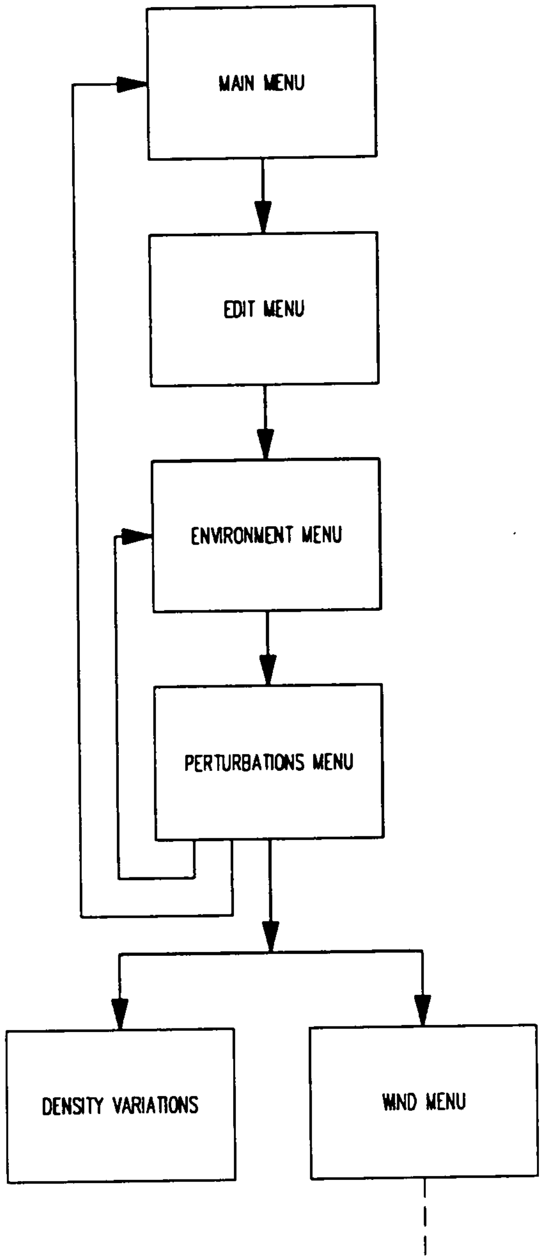


Fig. 6.20 - The Perturbations Menu.

6.3.5.2. (Tabulated) atmosphere perturbations.

Selecting option 1, **(Tabulated) atmosphere perturbations**, gives the following question on the screen:

```
Percentage of density deviation, default = <default>
Input new value (Enter to proceed):
```

We can enter any value for the percentage. It must be noted that the density variation is restricted to the tabulated atmospheres, i.e., Tabulated CIRA86 (Kourou), Mars Viking-1 and the three Lellouch-Hunten models. During the simulation, the atmospheric pressure is not affected by the density deviation, while the temperature is recomputed according to the Ideal Gas Law.

6.3.5.3. Wind model.

Wind Menu

Choosing option 2 from the Perturbations Menu, **Wind model**, the currently selected wind model is shown and the Wind Menu as shown below. However, when the Moon is the central body it may be obvious that the definition of wind has no meaning due to the absence of an atmosphere. In that case, an error message is printed on the screen. After accepting this message by pressing [Enter], we return to the Perturbation Menu.

Starting from the Wind Menu, it is possible to fully define a wind model, as can be seen in Fig. 6.21. In this Figure, the complete menu structure is indicated. Any further discussion on the wind model will be based on this Figure.

-1- No wind
-2- Simplified wind model
-3- User-defined wind model
-9- Return to previous menu
-0- Return to main menu

Coming back to the Wind Menu, we see three options related to the definition of wind. The default options [9] and [0], result, as usual, into a return to the previous (i.e., the Perturbations Menu) and the Main Menu, respectively.

Option 1, **No wind**, will exclude any wind definition from the simulation. It will not erase any defined wind model in memory, so when later on the user decides to edit the wind model again, the data are still intact. But, these data are not written to any input file as long as this option has been selected. After pressing [1], we return to the Perturbations Menu.

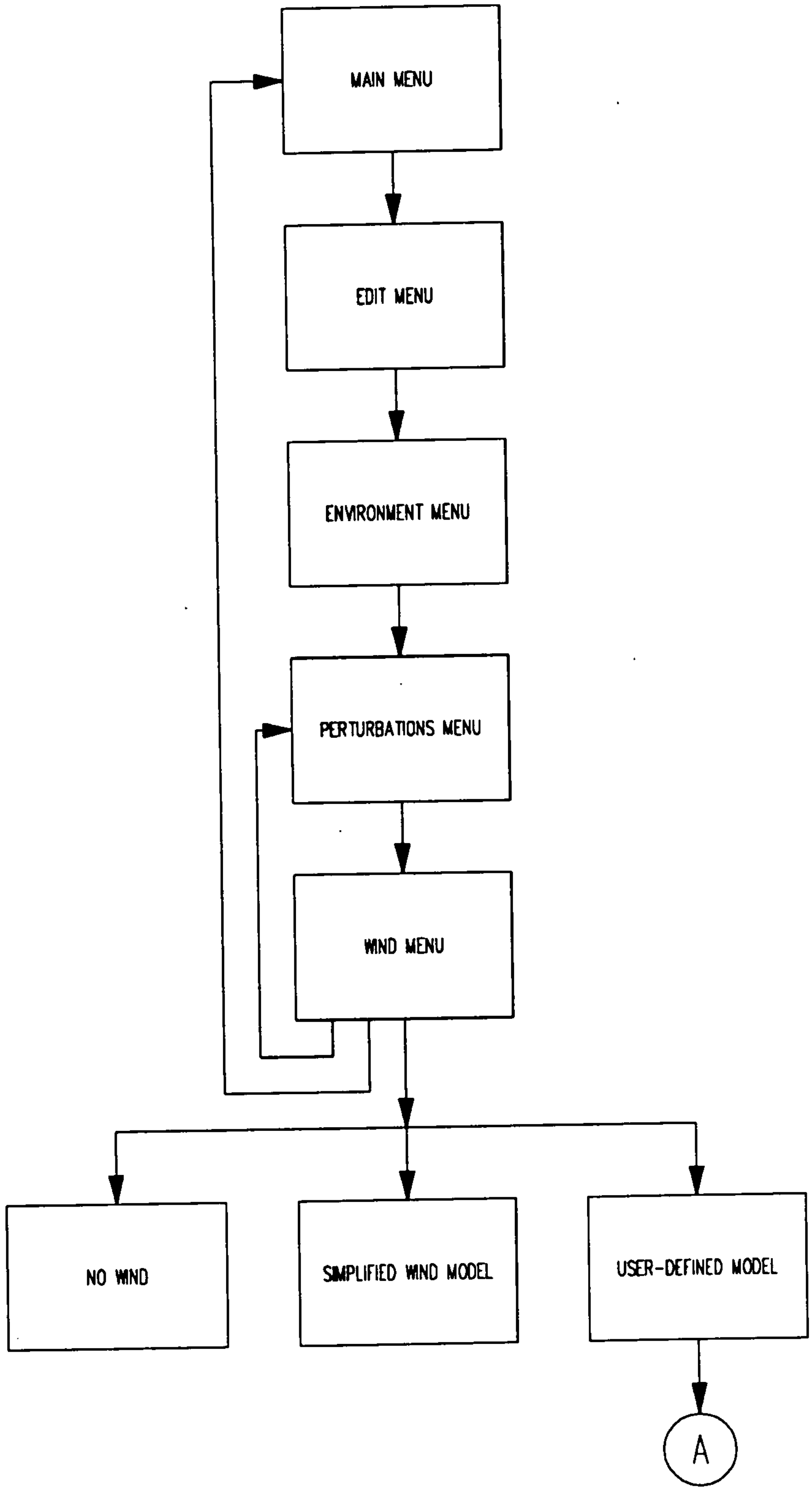
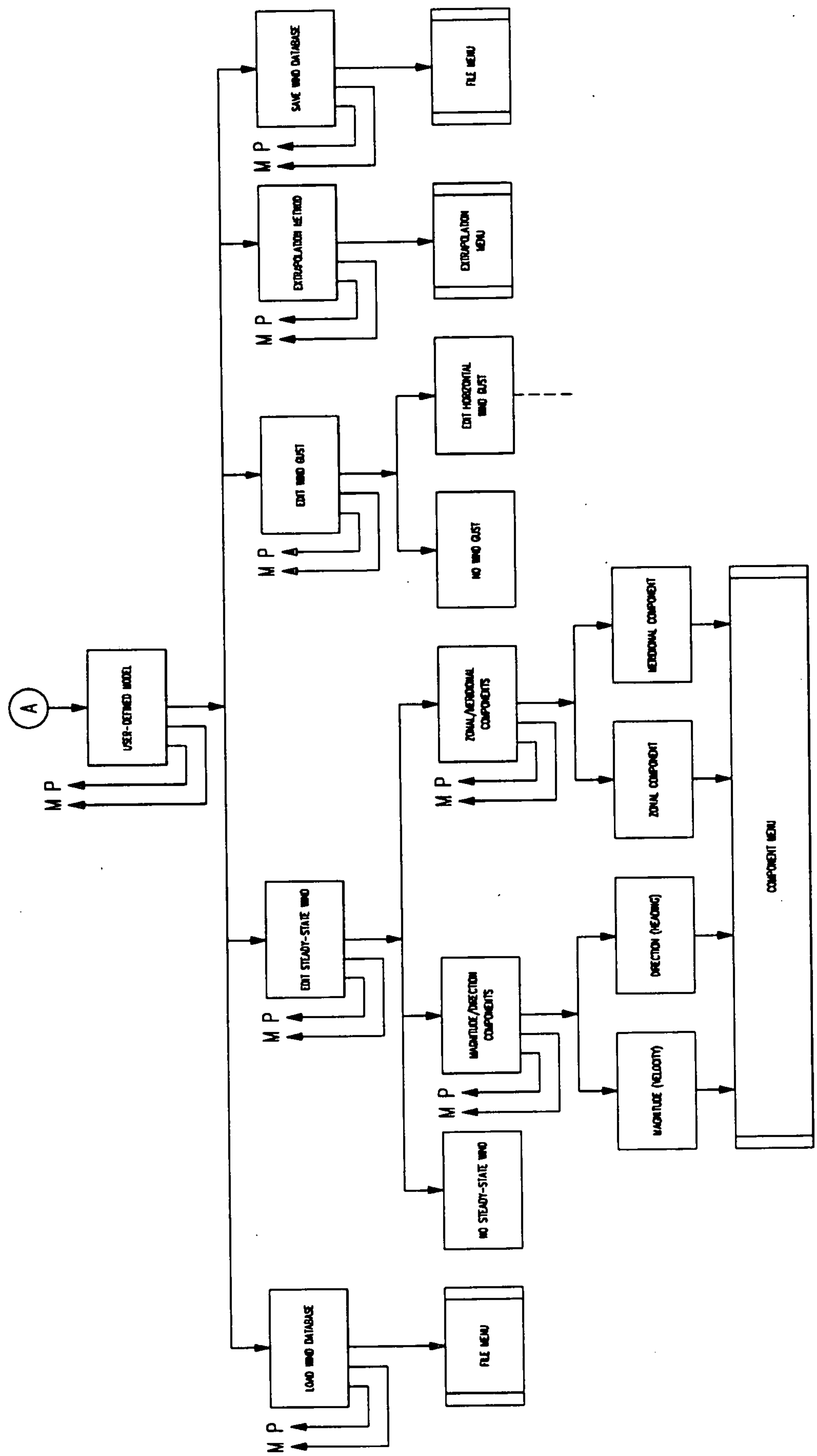


Fig. 6.21 - The menu structure related to the wind data (continued overleaf).


A
USER-DEFINED MODEL
M
P
SAVE WIND DATABASE
FILE MENU
EXTRAPOLATION METHOD
EXTRAPOLATION MENU
EDIT WIND GUST
EDIT HORIZONTAL WIND GUST
NO WIND GUST
EDIT STEADY-STATE WIND
ZONAL/MERIDIONAL COMPONENTS
MERIDIONAL COMPONENT
ZONAL COMPONENT
MAGNITUDE/DIRECTION COMPONENTS
DIRECTION (HEADING)
MAGNITUDE (VELOCITY)
COMPONENT MENU
NO STEADY-STATE WIND
LOAD WIND DATABASE
FILE MENU

Simplified wind model

The second option from the Wind Menu, **Simplified wind model**, will select a zonal steady state wind, based on the rotational rate of the planet. The wind is given by the following equation:

$$V_w = \frac{\Delta\omega_{cb}}{100}\,\omega_{cb}\, r \cos\delta \tag{6.1}$$

with

$\Delta\omega_{cb}$ = percentage of rotational rate
ω_{cb} = planetary rotational rate (rad/s)
r = distance to CoM of central body (m)
δ = planetocentric latitude (rad)

The user is asked to specify $\Delta\omega_{cb}$; this can in principle be any value. Depending on the sign of $\Delta\omega_{cb}$ is the direction of the wind. For a positive value, the wind is directed parallel to the equator in eastern direction (heading 90°). A negative value results in a zonal wind positive in western direction (heading 270°). After entering the value for $\Delta\omega_{cb}$, the user returns to the Wind Menu.

User-defined wind model

Option 3 from the Wind Menu, **User-defined wind model**, results in a new menu, as is indicated below. We will call this menu the User-Wind Menu. The menu has 7 entries, apart from the options [9] (return to the Wind Menu) and [0] (return to the Main Menu). Options 4, **Edit wind shear** and 5, **Edit turbulence**, have not been implemented yet. They are part of future extensions. We will now concentrate on the remaining options.

```
-1- Load wind database
-2- Edit steady-state wind
-3- Edit wind gust
-4- (*) Edit wind shear
-5- (*) Edit turbulence
-6- Extrapolation method
-7- Save wind database
-9- Return to previous menu
-0- Return to main menu
```

1) Load and save wind database

Choosing option 1, **Load wind database**, or option 7, **Save wind database**, gives the name of the currently defined wind database, and the standard File Menu, as indicated below.

```
-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu
```

The wind-database filename can be 'WIND.DAT' (program default) or the last user-specified name.

Loading or saving the wind database is done in the same way as the aerodynamic database (Section 6.2.5.2) or the parachute database (Section 6.2.6.2). Again, we will briefly repeat the procedure. We begin with loading a database (nota bene: the database consists of all wind-related data, which can be edited starting from the Wind Menu).

We can either accept the default database name by entering [1] or change the name by entering [2]. Entering a 'blank' name (option 2) also implies the use of the default filename. When the indicated database is not found, an error message is given. We can enter another filename (option 2) or decide to leave the File Menu (options 9 and 0). Also an I/O-error during the read process results in an error message and a return to the File Menu. The wind data, which may have been distorted by the I/O error are reset to the default values. This means that no wind is assumed.

By choosing option 9, we can go up one level in the menu structure (User-Wind Menu). Entering [0] results in a return to the top level of the menu structure, the Main Menu. When the wind database has been successfully loaded, the User-Wind Menu appears on the screen.

While saving a wind database, we specify the filename in exactly the same way as mentioned above. Once a valid name has been entered, a check is made whether the given database already exists. A warning is given if this is true, and the user can decide to overwrite the existing file or to return to the File Menu, to change the filename. When the database has been successfully saved, control is returned to the User-Wind Menu. An I/O error during the write process results in aborting the process and a return to the File Menu. An error during the write process will not affect the data stored in memory.

2) Edit steady-state wind

Choosing option 2 from the User-Wind Menu, **Edit steady-state wind**, gives the currently selected steady-state wind and the following Steady-State Menu, with three options to choose from. The first option, **No steady-state wind**, deselects the steady-state wind and we return to the User-Wind Menu. During the simulation, this type of wind is not taken into account (nota bene: when a steady-state wind has been defined, but later on the user decides to select **No wind** from the Wind Menu, the latter selection overrules any definition of wind components; no wind will be simulated).

-1- No steady-state wind
-2- Magnitude / direction components
-3- Zonal / meridional components
-9- Return to previous menu
-0- Return to main menu

There are two ways of defining the steady-state wind, either with magnitude/direction components (option 2), or with zonal/meridional components. Both ways of entering a steady-state wind are very similar, so we will describe the magnitude/direction components in detail, and restrict to some remarks in case of the zonal/meridional components.

Option 2 of the Steady-State Menu, **Magnitude / direction components**, gives again a sub-menu. Either the magnitude (or the wind *velocity*) can be edited, or the direction (the wind *heading*).

-1- Magnitude (velocity)
-2- Direction (heading)
-9- Return to previous menu
-0- Return to main menu

Selecting either of the two components, gives an overview of the related parameters of that particular wind component (see also Fig. 6.22). Firstly, the heading of the component is indicated. Since we are dealing here with a user-specified heading, no heading is indicated ('---'). When we come to discuss the zonal and meridional components, there will be a heading indication. Secondly, the so-called table variables are shown. Both components can be a function of 0, 1 or 2 table variables (or independent variables), as we have also seen with the aerodynamic coefficients (see Section 6.2.5.3). These table variables are valid for *both* components. Successively, the number of table variables, the actual table variables and the corresponding number of entries are shown. Thirdly (and finally), a menu is printed. We will call this menu the Component Menu.

```
         * * * * * EDIT INPUT DATA * * * * *

            *****************************
            **    VELOCITY COMPONENT   **
            *****************************


Heading of component        : ---
Number of table variables : 2
Table variable #1           : height
Number of entries var. #1 : 25
Table variable #2           : latitude
Number of entries var. #2 :  9

-1- Change any parameter.
-9- Return to previous menu.
-0- Return to main menu.

    Enter the number of your choice:
```

Fig. 6.22 - Overview screen for a wind component.

The Component Menu has three entries. Entering [9] or [0] results in a return to the previous menu (for the menu structure, the user is once again referred to Fig. 6.21) or Main Menu, respectively. Entry [1], **Change any parameter**, gives the user full access to the wind data.

-1- Change any parameter
-9- Return to previous menu
-0- Return to main menu

We already mentioned that the table variables are valid for both components. Therefore, the user is first asked whether he wants to edit the table variables. Answering [N] skips this part, and we directly continue with editing the actual component. Answering [Y], the number of table variables is printed (0, 1 or 2). When we enter [0], this means that the wind component has a constant value. The user is asked to enter this constant value, and the overview screen is printed again. Entering either [1] or [2], gives a list with possible table variables on the screen, together with the selection of the first table variable. Nota bene: variable 2, ln(pressure), means the natural logarithm of the atmospheric pressure. After choosing the variable, by typing the integer value of the variable - apart from [0], which has been added to show any possible default setting - the second variable has to be selected (if any!).

```
-0- none
-1- pressure
-2- ln(pressure)
-3- height
-4- latitude
```

After selecting the table variable(s), the number of entries per table variable must be specified. This can be any number from 1 to 40. Entering a number outside this range, gives an error message on the screen. Accepting this message by pressing [Enter], a new number has to be entered. Then, the actual entries of the table variable(s) have to be entered. Finishing the last entry, we come to the entries for the wind component. For each entry, the combination of table variables (their values) is printed on the screen, so that the user can see which entry he is editing. When the last entry has been edited, the overview screen is printed again. Nota bene: the velocity component has to be entered in meters per second, while the heading has to be specified in degrees (0° is a northern wind, 90° eastern, 180° southern and 270° western; of course any heading between 0° and 360° can be entered).

Entering option 2, **Zonal / meridional components**, from the Steady-State Menu can result in two possible menus, depending on the selected central body. For the Earth and Mars, the following menu is printed on the screen.

```
-1- Zonal component
-2- Meridional component
-9- Return to previous menu
-0- Return to main menu
```

Editing either of the two components is done in exactly the same way as has been described above, with only one exception. In this case, the heading of the component must be explicitly specified. Starting from the overview screen (Fig. 6.22), we select option 1, **Change any parameter**. Before we arrive at the edit procedure as described above, the possible headings for the particular component are shown on the screen, together with the question to input a new value (or accepting the default value by pressing [Enter]).

For the zonal component, we can specify either a wind from west to east, or vice versa, as indicated below (W-E is the default setting). A wind from west to east means, that a positive wind is blowing in that direction. If a wind component is negative, then the wind is blowing *from east to west*, for *this* setting. It may be obvious, that when a user has specified positive components only, he can invert the direction of the wind by simply changing the heading. Any heading must be entered, by typing the heading number ([1] or [2] for the zonal component).

-1- W-E
-2- E-W

For the meridional component, we have two different headings as well, as can be seen below. The default setting for this component is a wind from south to north (S-N). The heading must now be entered by typing [3] or [4].

-3- S-N
-4- N-S

In case the selected central body is Titan, we get a slightly different menu on the screen. We can see an additional menu entry (entry 1). For Titan, it assumed that there is only a (strong) zonal component. In Mooij (1992), a simplified engineering model for the zonal wind has been described. This model is given by the following analytical formula:

-1- Zonal component (Flasar)
-2- Zonal component (tabulated)
-3- Meridional component (tabulated)
-9- Return to previous menu
-0- Return to main menu

$$|V_{ss} - V_{ss,s}| \leq V_{ss,\max}\left[1 + \frac{1}{8}\ln\left(\frac{p_{ref}}{p}\right)\right]\cos\delta \qquad (6.2)$$

with

V_{ss} = steady-state wind velocity (m/s)
$V_{ss,s}$ = steady state wind velocity at surface, with $|U_s| < 2$ m/s
$V_{ss,max}$ = maximum steady state wind velocity = 200 m/s
p_{ref} = reference pressure = 50 N/m^2 (0.5 mbar)
p = atmospheric pressure (N/m^2)
δ = planetocentric latitude (rad)

This steady state model is referred to as the Flasar model.

After selecting this option from the above menu, the user must specify the related parameters for this model. Although the model knows fixed parameters, these have been made variable to enable the user to study the uncertainty of this model. The following entries are successively shown on the screen:

```
Surface speed (nom. 2 m/s),           default =  0.2000000000D+01
Input new value (Enter to proceed):

Maximum windspeed (nom. 200 m/s),     default =  0.2000000000D+03
Input new value (Enter to proceed):

Reference pressure (nom. 50 N/m**2), default =  0.5000000000D+02
Input new value (Enter to proceed):
```

Furthermore, the following question should be answered:

```
Full evaluation <Y/N>,                default = N
```

A full evaluation (entering [Y]) means, that Eq. (6.2) is used to compute the wind velocity for any height. The alternative is no full evaluation (answer [N]), meaning that up to the reference altitude (for an atmospheric pressure of 50 N/m^2, this altitude is about 220 km) the Flasar model is valid and above the reference altitude the wind is assumed to be constant (≈ 200 m/s). The direction of the wind is, for a positive U_{max}, in eastern direction.

After answering the last question, the user returns to the Zonal / Meridional Menu.

3) Edit wind gust

Choosing option 3, **Edit wind gust**, from the User-Wind Menu, the following menu appears on the screen. Entering [1], **No wind gust**, excludes the wind gust from the simulation and we return to the User-Wind Menu. By entering [2], **Edit horizontal wind gust**, the user can edit this type of gust. The vertical wind gust has not been implemented yet, as is indicated by an asterix in the menu.

-1- No wind gust
-2- Edit horizontal wind gust
-3- (*) Edit vertical wind gust
-9- Return to previous menu
-0- Return to main menu

For the horizontal wind gust we consider two types, as is depicted in Fig. 6.23. These two types are designated as the 3*t*- and the 6*t*-type. Particular parameters, which must be known for these wind gusts are:

- h_{hg} = initial altitude for horizontal gust (m)
- t_{hg} = thickness of horizontal gust (m)
- $V_{hg,max}$ = maximum velocity for horizontal gust (m/s)

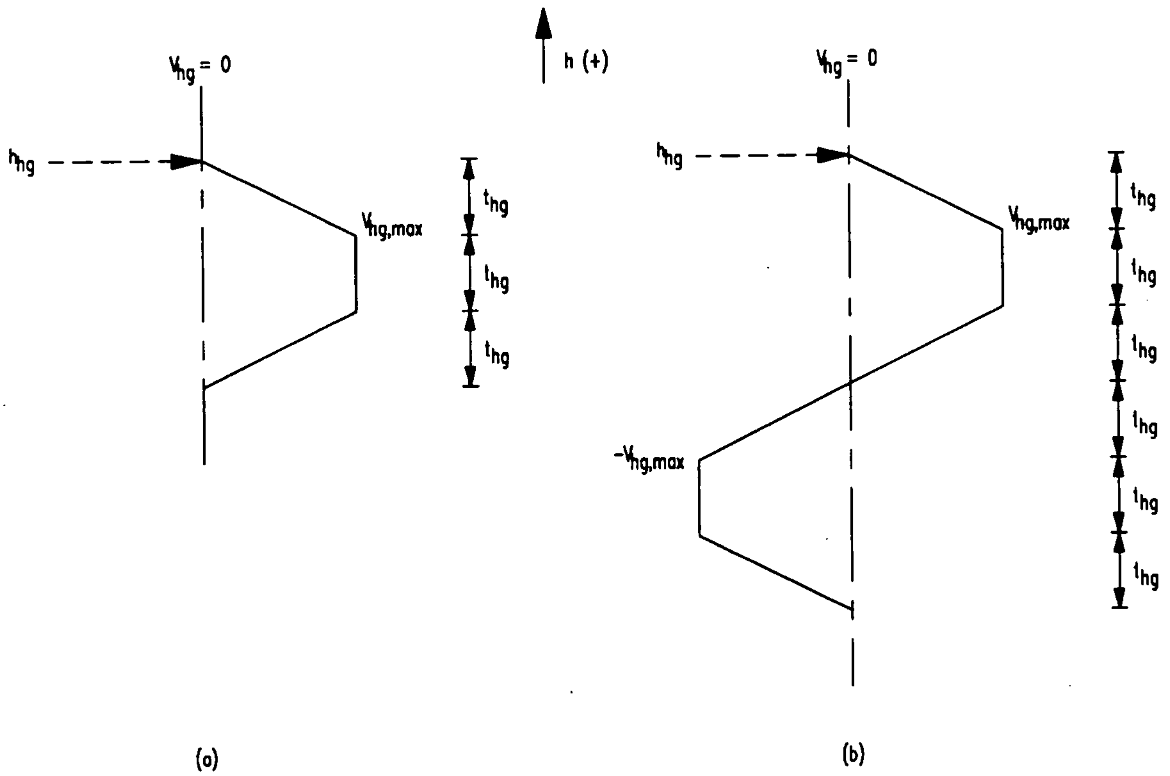


Fig. 6.23 - Horizontal wind gust models: (a) 3*t*-model and (b) 6*t*-model.

The first question the user is asked, is the number of wind gusts. This number can be any integer value in the range from 0 to 10. When zero is entered, one directly returns to the User-Wind Menu. For any other number, per wind gust the following parameters must be entered. To start with, the shape of the gust. As we saw in Fig. 6.23, two shapes have been predefined. The following menu shows these shapes, and the user has to enter the (integer) shape number (either 1 or 2). Nota bene: the number of the horizontal gust, which is currently being edited, is shown above this menu.

```
-1- 3t-shape
-2- 6t-shape
```

After the shape number, the following four parameters can be edited (the default variables, which have been used, serve as an example; they may be different in an actual editing session):

```
Initial altitude (m),          default =  0.9000000000D+05
Input new value (Enter to proceed):

Gust thickness (m),            default =  0.6000000000D+02
Input new value (Enter to proceed):

Maximum wind velocity (m/s),   default =  0.6000000000D+01
Input new value (Enter to proceed):

Heading for wind vector (deg), default =  0.9000000000D+02
Input new value (Enter to proceed):
```

After the last parameter, we start with the shape number of the next horizontal gust (if any). When the heading for the wind vector of the last gust has been edited, control is returned to the User-Wind Menu.

4) Extrapolation method

Option 6 of the User-Wind Menu, **Extrapolation method**, gives access to the Extrapolation Menu, as is shown below. We already saw this menu, when we were discussing the aerodynamic coefficients of both the entry vehicle (Section 6.2.5.5) and the parachute system (Section 6.2.6.4). The description given there fully applies in this case; the user is referred to Section 6.2.5.5 for more information.

```
-1- Coefficient not defined
-2- Use boundary value
-3- Extrapolation
-9- Return to previous menu
-0- Return to main menu
```

6.4. Mission aspects.

6.4.1. The Mission Menu.

Choosing option 3, **Mission**, from the Edit Menu, gives the Mission Menu on the screen, as shown below.

-1- Initial state
-2- Parachute operations
-3- Configuration changes
-4- Propulsion operations
-5- (*) Operational constraints
-9- Return to previous menu
-0- Return to main menu

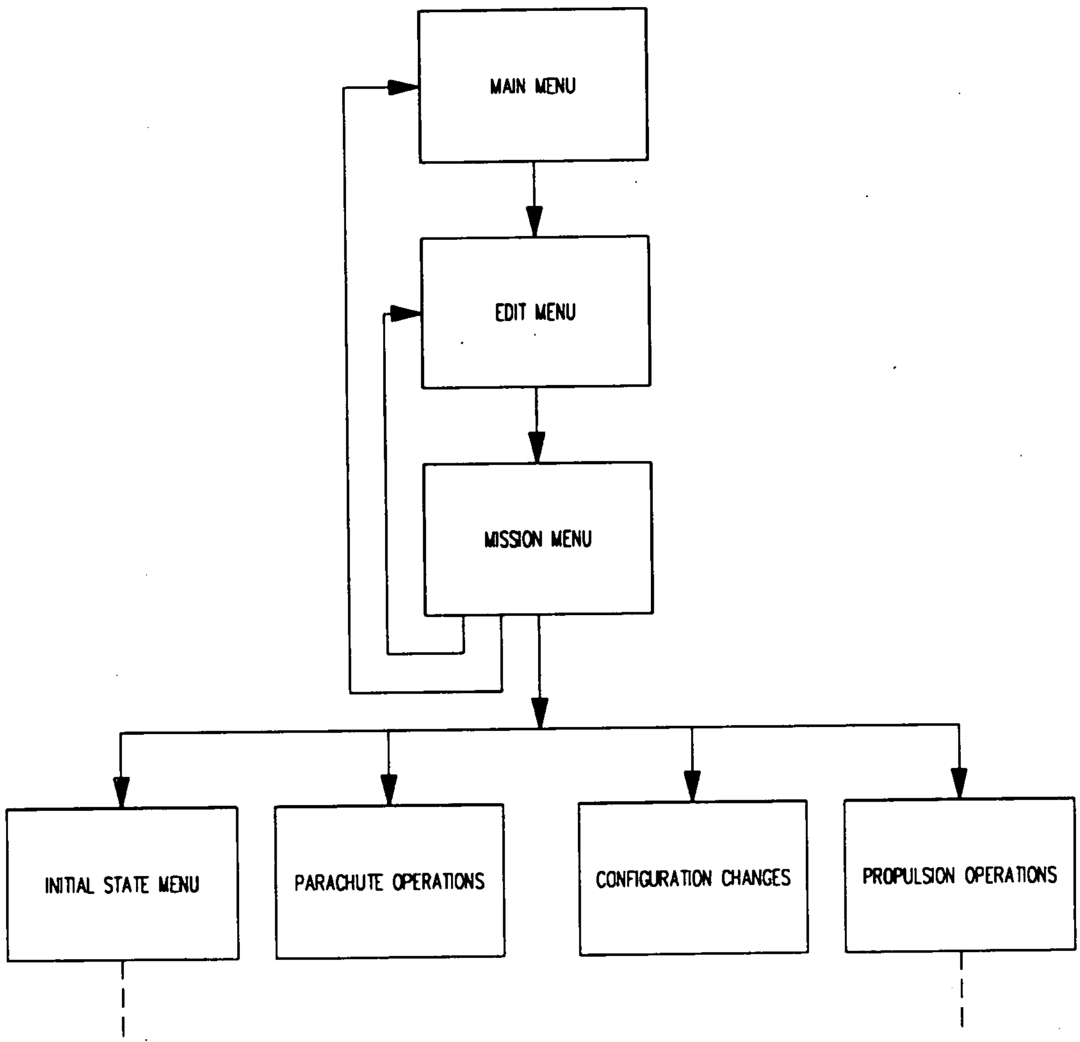


Fig. 6.24 - The Mission Menu.

An asterix in the menu, means that these options have not been implemented yet (future extensions). Entering [1], [2], [3] or [4] enables us to enter and/or change mission-related input data. These menu entries will be discussed in the next three Sections. We can leave the Mission Menu in two ways, by entering either [9] or [0]. Fig. 6.24 shows us the relation between the several menus.

6.4.2. Initial state.

In order to start a simulation, we must provide START with the initial condition of the entry vehicle. By entering [1] from the Mission Menu, **Initial state**, the following Initial State Menu is printed on the screen.

-1- Position and velocity
-2- Vehicle attitude and angular velocities
-9- Return to previous menu
-0- Return to main menu

The initial conditions, which one has to provide, are depending on the kind of simulation he wants to perform. In the 3-dof simulation, the re-entry vehicle is considered to be a mass point. Only translations can be analyzed. In principle, we can restrict the initial conditions to position and velocity. However, it is possible to define a constant attitude of the re-entry vehicle, so we must always be sure, whether the proper attitude has been defined.

W.r.t. the aerodynamic forces, the attitude angles are used as follows: the angle of attack α (used for a constant-lift entry)[7], the angle of sideslip β (comparable with α, but in this case resulting in a side force) and the bank angle σ (for out-of-plane manoeuvres by tilting the lift force). When thrust operations are being performed, the angles are also of importance, because they (partly) define the orientation of the thrust vector w.r.t. the velocity. To understand the influence of these angles, the interested reader is referred to the equations of motion, presented in the technical documentation (e.g., Mooij (1993a)).

We can leave the Initial-State Menu, by entering [9] or [0], to return to the Edit Menu and the Main Menu, respectively. The layout of the related menu structure is shown in Fig. 6.25.

Position and velocity

Choosing option 1, **Position and velocity**, from the Initial-State Menu, gives rise to three possible ways of entering the initial state, as can be seen in the following menu. Besides, the two standard entries [9] and [0] have been added (see also Fig. 6.25).

[7] We have to specify α, when the aerodynamic force coefficients are defined as tables as a function of α. In that case, the coefficients are computed for this (constant) α. If we have defined the force coefficients to be constant, then α is already included in the value of the coefficients. In that case, α is not used to compute aerodynamic forces.

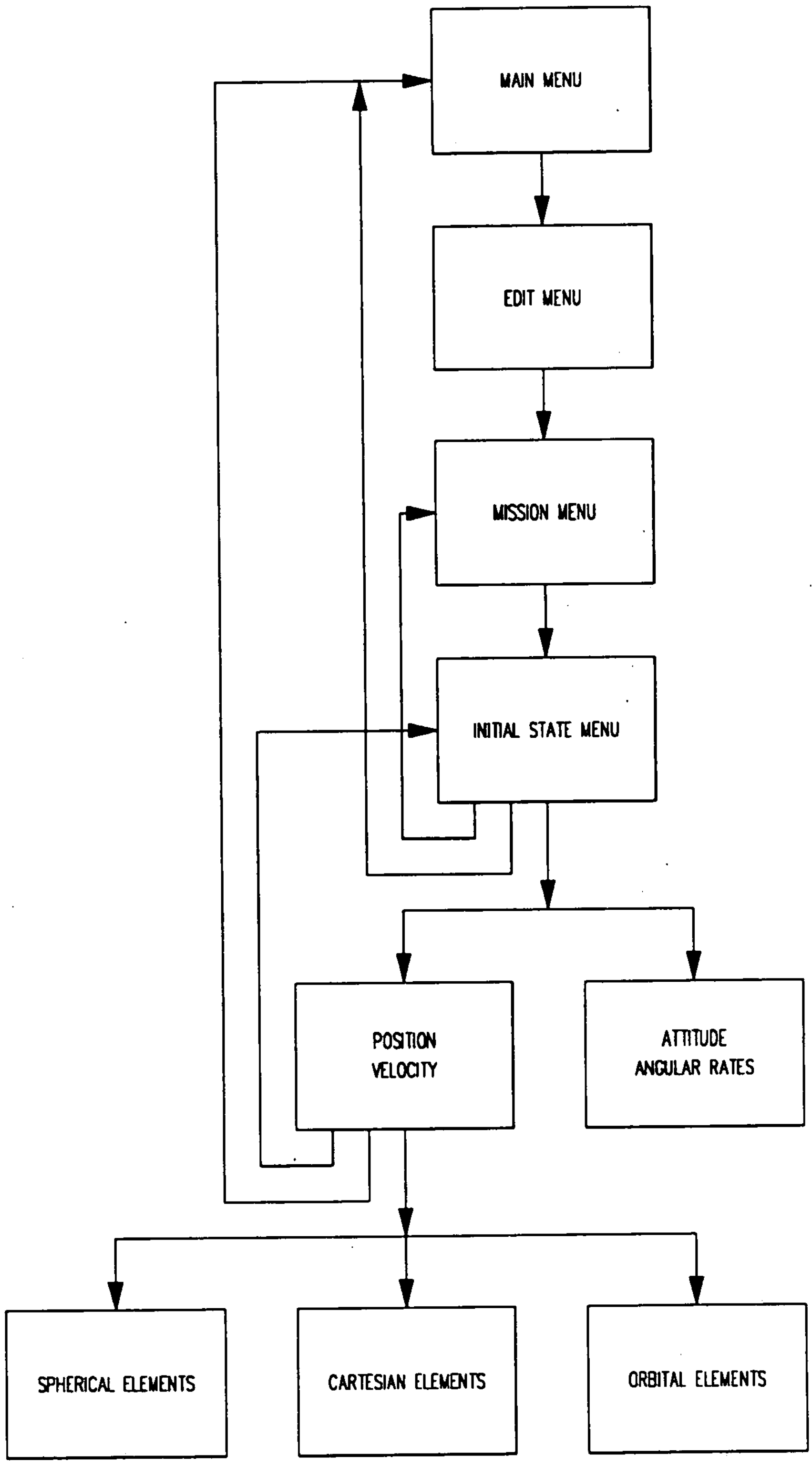


Fig. 6.25 - The Initial-State Menu, with the corresponding Position-and-Velocity options.

-1- Spherical elements (rotating planetocentric frame) -2- Cartesian elements (rotating planetocentric frame) -3- Classical orbital elements -9- Return to previous menu -0- Return to main menu

The equations of translational motion of START are based on spherical components, defined w.r.t. the rotating planetocentric frame, index *R* (the origin coincides with the CoM of the central body, the *X*-axis intersects the equator at zero longitude, the *Z*-axis is pointing in the same direction as the rotation vector of the central body, and the *Y*-axis completes the right-handed system). For a flexible input of position and velocity, cartesian components for the initial state have been added. The third way of entering the initial state for position and velocity is by means of the classical orbital elements. These elements are expressed w.r.t. to the inertial planetocentric frame, index *I*[8].

Spherical elements

With spherical components, position and velocity (w.r.t. the *R*-frame) can be expressed by (Fig. 6.26):

Position: distance r, longitude τ and latitude δ

Velocity: groundspeed V_G, flight-path angle γ_G and heading χ_G

The longitude is measured positively to the east ($0° \le \tau < 360°$). The latitude is measured along the appropriate meridian starting at the equator, positively in north direction ($0° \le \delta \le 90°$) and negatively to the south. The distance r, finally, is the distance from the Centre of Mass (CoM) of the central body to the CoM of the vehicle. The relative velocity V_G (i.e., the modulus of the velocity vector V) is expressed with respect to the *R*- frame. γ_G is the angle between V and the local horizontal plane; it ranges from -90° to +90° and is negative when V is below the local horizon. χ_G defines the direction of the projection of V in the local horizontal plane with respect to the local north and ranges from -180° to +180°. When χ_G = +90°, the vehicle is moving parallel to the equator to the east.

In order not to bother the user with the radius of the central body, r is not included as an initial state variable. Instead, the height h is used. h is related to r by the following relation:

$$h = r - R_e(1 - e\sin^2\delta) \tag{6.3}$$

[8] The inertial and rotating planetocentric frame are coincident at t = 0.

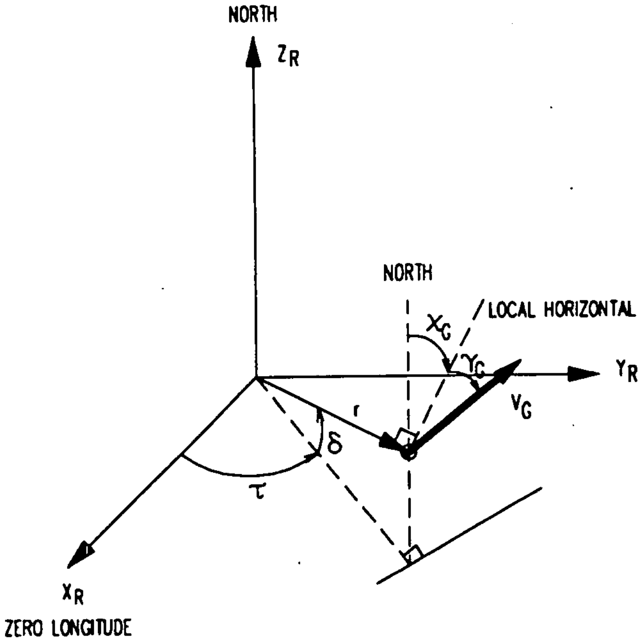


Fig. 6.26 - Definition of the six spherical flight parameters, the position (r,τ,δ) and velocity (V_G,γ_G,χ_G).

In this equation, R_e is the equatorial radius of the central body and e is the elipticity. Numerical values of these parameters have been discussed in Section 6.3.2.

Choosing the first option, **Spherical elements (rotating planetocentric frame)**, gives rise to the following set of questions:

```
Height h (m),            default =  0.2201360000D+06
Input new value (Enter to proceed):

Longitude tau (deg),     default =  0.2139590000D+03
Input new value (Enter to proceed):

Latitude delta (deg),    default =  0.4311800000D+01
Input new value (Enter to proceed):

Velocity vector V (m/s),         default =  0.1100000000D+05
Input new value (Enter to proceed):

Flight-path angle gamma (deg), default = -0.9563000000D+01
Input new value (Enter to proceed):

Heading chi (deg),               default =  0.5255600000D+02
Input new value (Enter to proceed):
```

Nota bene: as an example, we have given the default values of the input file, as shown in Appendix A. These values can be different for other missions.

The range of allowable values for the above variables, are:

h : $h > 0$ m
τ : $0° \leq \tau < 360°$
δ : $-90° < \delta < 90°$

V_G : $V_G > 0$ m/s
γ_G : $-90° \leq \gamma_G \leq 90°$
χ_G : $0° \leq \chi_G < 360°$

After having entered the value for the heading, we return to the Position/Velocity Menu.

Cartesian elements

Using cartesian components, the position and velocity with respect to the *R*-frame are defined by the following variables (Fig. 6.27):

Position: *x, y, z*

Velocity: *u, v, w*

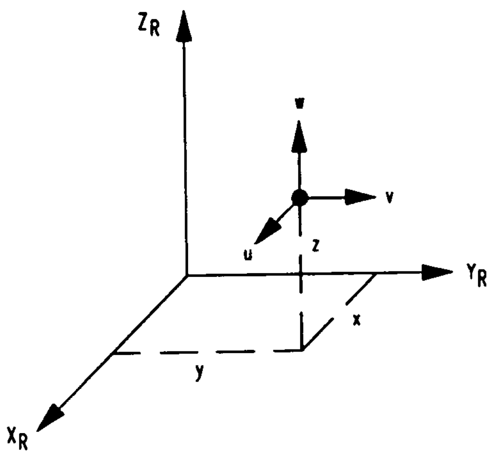


Fig. 6.27 - Definition of the cartesian position and velocity components.

Choosing the second option, **Cartesian elements (rotating planetocentric frame)**, shows the following set of questions on the screen:

```
x-position (m), default =
Input new value (Enter to proceed):

y-position (m), default =
Input new value (Enter to proceed):

z-position (m), default =
Input new value (Enter to proceed):

x-velocity (m/s), default =
```

```
Input new value (Enter to proceed):

y-velocity (m/s), default =
Input new value (Enter to proceed):

z-velocity (m/s), default =
Input new value (Enter to proceed):
```

Any value is valid for the above variables. However, it may be possible that a specified position lies inside the central body. No checks w.r.t. this is executed; it is left to the user's responsibility to enter a valid position.

After entering the z-velocity (i.e., *w*), the user returns to the Position/Velocity Menu.

Orbital elements

In case of an initial state defined by the classical orbital elements, we will restrict ourselves to elliptical orbits. The six parameters, defining the position and velocity of a spacecraft in an elliptical orbit are (see also Figs. 6.28 and 6.29):

e: the eccentricity ($0 \leq e < 1$)
a: the semi-major axis ($a > R_e$)
i: the inclination ($-180° \leq i \leq 180°$)

ω: argument of pericentre ($0° \leq \omega < 360°$)
Ω: the longitude of the ascending node ($0° \leq \Omega < 360°$)
M: mean anomaly ($0° \leq M < 360°$)

For more details on the definition of these parameters, one is referred to Mooij (1993a).

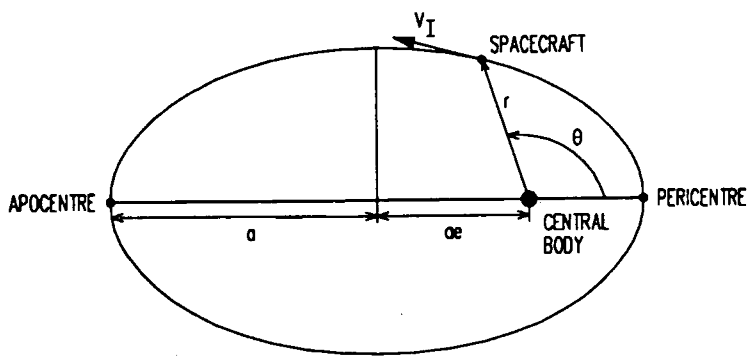


Fig. 6.28 - Definition of the semi-major axis a and the eccentricity e. The spacecraft is moving at a distance r with a velocity V_I w.r.t. to the inertial planetocentric frame (index I). The true anomaly is indicated by θ.

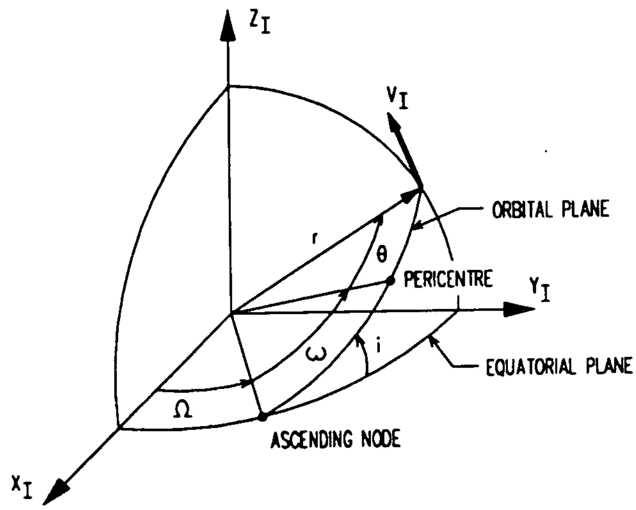


Fig. 6.29 - Definition of the three orbital parameters Ω, ω and *i*. The spacecraft is moving at a distance *r* with a velocity V_I w.r.t. to the inertial planetocentric frame (index *I*). The true anomaly is indicated by θ.

The following questions have to be answered:

```
Eccentricity e (-),    default =
Input new value (Enter to proceed):

Semi-major axis (km), default =
Input new value (Enter to proceed):

Inclination i (deg),  default =
Input new value (Enter to proceed):

Argument of pericentre omega (deg),      default =
Input new value (Enter to proceed):

Longitude of ascending node OMEGA (deg), default =
Input new value (Enter to proceed):

Mean anomaly M (deg),                    default =
Input new value (Enter to proceed):
```

After entering the value for the mean anomaly, control is returned to the Position/Velocity Menu.

Attitude and angular rates

The attitude is expressed by aerodynamic angles, i.e., the angle of attack α_G ($0° \leq \alpha_G < 360°$, for a 'nose-up' attitude $\alpha_G < 180°$)[9], the angle of sideslip β_G ($-180° \leq \beta_G \leq 180°$, β_G is positive for a 'nose-right' attitude) and the bank angle σ_G ($0° \leq \sigma_G < 360°$), see also Fig. 6.30. Nota

9 This definition of α means, that α = 180°, the so-called 'zero-angle-of-attack' corresponds with a ballistic flight (for a symmetrical body).

bene: these angles define the attitude of the vehicle w.r.t. the groundspeed, at least when they are used in the equations of motion. We will see in Section 8.2, that we can select an alternative set of kinematic attitude equations based on quaternions. In that case, the initial attitude is still based on the three aerodynamic angles.

The angular rate of the body is defined as the rotation of the body frame with respect to the inertial frame, expressed in components along the body axes. The rotation vector ω is defined by the roll rate p, the pitch rate q and the yaw rate r (Fig. 6.31).

Choosing option 2, **Attitude and angular rates**, gives the following set of initial state data on the screen. Again, we used default values as given in Appendix A.

```
Angle of attack alpha (deg),   default =  0.1569990000D+03
Input new value (Enter to proceed):

Angle of sideslip beta (deg), default = -0.8213830000D-03
Input new value (Enter to proceed):

Bank angle sigma (deg),        default =  0.1100030000D+03
Input new value (Enter to proceed):

Angular roll rate p (deg/s),   default =  0.1337782299D-01
Input new value (Enter to proceed):

Angular pitch rate q (deg/s), default =  0.1565778000D-01
Input new value (Enter to proceed):

Angular yaw rate r (deg/s),    default =  0.4344631302D-01
Input new value (Enter to proceed):
```

The range for the above variables is:

$\alpha_G : 0° \leq \alpha_G < 360°$
$\beta_G : 180° \leq \beta_G < 180°$
$\sigma_G : 0° \leq \sigma_G < 360°$

p]
q] Any value.
r]

After we have entered the new value for r, we return to the Initial-State Menu.

Nota bene: any angle (or angular rate) must be entered in degrees (or degrees per second).

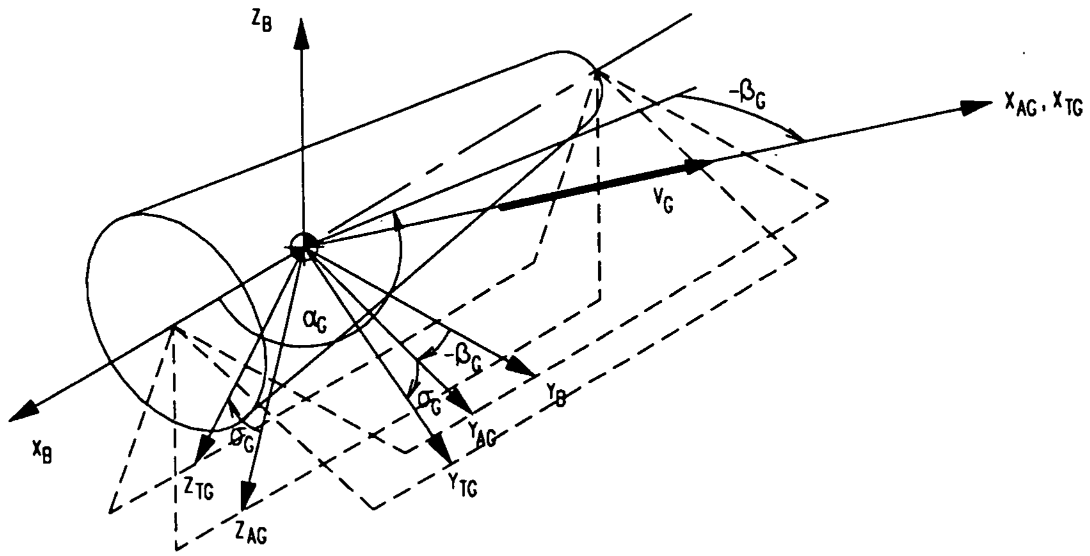


Fig. 6.30 - Definition of the aerodynamic attitude angles α_G, β_G and σ_G. The three related reference frames are the body frame (index *B*), the (groundspeed-based) aerodynamic frame (index *AG*) and the (groundspeed-based) trajectory frame (index *TG*).

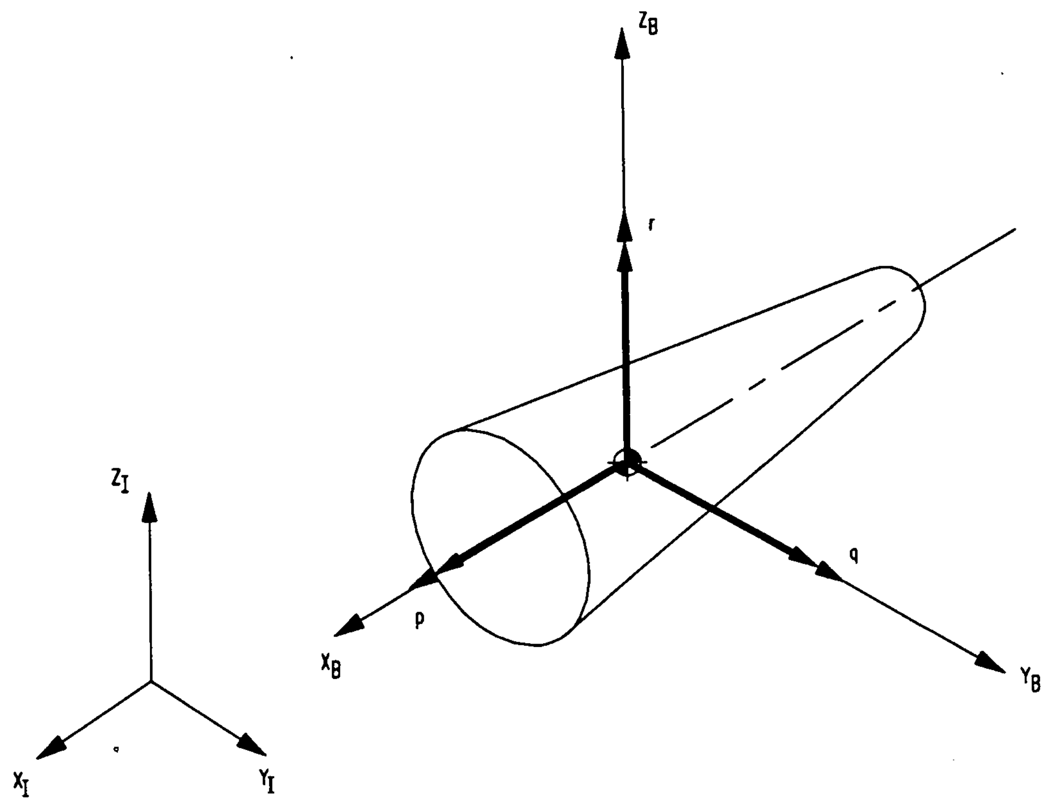


Fig. 6.31 - Definition of the angular rate of the vehicle, $\boldsymbol{\omega} = (p,q,r)^T$. The *I*- frame is the inertial planetocentric frame, which has its origin in the CoM of the central body. The origin of the body frame (index *B*) is located in the CoM of the vehicle. The body frame is fixed to the body.

6.4.3. Parachute operations.

Choosing option 2 from the Mission Menu, **Parachute operations**, is of course only meaningful when at least one parachute system has been defined. Choosing this option, if the number of parachute systems is equal to zero, results in an error message. After accepting this message, we return to the Mission Menu.

In case a parachute system has been defined, the user is asked to provide the number of the parachute system, which is going to be used for the operations. If only one system has been defined, it is obvious that this number must be one. Entering a number higher than the number of defined parachute systems is not possible.

Parachute operations are divided into three categories, namely deployment, reefing and release. For parachute deployment, we need to specify the condition at which this occurs[10]. A number of criteria is possible. They will be printed on the screen successively, together with the default setting. For each of these criteria, the user must specify, whether it is used ([Y] or [N]) and when it is used, what the value of this criterium is. More than one criterium may be specified.

The criteria are:

- Flight time (in sec)
- Height (in m)
- Relative velocity (in m/s)
- Mach number (-)
- Dynamic pressure (in N/m^2)

After the criterium of dynamic pressure, the user is asked, whether reefing will be applied at parachute deployment. If [N] for No is answered, the program continues with parachute release. We will discuss this later. First, we consider the situation that [Y] is answered, so the case that parachute reefing is applied. In that case, the number of reefing intervals must be specified. This may be any number between [1] and [5]. Per reefing interval, a number of data must be entered. These are:

- the reefing time, i.e., the length of the reefing interval (in sec)
- total percentage of deployment at the end of the interval (0-100%)

---

[10] Parachute deployment is, in principle, equal to a configuration change. Due to the specific nature of this event, we discuss it separately. However, the way parachute deployment affects the mass properties of the re-entry vehicle is the same as for configuration changes. Parachute deployment may have an influence on the location of the CoM and on the moments and products of inertia. Besides, the mass of the re-entry vehicle will change. Mass properties of the parachute system in packed condition (see also Section 6.2.6.2) are used to update the mass properties of the re-entry vehicle.

- Exponent for drag-coefficient development
- Exponent for parachute-area development

Nota bene: the percentage of deployment of reefing interval *i*, can never be smaller than the percentage of interval *i-1*. However, it can be equal, which would mean that we have introduced a stabilizing interval.

If the parachute is not going to be released, we must enter [N] on the question put on the screen. In that case, entering data related with parachute operations has finished and we return to the Mission Menu. On the other hand, answering [Y] gives need to specify the criterium (or criteria) for parachute release. These criteria are the same as for parachute deployment, so

- Flight time (in sec)
- Height (in m)
- Relative velocity (in m/s)
- Mach number (-)
- Dynamic pressure (in N/m^2)

Again, we must indicate which criterium is used ([Y] or [N]) and provide the numerical value if it is used. After (de)selecting the dynamic pressure, we return to the Mission Menu.

6.4.4. Configuration changes.

As we described in Section 6.2.2, the entry vehicle can be modelled by means of a number of mass elements. If the number of mass elements is greater than 1, it is possible to delete one (or more, depending on the total number of mass elements) element, depending on a predefined flight condition. In this way, we can simulate a configuration change of the entry vehicle, e.g., the jettisoning of an aerodynamic shell.

We can define configuration changes by entering [3], **Configuration changes**, from the Mission Menu. If only one mass element has been defined, an error message is given. After pressing [Enter], we return to the Mission Menu. In that case we have to increase the number of mass elements to at least 2, before we can define configuration changes.

Let us assume, that the number of mass elements is greater than one. In that case, after selecting **Configuration changes** from the Mission Menu, we must specify the number of configuration changes. This number can be 3 as a maximum, but cannot be higher than the number of mass elements minus one (always at least one mass element should remain defined). Per configuration change, a number of data must be entered.

First, we must specify the mass element for the configuration change by entering its number. Giving a number higher than the number of mass elements is rejected. If we input a number, which has already been defined for a configuration change, an error message appears. This message can be accepted by pressing [Enter], so that we can enter a new number.

Then, we must give the shift of the aerodynamic reference point with respect to which the aerodynamic coefficients are defined, here indicated as Centre of Pressure (CoP). Both the *dX*-, *dY*- and *dZ*-shift must be entered.

Apart from a shift of the aerodynamic reference point, also the reference geometry may change, as well as the aerodynamic coefficients themselves. The next three data correspond with the reference geometry, the aerodynamic reference length d and area S, and the reference length for computation of the Reynolds number, L_{ref} (see also Section 6.2.4). Then, the user is asked whether a new aerodynamic database, containing the aerodynamic coefficients, should be linked at the configuration change (so that we can change the aerodynamic properties of the re-entry vehicle). Answering [N] skips the next input, the one of entering the file name of the database. If, after answering [Y], the specified database does not exist, a warning is given to remind the user. The warning can be accepted by pressing [Enter]. Nota bene: if the database is not found during the simulation, it is aborted.

Finally, the event for the configuration change must be entered. The same criteria, as discussed before, apply. They are restated below:

- Flight time (in sec)
- Height (in m)
- Relative velocity (in m/s)
- Mach number (-)
- Dynamic pressure (in N/m^2)

We can (de)select one (or a combination) of the above criteria, by entering [Y] ([N]) for the proper criterium. Having selected the criterium, we must also provide the numerical value of the criterium.

After (de)selecting the dynamic pressure, we can either decide to edit the next configuration change (if any) by entering [Y], or to return to the Mission Menu (entering [N]). After the last configuration change, we automatically return to the Mission Menu.

6.4.5. Propulsion operations.

Choosing option 4, **Propulsion operations**, from the Mission Menu, gives the following sub-menu on the screen. In principle, this menu was not necessary, because there is only one menu entry (Deorbit-burn manoeuvre). However, with respect to future extensions the menu has already been implemented. The related menu structure is schematically shown in Fig. 6.32.

```
-1- Deorbit-burn manoeuvre
-9- Return to previous menu
-0- Return to main menu
```

Entering [1] from the above Propulsion Operations Menu, **Deorbit-burn manoeuvre**, results in the question whether the user wants to select the deorbit-burn manoeuvre or not. Answering [N] results in a return to the Propulsion Operations Menu. Giving [Y] as an answer, gives a table with the three implementations, as can be seen below. The currently selected implementation of the manoeuvre is printed below the table, and the user is asked to enter his choice, or to accept the default choice by pressing [Enter].

```
-1- Impulsive dV
-2- mfuel by Tsiolkovsky
-3- mfuel specified
```

The three deorbit-burn implementations can be divided into two essentially different methods. The *impulsive dV*, is, as the name indicates, an instantaneous manoeuvre. No thrust is included. The two other implementations, *mfuel by Tsiolkovsky* and *mfuel specified* are so-called finite-thrust manoeuvres. The two methods will now be discussed below.

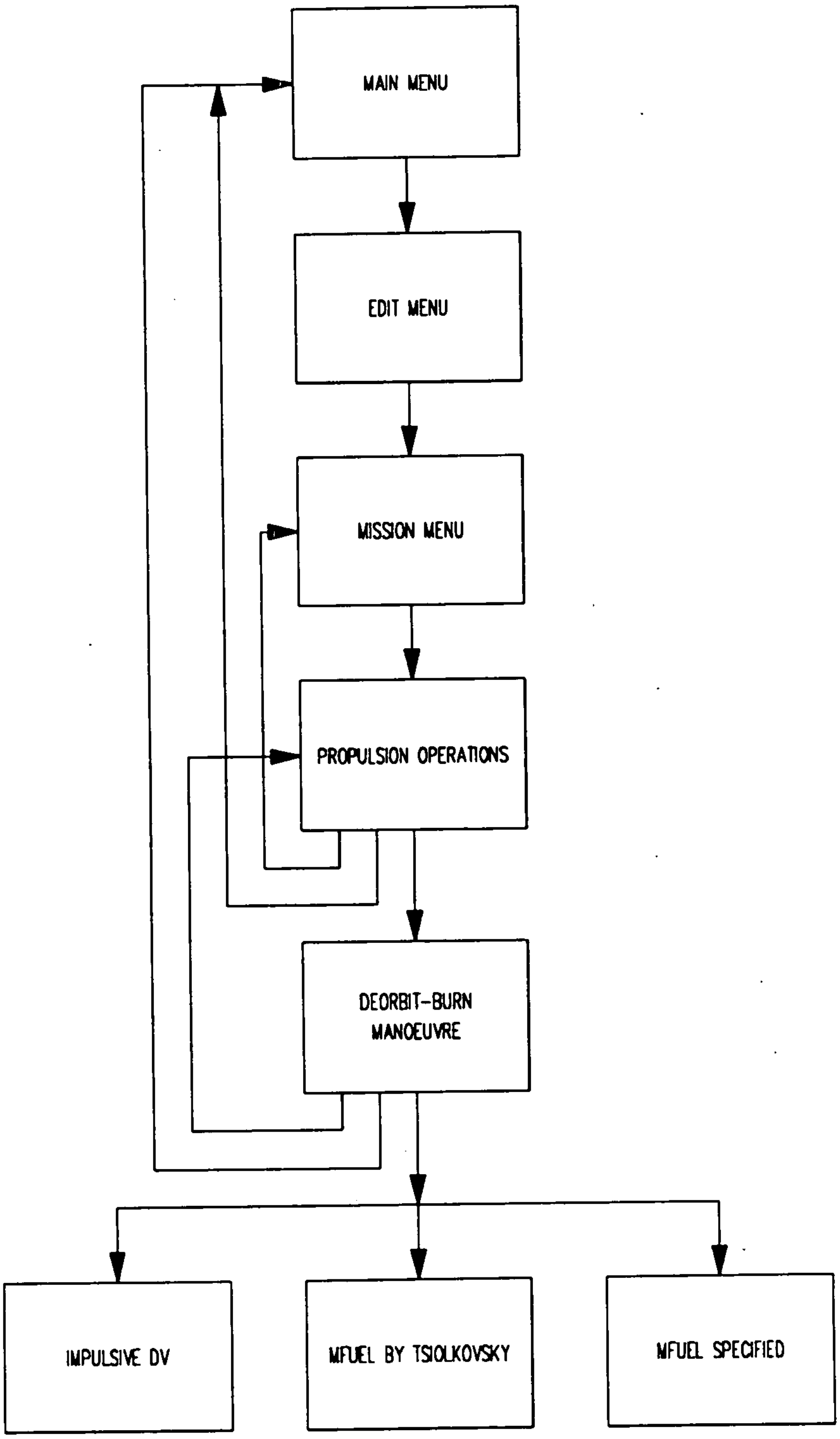


Fig. 6.32 - The menu structure for propulsion operations, including the deorbit-burn manoeuvre.

Impulsive dV

The (inertial) ΔV-vector is vectorially added to the initial velocity of the spacecraft. $\Delta \boldsymbol{V}$ is given as a modulus and two direction angles, *relative to the inertial velocity of the vehicle* (Fig. 6.33).

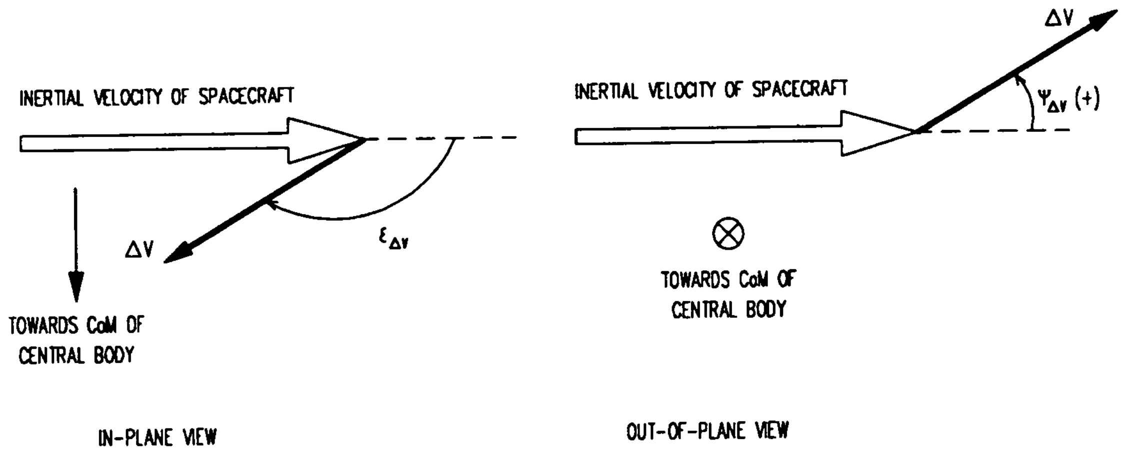


Fig. 6.33 - Definition of the ΔV-vector.

Finite thrust manoeuvre

Also in this case, the inertial ΔV-vector is given as a modulus and two (relative) direction angles. The ΔV is now achieved by a thrusted manoeuvre. The direction of the thrust is computed on basis of the (fixed) orientation in inertial space. So when the spacecraft is orbiting the central body, the thrust direction is constantly adjusted, because the orientation of the body frame (in which the thrust is defined) is continuously changing w.r.t. the inertial frame. As a stop criterium for thrusting, the achieved (total) ΔV in thrust direction is taken. This implies, that we assume a drag-free deorbit-burn manoeuvre, i.e., an exoatmospheric manoeuvre.

Choosing option 1, **Impulsive dV**, from the Deorbit-Burn Menu gives rise to three questions:

```
Delta V (> 0 m/s),                default =
Input new value (Enter to proceed):

The next two angles define the orientation of the dV vector.

In-plane angle (0, 360 deg),      default =
Input new value (Enter to proceed):

Out-of-plane angle (-90, +90 deg), default =
Input new value (Enter to proceed):
```

The ranges of the two angles are:

$0° \leq \varepsilon_{\Delta V} < 360°$
$-90° \leq \psi_{\Delta V} \leq 90°$

After entering the out-of-plane angle $\psi_{\Delta V}$, we return to Propulsion Operations Menu.

By choosing option 2, **mfuel by Tsiolkovsky**, we select a finite-thrust manoeuvre. Naturally, such a manoeuvre can only be executed once the deorbit-burn engine has been selected. If not so, a warning is given:

```
Warning: no deorbit-burn engine specified!
Press Enter to continue.
```

After accepting the warning (or when the deorbit-engine was specified, and the warning was not given), the same questions as mentioned above appear on the screen. During the simulation, the fuel mass needed for the manoeuvre is computed using Tsiolkovsky's Equation:

$$m_f = m_0 \left(1 - e^{\frac{\Delta V}{g_0 I_{sp}}}\right) \qquad (6.4)$$

with

m_f = fuel mass
m_0 = mass of entry vehicle (kg)
ΔV = modulus of ΔV-vector (m/s)
I_{sp} = specific impulse of deorbit-burn engine in vacuum (sec)
g_0 = gravitational acceleration at sea level (m/s^2)

The thrusted manoeuvre will end when all the fuel has been used.

With option 3, **mfuel specified**, the user can specify the fuel mass himself. Again a check is made, whether the deorbit-burn engine has been specified. Then, after a warning or not, first the fuel mass has to be specified:

```
Fuel mass for deorbit burn (> 0 kg), default =
Input new value (Enter to proceed):
```

Then, the ΔV is specified in the same way as mentioned above, by specifying the modulus and two direction angles. The thrusted manoeuvre will end, when (a) the fuel mass is zero, before the ΔV has been achieved, or (b) the ΔV has been achieved (in thrust direction!).

After specifying the out-of-plane angle, we return to the Propulsion Operations Menu.

6.5. Simulation aspects.

6.5.1. The Simulation Menu.

Choosing option 4 from the Edit Menu, **Simulation**, enables us to edit simulation related variables. The following menu, the so-called Simulation Menu, appears on the screen:

-1- Integration method
-2- Maximum integration step size
-3- Output filing rate
-4- Tolerances
-5- Stop criteria
-9- Return to previous menu
-0- Return to main menu

The first five menu entries are related with simulation aspects, and will be discussed in the next Sections. Entering [9] or [0], results in a return to the Edit Menu (the previous menu) or the Main Menu. The related menu structure is shown in Fig. 6.34.

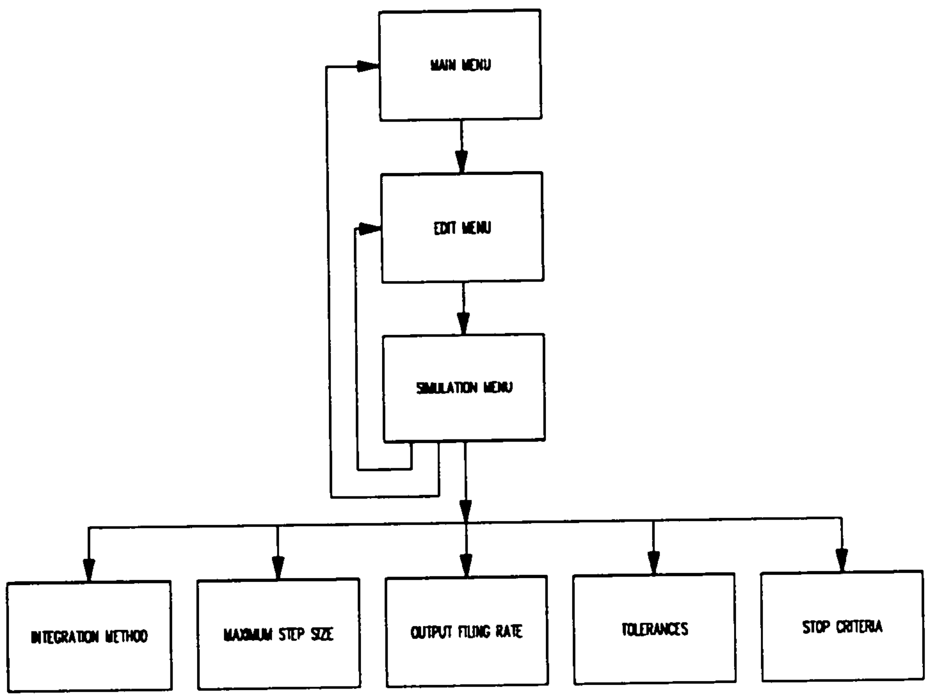


Fig. 6.34 - The Simulation Menu.

6.5.2. Integration method.

Entering [1] from the Simulation Menu, **Integration method**, gives the current selection of the integration method on the screen, together with a menu with available integration methods.

```
-1- Fixed step, 4th order Runge-Kutta
-2- Variable step, 7th order RK-Fehlberg
-3- Variable step, variable order ABAM
-4- Fixed step, 2nd order Adams-Bashf.
-5- Fixed step, 3rd order Adams-Bashf.
-6- Fixed step, 4th order Adams-Bashf.
-9- Return to previous menu
-0- Return to main menu
```

We can select one of the six integration methods by entering [1], [2], ... [6]. It is recommended to use the variable-step, seventh-order Runge-Kutta-Fehlberg method ([2]) for 6-dof simulations, and the variable-step, variable-order Adams-Bashforth Adams-Moulton ([3]) for 3-dof simulations.

Selecting an integrator will automatically adjust the maximum integration step size. For the fixed-step fourth-order Runge-Kutta and the fixed-step Adams-Bashforth integration methods, this maximum step corresponds with the fixed step size, and is equal to dt = 0.01 s. For the two variable-step integrators, the maximum step size is equal to dt_{max} = 1 sec. After selecting an integration method, we return to the Simulation Menu. We can leave the menu with [9] or [0] as well.

6.5.3. Maximum integration step size.

Entering [2] from the Simulation Menu, **Maximum integration step size**, gives the current value of the maximum integration step size dt_{max}. For the fixed step-size integrators, this maximum step corresponds with the fixed step-size dt. We can enter a new value for dt_{max}, or accept the current value by pressing [Enter]. The value we enter, must be greater than zero, of course. Hereafter, we return to the Simulation Menu.

6.5.4. Output filing rate.

Choosing option 3 from the Simulation Menu, enables us to edit the values for the output filing rate. We must specify two output filing rates, i.e., the one for the quicklook data (data, which are printed on the screen during the simulation, in order to monitor the computations; these data are also written to a file) and the one for the plot data. Below, we have indicated what will appear on the screen, using the default values of Appendix A.

```
The quicklook data filing rate (s), default =  0.2000000000D+01
Input new value (Enter to proceed):

The plot data filing rate (s),      default =  0.1000000000D+01
Input new value (Enter to proceed):
```

It is obvious, that the filing rates must have values greater than zero. After specifying the plot filing rate, we return to the Simulation Menu.

6.5.5. Tolerances.

The variable-step integrators require tolerance values for the state variables, in order to be able to compute the integration step size. We can specify these tolerances, by entering [3], **Tolerances**, from the Simulation Menu. The tolerances, which we can edit, are, in successive order:

- Tolerance for velocity V (m/s)
- Tolerance for flight-path angle γ (deg)
- Tolerance for heading χ (deg)
- Tolerance for position r (m)
- Tolerance for position angles τ and δ (deg)
- Tolerance for angular rates p, q and r (deg/s)
- Tolerance for attitude α, β and σ (deg)

All tolerance values must be positive and unequal to zero.

Having entered the tolerance for the attitude angles, we return to the Simulation Menu. Nota bene: when quaternions are used as state variables, the attitude tolerances are picked as tolerances for the quaternions.

6.5.6. Stop criteria.

Simulation will continue until some pre-defined stop criterium has been met, or when we reach the so-called internal stop criterium. This criterium is:

- reaching the surface of the central body (h = 0 m)

The user-defined stop criteria can be defined by choosing option 5 from the Simulation Menu, **Stop criteria.** We get a similar list, as discussed for parachute operations (Section 6.4.3) and configuration changes (Section 6.4.4). For the sake of convenience, the possible criteria are repeated below.

- Flight time (in sec)

- Height (in m)
- Relative velocity (in m/s)
- Mach number (-)
- Dynamic pressure (in N/m^2)

Again, we can (de)select each of the above criteria, by entering [Y] ([N]). When we have selected a criterium, we must also specify the corresponding numerical value. After (de)selection of the dynamic pressure, we return to the Simulation Menu.

7. Save input data.

We can save the input data, by choosing the option **Save input data** from the Main Menu. In that case, the default input filename and a File Menu, as shown below, appear on the screen. The default file name can be 'INPUT.DAT' (program default) or the last user specified name.

-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu

This File Menu has been discussed before, so we will just refer to Chapter 4. Having entered a file name, which already exists, a message appears on the screen:

```
This file already exists. Overwrite <Y/N>?
```

Entering [N] results in a return to the File Menu, so that we can alter the file name. If any error occurs during the write process, an error message is given. After accepting this message by pressing [Enter], we return to the File Menu.

The related menu structure is given in Fig. 7.1.

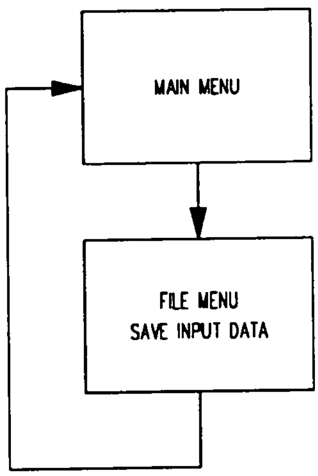


Fig. 7.1 - The File Menu for saving input data.

8. Simulation.

8.1. Simulation Menu.

Entering [5] from the Main Menu, option **Simulation**, gives the settings of the selected simulation parameters and the following menu on the screen. The simulation parameters consist of the choice of the position and velocity variables, the choice of the kinematic attitude variables and the simulation mode.

```
-1- Change any parameter
-2- Start simulation
-9- Return to previous menu
-0- Return to main menu
```

For the sake of convenience, we have given this menu the name Simulation Menu. However, the user must not be mistaken with the Simulation Menu, which can be chosen from the Edit Menu (Section 6.5.1).

We can leave this menu, by entering [9] or [0]. In both cases we return to the Main Menu. This is visualized in Fig. 8.1. In the next two Sections, we will discuss the first two menu entries.

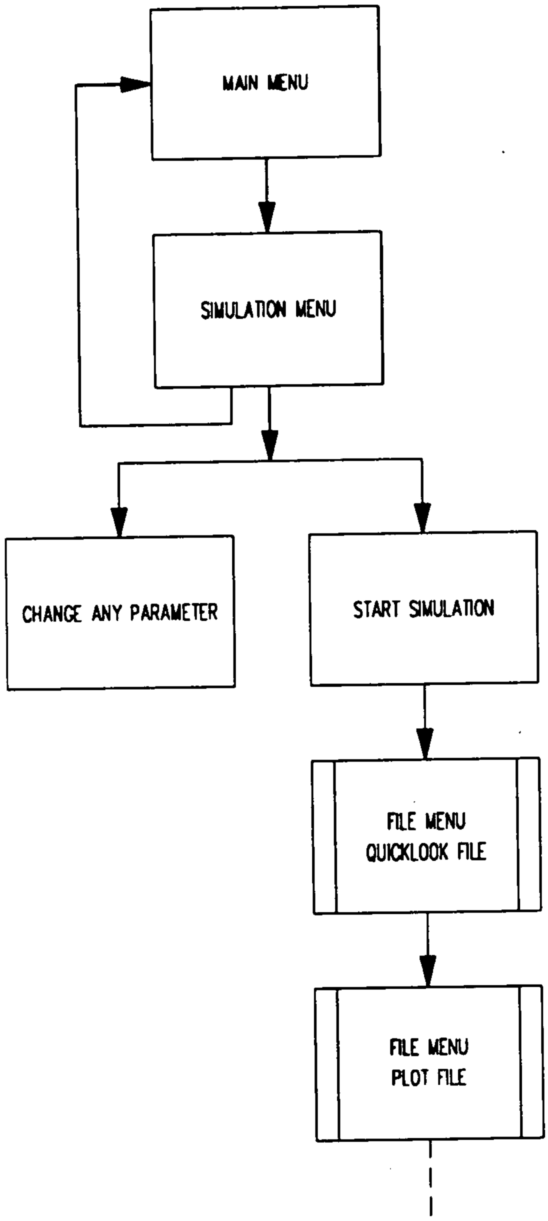


Fig. 8.1 - The Simulation Menu, including the two file menus for editing the name of the quicklook file and the plot file.

8.2. Change any parameter.

Choosing option 1 from the Simulation Menu, **Change any parameter**, enables the user to change the simulation parameters. First, the default selection of the position and velocity variables is shown, together with a list with possible options.

```
-1- spherical
-2- (*) cartesian
```

For the time being, the cartesian variables have not been implemented yet, so only the spherical components can be chosen.

Then, the next screen appears: the selected kinematic attitude variables plus a list with options. The choice of the variables has to be entered as an integer value.

```
-1- alpha, beta and sigma
-2- quaternions
```

The last simulation parameter concerns the simulation mode. The default selection and the two possible options are shown on the screen.

```
-1- 3 degrees of freedom
-2- 6 degrees of freedom
```

Nota bene: if parachute operations have been defined, we must in principal select 6 dof simulation, because we need all the twelve state variables to compute initial conditions for the parachute phase (the parachute model is a 6-dof one). However, when we select 3 dof simulation, we must provide initial conditions *for all twelve state variables*, so also attitude and angular rates. To compute initial conditions for the parachute phase, these values will be used in that case. For a 3-dof entry without parachute operations, the three aerodynamic angles appear in the equations of translational motion. These variables are constant, of course, with values the same as the initial conditions for these angles.

After selecting the simulation mode, we return to the Simulation Menu.

8.3. Start simulation.

Choosing option 2, **Start simulation**, from the Simulation Menu, does not immediately result in executing the simulation. First, some internal checks are made, whether the input data are correct to perform a simulation (check on the existence of the inverse of the inertia tensor in case of a 6 dof simulation; if it does not exist, an error message is given, resulting in a return to the Main Menu). Then, the user must specify the name of the quicklook file and the plot file.

For this reason, the default name of the quicklook file, 'OUTPUT.DAT', is shown on the screen, together with a File Menu, as shown below.

-1- Use default name
-2- Change filename
-9- Return to previous menu
-0- Return to main menu

This kind of file menu is used throughout the program and has been discussed several times before. The user is referred to Chapter 4 or Section 6.2.5.1.

If the selected file already exists, a message is given. The user can decide to overwrite the file (answering [Y] on the question *Overwrite?*), or return to the File Menu (answering [N]), to change the file name. At any time, the user can return to the previous menu or Main Menu.

Once we have specified the quicklook file, the default name of the plot file appears on the screen, together with a similar menu, as shown above. The same discussion applies. For an overview of the related menus, one is referred to Fig. 8.1.

After specifying the plot file name, the actual simulation begins and continues until a stop criterium is met. In that case, control is returned to the Main Menu.

Nota bene: just before the simulation begins, a copy of the current input data is written to the file 'xxxxxxxx'. During the simulation, some of the input data may be changed (think of loading an aerodynamic database). In order to keep the original set intact, they are read again after the simulation has finished.

9. Output of START.

The output of START can be divided into two categories. The first category deals with the quicklook data. During the simulation, the most important variables are printed on the screen at a user-defined rate (Section 6.5.4), so that the user can monitor the simulation. If any numerical instability occurs, it will be shown in the variables and the user can abort simulation. These quicklook data are also written to a user-specified file (for an example of the quicklook data, one is referred to Appendix B). In this file, also the complete set of input data, used for that particular simulation, can be found.

If a special event occurs during the simulation, i.e., parachute deployment, parachute release or a configuration change, a message is sent both to the screen and the quicklook file. In this way, it is easy to trace back the conditions at which these events actually occurred.

The second category deals with the plot data. Plot data are written to a user specified file, in a specific format. The same format must be used to write a conversion program, in order to convert the plot file to a file, which can be processed by a plotting software package. The plot data can be divided into three categories, namely the ones for the (re-)entry vehicle (index *r*), the parachute (index *p*) and the complete system (no index). They are written in the order as shown in the table below (index *g* means groundspeed based and index *a* airspeed based).

Nota bene

The simulation model for the entry vehicle alone and the parachute/payload system are two separate models. The former is based on spherical position and velocity components and the latter on cartesian ones. When the entry phase is considered, only the first 51 variables have a meaningful value. The other output variables are put to zero. Once the 'parachute mode'[11] has been entered, all 98 variables have a meaningful value. However, this does not apply to the variables indicated with a superscript '*'; these variables cannot be accessed for the time being.

The output variables:

1)	t	elapsed simulation time (flight time)	s
2)	δ	latitude	°
3)	τ	longitude	°
4)	h	height	km
5)	$V_{g,r}$	relative groundspeed of entry vehicle	m/s
6)	$\gamma_{g,r}$	flight-path angle (groundspeed) of entry vehicle	°
7)	$\chi_{g,r}$	heading (groundspeed) of entry vehicle	°

[11] With the 'parachute mode', we mean that the dynamical model representing the parachute system is used to integrate the equations of motion. After jettisoning of the parachute, this model is still used for computing the motion of the entry vehicle alone (and all 98 variables are being used for output). Part of future extensions is the implementation of cartesian position and velocity components for the entry phase, including full access of all plot variables.

8)	p	angular roll rate of system with respect to the inertial frame (expressed in components along the body axes)	°/s
9)	q	angular pitch rate of system with respect to the inertial frame (expressed in components along the body axes)	°/s
10)	r	angular yaw rate of system with respect to the inertial frame (expressed in components along the body axes)	°/s
11)	$\alpha_{g,r}$	angle of attack (groundspeed) of entry vehicle	°
12)	$\beta_{g,r}$	angle of sideslip (groundspeed) of entry vehicle	°
13)	$\sigma_{g,r}$	bank angle (groundspeed) of entry vehicle	°
14)	$\alpha_{T_{g,r}}$	total angle of attack (groundspeed) of entry vehicle	°
15)	$L_{a,r}$	lift force (airspeed) acting on entry vehicle	N
16)	$D_{a,r}$	drag force (airspeed) acting on entry vehicle	N
17)	$S_{a,r}$	side force (airspeed) acting on entry vehicle	N
18)	L/D_r	lift-to-drag ratio (airspeed) for entry vehicle	-
19)	$F_{G,r}(1)$	first component of gravity force acting on entry vehicle, i.e., gravitational force along position vector for spherical components and the cartesian component in *X*-direction (in case of the 3D-parachute model)	N
20)	$F_{G,r}(2)$	second component of gravity force acting on entry vehicle, i.e., zero for spherical components	N
21)	$F_{G,r}(3)$	third component of gravity force acting on entry vehicle, i.e., the gravitational force along the meridian for spherical components	N
22)	L_r	roll moment acting on entry vehicle	Nm
23)	M_r	pitch moment acting on entry vehicle	Nm
24)	N_r	yaw moment acting on entry vehicle	Nm
25)	$q_{dyn,r}$	dynamic pressure for entry vehicle	N/m^2
26)	M_r	Mach number of entry vehicle	-
27)	Re_r	Reynolds number for entry vehicle	-
28)	g_load_r	occurring dimensionless deceleration (deceleration/g_0) for entry vehicle	-
29)	p	atmospheric pressure	N/m^2
30)	ρ	atmospheric density	kg/m^3
31)	T_{kin}	kinetic temperature	K
32)	a	speed of sound	m/s
33)	ϕ	roll angle for system	°
34)	θ	pitch angle for system	°
35)	ψ	yaw angle for system	°
36)	dt	time step for integration	s
37)	$V_{a,r}$	relative airspeed of entry vehicle	m/s
38)	$\gamma_{a,r}$	flight-path angle (airspeed) of entry vehicle	°
39)	$\chi_{a,r}$	heading (airspeed) of entry vehicle	°
40)	$\alpha_{a,r}$	angle of attack (airspeed) of entry vehicle	°
41)	$\beta_{a,r}$	angle of sideslip (airspeed) of entry vehicle	°
42)	$\sigma_{a,r}$	bank angle (airspeed) of entry vehicle	°

43)	$\alpha_{T_{a,r}}$	total angle of attack (airspeed) of entry vehicle	°
44)*	$\dot{\alpha}_{a,r}$	time derivative of α (airspeed) for entry vehicle	°
45)*	$\dot{\beta}_{a,r}$	time derivative of β (airspeed) for entry vehicle	°
46)*	$L_{g,r}$	lift force (groundspeed) acting on entry vehicle	N
47)*	$D_{g,r}$	drag force (groundspeed) acting on entry vehicle	N
48)*	$S_{g,r}$	side force (groundspeed) acting on entry vehicle	N
49)	V_w	wind velocity (modulus)	m/s
50)	γ_w	flight-path angle of wind vector	°
51)	χ_w	heading of wind vector	°
52)	$V_{g,p}$	relative groundspeed of parachute	m/s
53)	$\gamma_{g,p}$	flight-path angle (groundspeed) of parachute	°
54)	$\chi_{g,p}$	heading (groundspeed) of parachute	°
55)	$\alpha_{g,p}$	angle of attack (groundspeed) of parachute	°
56)	$\beta_{g,p}$	angle of sideslip (groundspeed) of parachute	°
57)	$\alpha_{T_{g,p}}$	total angle of attack (groundspeed) of parachute	°
58)	$L_{a,p}$	lift force (airspeed) acting on parachute	N
59)	$D_{a,p}$	drag force (airspeed) acting on parachute	N
60)	$S_{a,p}$	side force (airspeed) acting on parachute	N
61)	$F_{G,p}(1)$	first cartesian component of gravity force acting on parachute	N
62)	$F_{G,p}(2)$	second cartesian component of gravity force acting on parachute	N
63)	$F_{G,p}(3)$	third cartesian component of gravity force acting on parachute	N
64)	L_p	roll moment acting on parachute	Nm
65)	M_p	pitch moment acting on parachute	Nm
66)	N_p	yaw moment acting on parachute	Nm
67)	$q_{dyn,p}$	dynamic pressure for parachute	N/m^2
68)	M_p	Mach number of parachute	-
69)	Re_p	Reynolds number for parachute	-
70)	g_load_p	occurring dimensionless deceleration (deceleration/g_0) for parachute	-
71)	$V_{a,p}$	relative airspeed of parachute	m/s
72)	$\gamma_{a,p}$	flight-path angle (airspeed) of parachute	°
73)	$\chi_{a,p}$	heading (airspeed) of parachute	°
74)	$\alpha_{a,p}$	angle of attack (airspeed) of parachute	°
75)	$\beta_{a,p}$	angle of sideslip (airspeed) of parachute	°
76)	$\alpha_{T_{a,p}}$	total angle of attack (airspeed) of parachute	°
77)*	$\dot{\alpha}_{a,p}$	time derivative of α (airspeed) for parachute	°
78)*	$\dot{\beta}_{a,p}$	time derivative of β (airspeed) for parachute	°
79)	S_p	parachute area	m^2
80)	I_{xx}	first moment of inertia for system	kg m^2
81)	I_{yy}	second moment of inertia for system	kg m^2

82) I_{zz}	third moment of inertia for system	kg m^2
83) m_a	added mass	kg
84) u	cartesian u-velocity for system	m/s
85) v	cartesian v-velocity for system	m/s
86) w	cartesian w-velocity for system	m/s
87) x	cartesian x-position for system	m
88) y	cartesian y-position for system	m
89) z	cartesian z-position for system	m
90) $M_{sw,x}$	swivel moment around X-axis	Nm
91) $M_{sv,x}$	moment around X-axis due to spin vanes	Nm
92) α_{sv}	angle of attack for spin vanes	°
93) β_{sv}	angle of sideslip for spin vanes	°
94) $\alpha_{T,sv}$	total angle of attack for spin vanes	°
95) $C_{L,sv}$	lift coefficient for spin vanes	-
96) $C_{D,sv}$	drag coefficient for spin vanes	-
97) $C_{X,sv}$	axial force coefficient for spin vanes	-
98) $C_{Z,sv}$	normal force coefficient for spin vanes	-

The format, in which the 98 variables are written to the plot file, is:

24(4g18.6,/),2g18.6

10. Quit the program.

Selecting option 6, **Quit the program**, from the Main Menu aborts execution of START. A closing screen is shown and control is returned to the operating system. Nota bene: no warning is given whether one really wants to stop the execution of START. This is left to the users own responsibility.

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2) Mooij, E.;
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3) Mooij, E.;
START User Manual, Version 1.0;
Thesis report Delft University of Technology, Faculty of Aerospace Engineering;
Delft, 1991c.

4) Mooij, E.;
Source listing of START, Version 1.0. Appendix to the User Manual;
Thesis report Delft University of Technology, Faculty of Aerospace Engineering; Delft, 1991d.

5) Mooij, E.;
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6) Mooij, E.;
The influence of the deorbit burn on the footprint of a re-entry capsule;
Report LR-727;
Delft University of Technology, Faculty of Aerospace Engineering, Delft, 1993a.

7) Mooij, E.;
Source listing of START, Version 2.1. Appendix to the User Manual;
Report LR-726;
Delft University of Technology, Faculty of Aerospace Engineering, Delft, 1993b.

Report LR-726

Appendix A - Example of input file

July 1993

Ir. E. Mooij

TU Delft
Delft University of Technology

Faculty of Aerospace Engineering

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```
******************************
**     MASS PROPERTIES      **
******************************

Number of mass elements                         1

**********> Data for mass element # 1

Mass at epoch (kg)                              0.4976000000D+04

X-coordinate CoM (m)                           -0.2570000000D+01
Y-coordinate CoM (m)                            0.0000000000D+00
Z-coordinate CoM (m)                            0.1370000000D+00

Ixx (kg m^2)                                    0.5617605456D+04
Iyy (kg m^2)                                    0.4454623056D+04
Izz (kg m^2)                                    0.4454801760D+04
Ixy (kg m^2)                                    0.0000000000D+00
Ixz (kg m^2)                                    0.1751999840D+04
Iyz (kg m^2)                                    0.0000000000D+00

******************************
**      REF. GEOMETRY       **
******************************

Ref. length d (m) for aerod. coeff.             0.3900000000D+01

Ref. area S (m^2) for aerod. coeff.             0.1200000000D+02

Ref. length Lref (m) for Re-number              0.3900000000D+01

******************************
**      AERODYNAMICS        **
******************************

Re-entry vehicle is axisymmetric body           1

Extrapolation method                            2

******************************
**     COEFFICIENT CD       **
******************************

Number of coefficient components                1

**********> Data for coefficient component #1

Order of derivation                             0

Number of table variables                       2

Table variable #1                               5 = Mach

Number of entries for table variable #1         10

                                 Entry  1       0.7000000000D+00
                                 Entry  2       0.9000000000D+00
                                 Entry  3       0.1100000000D+01
                                 Entry  4       0.1200000000D+01
                                 Entry  5       0.1350000000D+01
                                 Entry  6       0.1550000000D+01
                                 Entry  7       0.2000000000D+01
                                 Entry  8       0.2600000000D+01
                                 Entry  9       0.3000000000D+01
                                 Entry 10       0.3400000000D+01

Table variable #2                               3 = atot

Number of entries for table variable #2         5

                                 Entry  1       0.1400000000D+03
                                 Entry  2       0.1500000000D+03
                                 Entry  3       0.1600000000D+03
                                 Entry  4       0.1700000000D+03
                                 Entry  5       0.1800000000D+03

Function values for coefficient component

                                 C( 1, 1)       0.7000000000D+00
                                 C( 2, 1)       0.8000000000D+00
                                 C( 3, 1)       0.1000000000D+01
                                 C( 4, 1)       0.1000000000D+01
                                 C( 5, 1)       0.1100000000D+01
                                 C( 6, 1)       0.1050000000D+01
                                 C( 7, 1)       0.1000000000D+01
                                 C( 8, 1)       0.9500000000D+00
                                 C( 9, 1)       0.9500000000D+00
                                 C(10, 1)       0.9000000000D+00
                                 C( 1, 2)       0.8000000000D+00
```

```
C( 2, 2)      0.9000000000D+00
C( 3, 2)      0.1150000000D+01
C( 4, 2)      0.1100000000D+01
C( 5, 2)      0.1250000000D+01
C( 6, 2)      0.1200000000D+01
C( 7, 2)      0.1200000000D+01
C( 8, 2)      0.1150000000D+01
C( 9, 2)      0.1150000000D+01
C(10, 2)      0.1100000000D+01
C( 1, 3)      0.9500000000D+00
C( 2, 3)      0.1050000000D+01
C( 3, 3)      0.1250000000D+01
C( 4, 3)      0.1250000000D+01
C( 5, 3)      0.1350000000D+01
C( 6, 3)      0.1300000000D+01
C( 7, 3)      0.1400000000D+01
C( 8, 3)      0.1350000000D+01
C( 9, 3)      0.1300000000D+01
C(10, 3)      0.1300000000D+01
C( 1, 4)      0.1000000000D+01
C( 2, 4)      0.1100000000D+01
C( 3, 4)      0.1300000000D+01
C( 4, 4)      0.1300000000D+01
C( 5, 4)      0.1400000000D+01
C( 6, 4)      0.1250000000D+01
C( 7, 4)      0.1450000000D+01
C( 8, 4)      0.1450000000D+01
C( 9, 4)      0.1450000000D+01
C(10, 4)      0.1400000000D+01
C( 1, 5)      0.1000000000D+01
C( 2, 5)      0.1100000000D+01
C( 3, 5)      0.1300000000D+01
C( 4, 5)      0.1300000000D+01
C( 5, 5)      0.1400000000D+01
C( 6, 5)      0.1250000000D+01
C( 7, 5)      0.1450000000D+01
C( 8, 5)      0.1500000000D+01
C( 9, 5)      0.1450000000D+01
C(10, 5)      0.1450000000D+01

******************************
**      COEFFICIENT CL      **
******************************

Number of coefficient components              1

**********> Data for coefficient component #1

Order of derivation                             0

Number of table variables                       2

Table variable #1                               5 = Mach

Number of entries for table variable #1         10

                                 Entry  1       0.7000000000D+00
                                 Entry  2       0.9000000000D+00
                                 Entry  3       0.1100000000D+01
                                 Entry  4       0.1200000000D+01
                                 Entry  5       0.1350000000D+01
                                 Entry  6       0.1550000000D+01
                                 Entry  7       0.2000000000D+01
                                 Entry  8       0.2600000000D+01
                                 Entry  9       0.3000000000D+01
                                 Entry 10       0.3400000000D+01

Table variable #2                               3 = atot

Number of entries for table variable #2         5

                                 Entry  1       0.1400000000D+03
                                 Entry  2       0.1500000000D+03
                                 Entry  3       0.1600000000D+03
                                 Entry  4       0.1700000000D+03
                                 Entry  5       0.1800000000D+03

Function values for coefficient component

                                 C( 1, 1)       0.5200000000D+00
                                 C( 2, 1)       0.5400000000D+00
                                 C( 3, 1)       0.6400000000D+00
                                 C( 4, 1)       0.6400000000D+00
                                 C( 5, 1)       0.6400000000D+00
                                 C( 6, 1)       0.6000000000D+00
                                 C( 7, 1)       0.5600000000D+00
                                 C( 8, 1)       0.5200000000D+00
                                 C( 9, 1)       0.5200000000D+00
                                 C(10, 1)       0.5200000000D+00
                                 C( 1, 2)       0.4000000000D+00
                                 C( 2, 2)       0.4400000000D+00
```

```
C( 3, 2)      0.5600000000D+00
C( 4, 2)      0.5600000000D+00
C( 5, 2)      0.6000000000D+00
C( 6, 2)      0.5800000000D+00
C( 7, 2)      0.5600000000D+00
C( 8, 2)      0.5200000000D+00
C( 9, 2)      0.5200000000D+00
C(10, 2)      0.5000000000D+00
C( 1, 3)      0.3200000000D+00
C( 2, 3)      0.3400000000D+00
C( 3, 3)      0.4000000000D+00
C( 4, 3)      0.4000000000D+00
C( 5, 3)      0.4400000000D+00
C( 6, 3)      0.4000000000D+00
C( 7, 3)      0.4000000000D+00
C( 8, 3)      0.4000000000D+00
C( 9, 3)      0.4000000000D+00
C(10, 3)      0.4000000000D+00
C( 1, 4)      0.1800000000D+00
C( 2, 4)      0.2000000000D+00
C( 3, 4)      0.2200000000D+00
C( 4, 4)      0.2200000000D+00
C( 5, 4)      0.2400000000D+00
C( 6, 4)      0.2000000000D+00
C( 7, 4)      0.2200000000D+00
C( 8, 4)      0.2200000000D+00
C( 9, 4)      0.2200000000D+00
C(10, 4)      0.2200000000D+00
C( 1, 5)      0.0000000000D+00
C( 2, 5)      0.0000000000D+00
C( 3, 5)      0.0000000000D+00
C( 4, 5)      0.0000000000D+00
C( 5, 5)      0.0000000000D+00
C( 6, 5)      0.0000000000D+00
C( 7, 5)      0.0000000000D+00
C( 8, 5)      0.0000000000D+00
C( 9, 5)      0.0000000000D+00
C(10, 5)      0.0000000000D+00


*******************************
**      COEFFICIENT Cm       **
*******************************

Number of coefficient components          2


**********> Data for coefficient component #1

Order of derivation                          0

Number of table variables                    2

Table variable #1                            5 = Mach

Number of entries for table variable #1      10

                              Entry  1      0.7000000000D+00
                              Entry  2      0.9000000000D+00
                              Entry  3      0.1200000000D+01
                              Entry  4      0.1350000000D+01
                              Entry  5      0.2000000000D+01
                              Entry  6      0.3400000000D+01
                              Entry  7      0.4000000000D+01
                              Entry  8      0.6000000000D+01
                              Entry  9      0.8000000000D+01
                              Entry 10      0.1000000000D+02

Table variable #2                            3 = atot

Number of entries for table variable #2      5

                              Entry  1      0.1400000000D+03
                              Entry  2      0.1500000000D+03
                              Entry  3      0.1600000000D+03
                              Entry  4      0.1700000000D+03
                              Entry  5      0.1800000000D+03

Function values for coefficient component

                              C( 1, 1)      0.8000000000D-01
                              C( 2, 1)      0.3000000000D-01
                              C( 3, 1)     -0.4000000000D-01
                              C( 4, 1)     -0.6000000000D-01
                              C( 5, 1)     -0.7000000000D-01
                              C( 6, 1)     -0.5000000000D-01
                              C( 7, 1)     -0.4000000000D-01
                              C( 8, 1)     -0.2000000000D-01
                              C( 9, 1)     -0.4000000000D-01
                              C(10, 1)     -0.5000000000D-01
                              C( 1, 2)      0.4000000000D-01
                              C( 2, 2)      0.2000000000D-01
                              C( 3, 2)      0.0000000000D+00
```

```
                    C( 4, 2)     0.0000000000D+00
                    C( 5, 2)    -0.2000000000D-01
                    C( 6, 2)    -0.2000000000D-01
                    C( 7, 2)    -0.2000000000D-01
                    C( 8, 2)     0.0000000000D+00
                    C( 9, 2)    -0.2000000000D-01
                    C(10, 2)    -0.3000000000D-01
                    C( 1, 3)     0.2000000000D-01
                    C( 2, 3)     0.2000000000D-01
                    C( 3, 3)     0.1000000000D-01
                    C( 4, 3)     0.2000000000D-01
                    C( 5, 3)     0.0000000000D+00
                    C( 6, 3)     0.0000000000D+00
                    C( 7, 3)     0.5000000000D-02
                    C( 8, 3)     0.0000000000D+00
                    C( 9, 3)    -0.1000000000D-01
                    C(10, 3)    -0.1000000000D-01
                    C( 1, 4)     0.4000000000D-01
                    C( 2, 4)     0.2000000000D-01
                    C( 3, 4)     0.1000000000D-01
                    C( 4, 4)     0.2000000000D-01
                    C( 5, 4)     0.0000000000D+00
                    C( 6, 4)     0.0000000000D+00
                    C( 7, 4)     0.0000000000D+00
                    C( 8, 4)     0.5000000000D-02
                    C( 9, 4)     0.0000000000D+00
                    C(10, 4)     0.5000000000D-02
                    C( 1, 5)     0.1000000000D-01
                    C( 2, 5)     0.1000000000D-01
                    C( 3, 5)     0.1000000000D-01
                    C( 4, 5)     0.1000000000D-01
                    C( 5, 5)     0.0000000000D+00
                    C( 6, 5)     0.0000000000D+00
                    C( 7, 5)     0.0000000000D+00
                    C( 8, 5)     0.0000000000D+00
                    C( 9, 5)    -0.4000000000D-01
                    C(10, 5)    -0.2000000000D-01

**********> Data for coefficient component #2

Order of derivation                  1

Derivation variable #1               6 = omy_norm

Number of table variables            2

Table variable #1                                   5 = Mach

Number of entries for table variable #1             5

                              Entry  1      0.2500000000D+01
                              Entry  2      0.3000000000D+01
                              Entry  3      0.4000000000D+01
                              Entry  4      0.6000000000D+01
                              Entry  5      0.1020000000D+02

Table variable #2                                   3 = atot

Number of entries for table variable #2             5

                              Entry  1      0.1400000000D+03
                              Entry  2      0.1500000000D+03
                              Entry  3      0.1600000000D+03
                              Entry  4      0.1700000000D+03
                              Entry  5      0.1800000000D+03

Function values for coefficient component

                              C( 1, 1)     -0.4000000000D+00
                              C( 2, 1)     -0.4000000000D+00
                              C( 3, 1)     -0.4000000000D+00
                              C( 4, 1)     -0.4000000000D+00
                              C( 5, 1)     -0.4000000000D+00
                              C( 1, 2)     -0.6000000000D+00
                              C( 2, 2)     -0.6000000000D+00
                              C( 3, 2)     -0.6000000000D+00
                              C( 4, 2)     -0.1600000000D+01
                              C( 5, 2)     -0.4000000000D+00
                              C( 1, 3)     -0.6000000000D+00
                              C( 2, 3)     -0.6000000000D+00
                              C( 3, 3)     -0.6000000000D+00
                              C( 4, 3)     -0.8000000000D+00
                              C( 5, 3)     -0.4000000000D+00
                              C( 1, 4)     -0.6000000000D+00
                              C( 2, 4)     -0.6000000000D+00
                              C( 3, 4)     -0.6000000000D+00
                              C( 4, 4)     -0.6000000000D+00
                              C( 5, 4)     -0.4000000000D+00
                              C( 1, 5)     -0.6000000000D+00
                              C( 2, 5)     -0.6000000000D+00
                              C( 3, 5)     -0.6000000000D+00
                              C( 4, 5)     -0.6000000000D+00
```

```
                              C( 5, 5)       -0.4000000000D+00

******************************
**    PARACHUTE SYSTEMS     **
******************************

Number of parachute systems                   0

******************************
** EXTERNAL FORCES/MOMENTS  **
******************************

**********> Configuration #0

Spin vanes selected                           N

******************************
**    PROPULSION SYSTEM     **
******************************

Deorbit-burn engine present                   N

******************************
**       ENVIRONMENT        **
******************************

Central body                                  1 = Earth

Gravitational model                           1 = Central field

Atmosphere model                              3 = CIRA86 (tab)

******************************
**      PERTURBATIONS       **
******************************

Percentage of density deviation                0.0000000000D+00

******************************
**        WIND MODEL        **
******************************

No wind model defined                                   0

******************************
**      INITIAL STATE       **
******************************

Choice of initial position and velocity                 1 = spherical

**********> Position

Height h (km)                                            0.2201360000D+03
Longitude tau (deg)                                      0.2139590000D+03
Latitude delta (deg)                                     0.4311800000D+01

**********> Velocity

Relative velocity V (m/s)                                0.1100000000D+05
Flight-path angle gamma (deg)                           -0.9563000000D+01
Heading chi (deg)                                        0.5255600000D+02

**********> Attitude

Angle of attack alpha (deg)                              0.1569990000D+03
Angle of sideslip beta (deg)                            -0.8213830000D-03
Bank angle sigma (deg)                                   0.1100030000D+03

**********> Angular rates

Angular roll rate omega_x (deg/s)                        0.1337782299D-01
Angular pitch rate omega_y (deg/s)                       0.1565778000D-01
Angular yaw rate omega_z (deg/s)                         0.4344631302D-01

******************************
**  CONFIGURATION CHANGES   **
******************************

Number of configuration changes                          0

******************************
**  PROPULSION OPERATIONS   **
******************************
```

```
Deorbit-burn manoeuvre selected                  N

******************************
**       INTEGRATION        **
******************************

Integration method                               2 = V.S. 7(8) RKF

The maximum integration step size (s)             0.1000000000D+01

The quicklook data filing rate (s)                0.2000000000D+01

The plot data filing rate (s)                     0.1000000000D+01

******************************
**        TOLERANCES        **
******************************

Tolerance for velocity (m/s)                      0.1000000000D+00

Tolerance for flightpath angle (deg)              0.5729577951D-02

Tolerance for heading (deg)                       0.5729577951D-02

Tolerance for position (m)                        0.1000000000D+00

Tolerance for position angles (deg)               0.5729577951D-02

Tolerance for angular rates (deg/s)               0.5729577951D-04

Tolerance for attitude (deg)                      0.5729577951D-02

******************************
**      STOP CRITERIA       **
******************************

Stop by flight time                              Y
Elapsed flight time in sec                        0.2750000000D+03
Stop by height                                   N
Stop by velocity                                 N
Stop by Mach number                              N
Stop by dynamic pressure                         N
```

Report LR-726

Appendix B - Example of quicklook data

July 1993

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TU Delft
Delft University of Technology

Faculty of Aerospace Engineering

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On this and the following two pages, an example of the quicklook data, as they appear in the quicklook datafile, is given. To this file, the used input dataset is written as well (not included here). The majority of the quicklook data is also written to the screen during the simulation.

```
************************************************
************************************************
**                                            **
**                                            **
**          Q U I C K L O O K   D A T A       **
**                                            **
**                                            **
************************************************
************************************************
```

```
Simulation time (sec)
    0.000000E+00
Geodetic longitude, latitude (deg), height (km)
     213.959         4.31180         220.136
Flow velocity (m/s), path angle, heading (deg)
     11000.0        -9.56300         52.5560
V_air (m/s), gamma_air (deg), chi_air (deg)
     11000.0         0.000000E+00    0.000000E+00
Vehicle angular velocity (deg/sec)
    0.133778E-01     0.156578E-01    0.434463E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     156.999        -0.821383E-03    0.000000E+00    0.000000E+00
Bank angle, Alpha_tot_air (deg)
     110.003         156.999
Lift, Drag and Side force (N) (Vair)
    0.285097E-01     0.904319E-01    0.962815E-06
Lift, Drag and Side force (N) (R-frame)
    0.285097E-01     0.904319E-01    0.962815E-06
Aerodynamic moments in body frame (Nm)
    0.457035E-07     0.630064E-02    0.705554E-06
Dynamic press.(N/m**2), Mach, Reynolds
    0.552501E-02     17.5108         0.929514E-01
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
    0.269621E-04     0.913225E-10    1023.06
roll (deg), pitch (deg), yaw (deg)
    -67.9452         1.20942        -105.898
Par.drag (N), added mass (kg)
    0.000000E+00     0.000000E+00
```

```
Simulation time (sec)
     2.00000
Geodetic longitude, latitude (deg), height (km)
     214.109         4.42638         216.501
Flow velocity (m/s), path angle, heading (deg)
     11003.0        -9.45503         52.5704
V_air (m/s), gamma_air (deg), chi_air (deg)
     11003.0         0.000000E+00    0.000000E+00
Vehicle angular velocity (deg/sec)
    0.133777E-01     0.158684E-01    0.434387E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     157.002         0.722503E-02    0.160730E-02    0.400830E-02
Bank angle, Alpha_tot_air (deg)
     109.999         157.002
Lift, Drag and Side force (N) (Vair)
    0.324565E-01     0.102964       -0.964299E-05
Lift, Drag and Side force (N) (R-frame)
    0.324565E-01     0.102964       -0.964299E-05
Aerodynamic moments in body frame (Nm)
   -0.457688E-06     0.717038E-02   -0.706597E-05
Dynamic press.(N/m**2), Mach, Reynolds
    0.629034E-02     17.6392         0.106733
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
    0.302332E-04     0.103916E-09    1008.15
roll (deg), pitch (deg), yaw (deg)
    -67.9854         1.11845        -105.884
Par.drag (N), added mass (kg)
    0.000000E+00     0.000000E+00
```

```
Simulation time (sec)
     4.00000
Geodetic longitude, latitude (deg), height (km)
     214.259         4.54105         212.906
Flow velocity (m/s), path angle, heading (deg)
     11006.0        -9.34695         52.5852
V_air (m/s), gamma_air (deg), chi_air (deg)
     11006.0         0.000000E+00    0.000000E+00
```

```
Vehicle angular velocity (deg/sec)
     0.133776E-01      0.161048E-01      0.434307E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
      157.006          0.151523E-01      0.182430E-02      0.394877E-02
Bank angle, Alpha_tot_air (deg)
      109.995           157.006
Lift, Drag and Side force (N) (Vair)
     0.368854E-01      0.117030         -0.229868E-04
Lift, Drag and Side force (N) (R-frame)
     0.368854E-01      0.117030         -0.229868E-04
Aerodynamic moments in body frame (Nm)
    -0.109089E-05      0.814555E-02     -0.168425E-04
Dynamic press.(N/m**2), Mach, Reynolds
     0.714927E-02      17.7477           0.122174
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
     0.339224E-04      0.118041E-09       995.811
roll (deg), pitch (deg), yaw (deg)
     -68.0256           1.02744          -105.870
Par.drag (N), added mass (kg)
     0.000000E+00      0.000000E+00
________________________________________

Simulation time (sec)
      6.00000
Geodetic longitude, latitude (deg), height (km)
      214.410           4.65581          209.351
Flow velocity (m/s), path angle, heading (deg)
      11008.9          -9.23877           52.6003
V_air (m/s), gamma_air (deg), chi_air (deg)
      11008.9          0.000000E+00      0.000000E+00
Vehicle angular velocity (deg/sec)
     0.133773E-01      0.163708E-01      0.434223E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
      157.010          0.229606E-01      0.207029E-02      0.388927E-02
Bank angle, Alpha_tot_air (deg)
      109.991           157.010
Lift, Drag and Side force (N) (Vair)
     0.418120E-01      0.132682         -0.394924E-04
Lift, Drag and Side force (N) (R-frame)
     0.418120E-01      0.132682         -0.394924E-04
Aerodynamic moments in body frame (Nm)
    -0.187394E-05      0.922933E-02     -0.289341E-04
Dynamic press.(N/m**2), Mach, Reynolds
     0.810493E-02      17.8324           0.139270
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
     0.380691E-04      0.133748E-09       986.298
roll (deg), pitch (deg), yaw (deg)
     -68.0659           0.936407         -105.856
Par.drag (N), added mass (kg)
     0.000000E+00      0.000000E+00
________________________________________

Simulation time (sec)
      8.00000
Geodetic longitude, latitude (deg), height (km)
      214.561           4.77066          205.836
Flow velocity (m/s), path angle, heading (deg)
      11011.9          -9.13048           52.6157
V_air (m/s), gamma_air (deg), chi_air (deg)
      11011.9          0.000000E+00      0.000000E+00
Vehicle angular velocity (deg/sec)
     0.133768E-01      0.166707E-01      0.434132E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
      157.014          0.306499E-01      0.234904E-02      0.382973E-02
Bank angle, Alpha_tot_air (deg)
      109.987           157.014
Lift, Drag and Side force (N) (Vair)
     0.475351E-01      0.150870         -0.599470E-04
Lift, Drag and Side force (N) (R-frame)
     0.475351E-01      0.150870         -0.599470E-04
Aerodynamic moments in body frame (Nm)
    -0.284406E-05      0.104872E-01     -0.439161E-04
Dynamic press.(N/m**2), Mach, Reynolds
     0.921527E-02      17.9419           0.159505
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
     0.427240E-04      0.151990E-09       974.046
roll (deg), pitch (deg), yaw (deg)
     -68.1063           0.845374         -105.842
Par.drag (N), added mass (kg)
     0.000000E+00      0.000000E+00
________________________________________

Simulation time (sec)
      10.0000
Geodetic longitude, latitude (deg), height (km)
      214.712           4.88560          202.361
Flow velocity (m/s), path angle, heading (deg)
      11014.8          -9.02208           52.6314
V_air (m/s), gamma_air (deg), chi_air (deg)
      11014.8          0.000000E+00      0.000000E+00
Vehicle angular velocity (deg/sec)
     0.133761E-01      0.170087E-01      0.434035E-01
```

```
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     157.019         0.382198E-01       0.266488E-02       0.377003E-02
Bank angle, Alpha_tot_air (deg)
     109.983         157.019
Lift, Drag and Side force (N) (Vair)
    0.541790E-01     0.171992          -0.852222E-04
Lift, Drag and Side force (N) (R-frame)
    0.541790E-01     0.171992          -0.852222E-04
Aerodynamic moments in body frame (Nm)
   -0.404245E-05     0.119459E-01      -0.624259E-04
Dynamic press.(N/m**2), Mach, Reynolds
    0.105045E-01     18.0733            0.183429
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
    0.479502E-04     0.173164E-09       959.525
roll (deg), pitch (deg), yaw (deg)
    -68.1468         0.754367          -105.828
Par.drag (N), added mass (kg)
    0.000000E+00     0.000000E+00
```

```
Simulation time (sec)
     12.0000
Geodetic longitude, latitude (deg), height (km)
     214.863         5.00061            198.927
Flow velocity (m/s), path angle, heading (deg)
     11017.6        -8.91359            52.6475
V_air (m/s), gamma_air (deg), chi_air (deg)
     11017.6         0.000000E+00       0.000000E+00
Vehicle angular velocity (deg/sec)
    0.133752E-01     0.173904E-01       0.433929E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     157.025         0.456699E-01       0.302348E-02       0.371004E-02
Bank angle, Alpha_tot_air (deg)
     109.979         157.025
Lift, Drag and Side force (N) (Vair)
    0.615623E-01     0.195475          -0.115745E-03
Lift, Drag and Side force (N) (R-frame)
    0.615623E-01     0.195475          -0.115745E-03
Aerodynamic moments in body frame (Nm)
   -0.548912E-05     0.135648E-01      -0.847743E-04
Dynamic press.(N/m**2), Mach, Reynolds
    0.119377E-01     18.1767            0.209870
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
    0.538348E-04     0.196687E-09       948.444
roll (deg), pitch (deg), yaw (deg)
    -68.1874         0.663416          -105.815
Par.drag (N), added mass (kg)
    0.000000E+00     0.000000E+00
```

```
Simulation time (sec)
     14.0000
Geodetic longitude, latitude (deg), height (km)
     215.014         5.11571            195.533
Flow velocity (m/s), path angle, heading (deg)
     11020.4        -8.80499            52.6640
V_air (m/s), gamma_air (deg), chi_air (deg)
     11020.4         0.000000E+00       0.000000E+00
Vehicle angular velocity (deg/sec)
    0.133740E-01     0.178225E-01       0.433812E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     157.032         0.529994E-01       0.343082E-02       0.364959E-02
Bank angle, Alpha_tot_air (deg)
     109.976         157.032
Lift, Drag and Side force (N) (Vair)
    0.699606E-01     0.222200          -0.152694E-03
Lift, Drag and Side force (N) (R-frame)
    0.699606E-01     0.222200          -0.152694E-03
Aerodynamic moments in body frame (Nm)
   -0.723968E-05     0.154036E-01      -0.111822E-03
Dynamic press.(N/m**2), Mach, Reynolds
    0.135683E-01     18.2789            0.240131
Atm. press. (N/m**2), Dens. (kg/m**3), Temp. (K)
    0.604634E-04     0.223439E-09       937.687
roll (deg), pitch (deg), yaw (deg)
    -68.2280         0.572554          -105.802
Par.drag (N), added mass (kg)
    0.000000E+00     0.000000E+00
```

```
Simulation time (sec)
     16.0000
Geodetic longitude, latitude (deg), height (km)
     215.166         5.23089            192.179
Flow velocity (m/s), path angle, heading (deg)
     11023.2        -8.69629            52.6807
V_air (m/s), gamma_air (deg), chi_air (deg)
     11023.2         0.000000E+00       0.000000E+00
Vehicle angular velocity (deg/sec)
    0.133724E-01     0.183114E-01       0.433684E-01
Alpha, Beta (deg), Alpha_dot, Beta_dot (deg/sec)
     157.039         0.602070E-01       0.389306E-02       0.358851E-02
```

934464