R. Schriger 6-23-65

N. D. Wells NDW-65-60

Contract AF33(600)-10317, Space Flight Simulator, Item 9(1)

Attached is a review copy of the T-27 Technical Documentary Report which may be forwarded to ASD for their examination and approval as required by AFSCM5-1, Paragraph 6. In your letter of transmittal please advise that the layout of the final TDR will be altered to start Section VI on a right-hand page, and also request assignment of a dash number for the last part of the overall TDR number.

By copy of this memo, Messers Hart and Wilson are requested to examine a copy of the TDR and forward pertinent comments to the undersigned.

NDW

NDW:bb
Attachment

cc: G. W. Hart (with attachment)
F. K. Kennedy
R. M. Wilson (with attachment) ✓ PROG ENGR
GEORGE HART PROG MGR

ASD-TDR-65- ?

John J Lach

Review Copy of

A THEORETICAL ANALYSIS AND DESCRIPTION OF MAJOR ELEMENTS OF THE T-27 SPACE FLIGHT SIMULATOR

Technical Documentary Report No. ASD-TDR-65-?
June 1965

Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

(Prepared under Contract AF33(600)-10317
by Link Group - Systems Division,
General Precision, Inc., Binghamton, N. Y.)

FOREWORD

This report covers six areas of significant advancement in Space Flight Simulation which culminated in the T-27 Simulator built and installed by Link Group, General Precision, Inc., at the Aerospace Research Pilot's School, Edwards Air Force Base, California.

These areas are:

1. Hybrid computer system generation and associated time delays.
2. Simulation program initialization capability.
3. Star field computer program mechanization.
4. Rendezvous and docking visual generation system.
5. Infinity Image Visual System, star field visual generation, and occulting system.
6. Simulator motion system.

This report has been prepared to meet the requirement of Item 9 (1) on Contract AF33(657)10317 and is in a form consistent with AFSCM Manual No. 5-1 dated 1 November 1961.

ABSTRACT

The most unique features of the T-27 Space Flight Simulator, which was placed in service on 17 February 1965 at Edwards AF Base, are described herein.

Simulation of complex and lengthy space missions is accomplished by using a hybrid computer installation consisting of a Link Mark II high speed, high capacity digital computer and an Electronic Associates, Inc. PACE 2$\underset{3}{\mathrm{B}}$1R analog computer with necessary input and output peripheral equipment.

The digital computer, in addition to solving at high speed and at high accuracy the equations of motion, visual guidance, and motion, provides the high memory capacity necessary for the wide variety of initial conditions required of this simulator. The analog computer solves aerodynamic moments, body accelerations and rates of the vehicle, and simulates the adaptive autopilot on reentry.

Initialization capability for 32 different pre-established initial conditions is accomplished utilizing the Data Preselect Band of the Mark II computer. Another group of core locations can be loaded with another initial condition which is variable and selectable by the instructor/operator. Initialization in any of the 32 regular modes or the 33rd is simple and quick, once the appropriate 128 words of information have been loaded onto the Data Preselector band of the drum, as it entails only dialing in the number desired.

The evolution and present state of development of the infinity-image visual system referred to herein as the "out-the-window" visual system is described in some detail together with the Star Background Generator and Occulting Mask, which form an integral part of the system. Its capabilities include an authentic full color film input of such mission effects as blue sky and clouds, earth terrain and a TV input for operating views of another orbiting spacecraft, and a background of stars in the celestial sphere, all presented in appropriate relationship to the pilot's geographic position and attitude.

The T-27 motion system, which provides realistic motion cues fully integrated with the visual cues and other performance indications to the trainee in the crew station, is unique in spacecraft trainers in that it completes a system which permits the closest approach to true simulation developed to date. Its characteristics, performance, and safety features are described in the final section of this report.

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INTRODUCTION

The simulation facility referred to in this report was designed, built, and installed at the Aerospace Research Pilot's School, Edwards Air Force Base, to meet both the training and research objectives of this facility at the AF Flight Test Center.

The contract for its design and delivery was received 30 November 1962. The simulator was accepted by the AF (less the Mission Effects Projector) on 17 February 1965.

Link Group - Systems Division of General Precision, Inc. and its associated subcontractors - Farrand Optical Company, Inc. for the infinity image visual system, American Machine & Foundry for the motion system, Hughes Aircraft Company for the spacecraft attitude and thrust controllers and certain cockpit displays, and Electronic Associates Inc. for the analog computer - designed and delivered a simulator unique in many respects.

The flexibility and versatility of the facility to meet the dynamics characteristics of the school's training mission are particularly unique because of its:

1) Adaptability to simulate a wide variety of types of space vehicle missions, ranging from high lift over drag types to low lift over drag vehicles.

2) Visual system affording the most realistic out-the-window view of star field and another orbiting vehicle for rendezvous mission training, and provision for earth view from altitudes up to 1000 NM.

3) Motion system affording characteristics integrated with the visual cues and responsive to aerodynamic, crew, and booster functions.

4) Computer system capable of readily being programmed to handle any computational problem arising in the simulation of the wide variety of types of aerospace vehicles, subsystems, and missions contemplated as useful within its defined purpose.

In the sections of this report which follow, the most significant features of the design and operation of the T-27 Space Flight Simulator, now in use at Edwards Air Force Base, are described in some technical detail.

SECTION ONE

HYBRID COMPUTER OPERATION AND ASSOCIATED TIME DELAY

The Edwards hybrid computer consists of a Link Mark II digital computer and a Pace 231R analog computer with the necessary input and output peripheral equipment. Basically, those computations which require either considerable logic or drift free high accuracy are performed on the digital computer and the computational tasks requiring simulation of high frequency signals are performed on the analog computer. In determining a logical break point in the equations which were to be assigned to the two computers, other factors had to be considered. One of these was the number of signals which had to be transferred between analog and digital. The fewer of these there are, the more trouble free will be the operation. Also of prime consideration is the mission initialization problem. The analog computer has essentially no memory capacity and, if computations which require different initialization values are done in the analog computer, they must be stored in the digital computer and transferred to the analog at the proper time. Of course initial conditions are no problem for the digital computer because of its large memory capacity. It should be kept in mind that the T-27 Space Flight Simulator had to be capable of starting a mission at any of thirty-two different points which could be at launch, orbit, or re-entry.

The Pace computer was used to solve the aerodynamic moments, body accelerations, and rates of the vehicle, as well as the simulation of the adaptive autopilot on re-entry. All other equations of motion, visual, and guidance were solved in the digital computer.

It should be noted that the co-efficient terms are generated on the L.F.I. of the digital computer. The partials of the moments are formed and divided by the inertias. These partials are transferred to the analog computer where they are multiplied by rapidly changing variables, such as control surface deflection. All of the partials are added together to form the total acceleration. The equations were handled in this manner to keep the signal to noise ratio as large as possible. The inertias are normally fairly large numbers and so are many of the co-efficient terms under certain conditions, such as when dynamic pressure is high. By performing the division in the digital computer we have a signal which does not vary over such a large range of values and allows us to work in an area above the signal noise level for most maneuvering. For example the term $\frac{MD \times b_1}{I_{xx}\, Sa} = \frac{7040\, qcl_1}{I_{xx}}$: Some typical maximum values for re-entry might be as follows: $I_{xx} = 5130$ $q = 300$ $cl_1 = 0.0009$. The term becomes $\frac{7040 \times 300 \times 0.0009}{5130} =$ 0.37. While q and cl can vary over rather large ranges the final value that is transferred to the analog computer is a rather well-behaved number that can change from 0 to 0.37. This simplifies the scaling in the analog computer and also allows the multiplication of the portions of the number that are sometimes quite small to be carried out with high accuracy in the digital computer. The resultant is multiplied by the variable Sa in the analog computer. The Sa being the high frequency component of the term. Wherever possible this procedure was followed in getting information into the analog computer.

The computation of the vehicle body rates was carried out in the analog computer and transmitted to the digital computer via the A/D's. From the body rates the B-H frame body rates are computed and then the quaternians. The loop is closed through the euler angle indications and the pilot. The autopilot loop is closed entirely within the analog computer. Only the necessary switch controls and the D.C. voltages of the side arm controller are external. By doing this we avoid any time delays in the control system loop. The limit cycle frequencies of the autopilot are in the order of from two to five cycles. By keeping the entire problem in the analog computer, no degradation of the autopilot simulation occurs.

The translation equations were done in the digital computer to take advantage of the high accuracy that could be obtained from the 23 bit words. In some cases this computation was done in double precision giving us an accuracy of 46 bits. This accuracy is quite important in locating two orbiting vehicles within a few feet of each other for rendezvous maneuvers.

Problems inherent in a large real time simulation facility and especially in a hybrid computer installation are noise and system time delays due to the transfer of information from one computer to the other. Measurements were taken of the closed loop response between the analog and digital computer with the necessary interface and conversion equipment. A sine wave generated in the analog computer was fed to the A/D converter which was read 40 times per second by the digital computer. The signal at the A/D was transferred via the arithmetic unit to the D/A. The output wave form from the digital computer as well as the input were recorded on a time history recorder and compared for amplitude and phase shift. The closed loop response time was measured at 125 milliseconds. The phase shift is less than 90 degrees for frequencies less than one cycle. At five cycles the phase shift is approximately 180 degrees. Although the time delay does not vary with frequency, the amplitude is affected by frequency. At one cycle per second the amplitude loss is approximately 5% and at 5 cycles/sec the amplitude is less than 40%.

Areas were encountered in which phase shift became a problem. This was in the moment terms which were multiplied by alpha and beta. The method of computing these two terms made it expedient to compute them digitally. These terms, however, can have reasonably high frequency components and the delays caused by getting out of the digital computer to the analog did cause some trouble. If we assume that the computer time logs a can be expressed in the form of $\frac{1}{\tau_1 S+1}$. Then we can create within the computer a term $(\beta + K\dot{\beta})$ which is $\beta(1+\tau_1 S)$. Our output voltage to the analog computer then becomes $\beta\frac{(\tau_1 S + 1)}{(\tau_1 S + 1)} = \beta$. In practice this worked out very well for the frequencies of interest. Phase shifts could be compensated for up to approximately 5 cycles. However, at the higher frequencies the amplitude loss was over-compensated. A similiar method can be used to reduce noise when transferring information from the analog to the digital computer. If we place a lag network of 1 megohm and 1 M.F.D. at the input to the computer, and if the input impedance of the A/D converter can be considered infinite, then the transfer function of the network is again $\frac{1}{(\tau_1 S + 1)}$. If we assume that roll rate (pb) is the quantity of interest then we can create in the analog computer the term $(pb + \dot{p}b) = pb(1 + \tau_1 s)$. The input to the computer then becomes -

$$pb\frac{(\tau_1 S + 1)}{(\tau_1 S + 1)} = pb$$

In this case we get considerable noise attenuation without introducing any phase shift. It is of course possible to introduce a lead or a lag by the same method.

Another area of great importance in programming the digital computer is the order in which the equations are computed. They should be arranged in a logical fashion so that the (n + 1) values are not being used for parts of the computation. The critical L.F.I. functions should be generated on a band that is read after the flight equations. The coefficient equations in which these are used in the determination of forces and moments should be done at the very beginning of the flight equations. This insures that all forces and moments have updated values and that all flight equations are generated from updated values. The effects of a non-logical equation order can be rather drastic and can give results which are very confusing to the programmer.

SECTION TWO

INITIALIZATION CAPABILITY

Initialization of the Edwards simulator is controlled by the Mark II Digital Computer through the Data Preselect (DP) band. The Data Preselect of the Mark II is composed of one band (four quadrants) of information. Each quadrant contains eight initial conditions, each of which is made up of 128 words of information. This gives a total of 32 different initial conditions which can be accommodated in the computer without reloading any tapes. The initial conditions can be transferred to the 128 core memory locations by use of the reset switch on the instructor's console. The D.P. has priority over all other computer operations during the single drum revolution in which it transfers. The D.P. is loaded by means of a paper tape in the same manner as the general purpose portion of the computer. A typical breakdown of types of initial conditions might be as follows:

1. Eight different launch configurations
2. Eight different orbital configurations
3. Eight different rendezvous conditions
4. Eight different re-entry conditions

The number of each type of initial condition is arbitrary, however, a maximum of 32 can be accommodated in the computer at one time. Once the initial condition values have been established in the core memory, both manned vehicle and target vehicle are governed by the equations of motion and instructor or pilot controls.

Some typical quantities which are stored in the initial conditions are as follows:

1. Distance from the center of the earth of manned vehicle and target (r).
2. Rate of change of r.
3. Path heading of manned vehicle and target.
4. Latitude and longitude of manned vehicle and target.
5. Attitude of manned vehicle and target.
6. Boolean quantities required for different phases of the mission.
7. Launch booster information for the manned vehicle.
8. Launch guidance information for the manned vehicle.
9. Visual display initial condition parameters.

Other quantities may be added to the initial conditions when necessary. It should be remembered that the D.P. will initialize all 128 cores in the reset mode either with pertinent information or with zeros.

In addition to the 32 initial conditions on the data preselect band, there is another group of 128 core locations which can, by means of a switch on the instructor's console, be loaded with all pertinent information of a mission at some point in time when the switch is operated. At any time later, the problem may be returned to that point and restarted. This gives the computer another initial condition which is variable and selectable by the instructor. It allows the instructor to demonstrate an error, made by the student, or to obtain information for a permanent initial condition.

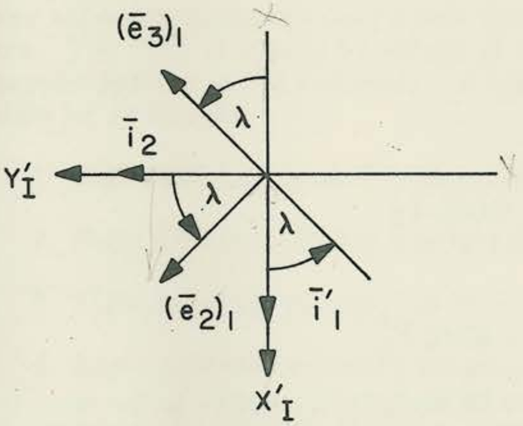
Initializing the digital computer in any of the 32 regular modes, or in the 33rd position, is relatively easy inasmuch as we have ample memory locations to do it and a stored source of information with which to work. To initialize the analog equipment in more than one mode becomes extremely difficult inasmuch, as it does not have this memory capacity. Fortunately, most of the pertinent information is contained in the digital computer. There is an exception to this rule. In re-entry, when the vehicle is in the atmosphere, it would be desirable to reset the vehicle to some particular point as far as attitude and autopilot configuration is concerned. Since the analog computer cannot handle this infinite number of possibilities, it becomes a difficult situation. One approach might be to transfer all pertinent information to the digital computer and hold it there until needed. This would entail the use of a rather large number of input - output locations. It is possible that the number of pieces of information could be minimized and still get reasonable correct results. Another method, and by far the simplest, would be to return the analog computer to a static condition with all body rates at zero and the autopilot in a stable condition. While this, in some respects, defeats the philosophy of initial conditions, it does allow the problem to be re-run. The criterion then becomes one of whether the student will get into the same situation again, not whether he can get out of it.

Preparing the cards, tapes, etc., to put initial conditions on the computer is a relatively simple matter. The only problem that occurs is the loading of the value with sufficient accuracy to obtain the desired results. It is usually somewhat more difficult to obtain the correct mathematical values for an initial condition. One approach is to set up the equations the computer will solve, or equations similar to them, and manually compute the points. In many cases this is not too difficult. An example of this type of initial condition would be the placing of the vehicle in a circular orbit. Other problems such as launching into a particular orbit are more difficult and are not so easily computed. The best approach to this type of initialization is to let the computer do the work. If reasonably good approximations of the values need are known, successive runs on the computer will allow the operator to determine the exact quantities required. It is also frequently feasible to fly the vehicle or vehicles through a desired situation and then read out the values from the computer. All three of these methods have been used for obtaining initial conditions on the Edwards Simulator.

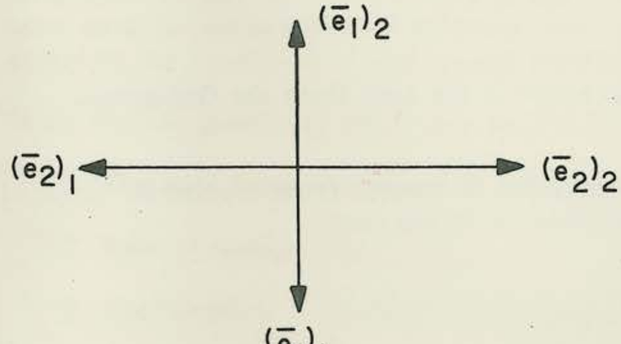
SECTION THREE

STAR FIELD COMPUTER PROGRAM MECHANIZATION

Suppose the inertial frame of reference (either rotating or fixed) were defined by fixing the X and Y inertial axes in the equatorial plane, and the Z inertial axes positive out of the south pole. Then let longitude be positive in the westward direction and latitude positive in the northern hemisphere. With these definitions and the conventional E-frame definition, the following I-frame to E-frame transformation results.

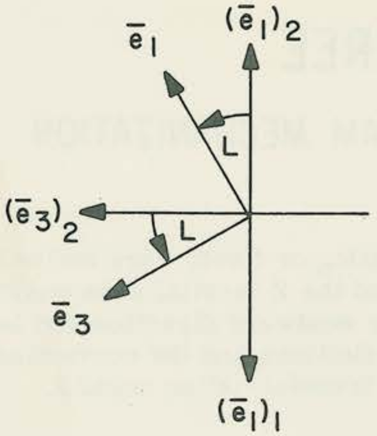


$$(\bar{e}_1)_1 = \bar{i}_3'$$
$$(\bar{e}_2)_1 = \mathrm{SIN}\,\lambda\,\bar{i}_1' + \mathrm{COS}\,\lambda\,\bar{i}_2'$$
$$(\bar{e}_3)_1 = -\mathrm{COS}\,\lambda\,\bar{i}_1' + \mathrm{SIN}\,\lambda\,\bar{i}_2'$$



$$(\bar{e}_1)_2 = -(\bar{e}_1)_1$$
$$(\bar{e}_2)_2 = -(\bar{e}_2)_1$$
$$(\bar{e}_3)_2 = (\bar{e}_3)_1$$

$$(\bar{e}_1)_2 = -\bar{i}_3'$$
$$(\bar{e}_2)_2 = -\mathrm{SIN}\,\lambda\,\bar{i}_1' - \mathrm{COS}\,\lambda\,\bar{i}_2'$$
$$(\bar{e}_3)_2 = -\mathrm{COS}\,\lambda\,\bar{i}_1' + \mathrm{SIN}\,\lambda\,\bar{i}_2'$$



$$\bar{e}_1 = \mathrm{COSL}\,(\bar{e}_1)_2 + \mathrm{SINL}(\bar{e}_3)_2$$

$$\bar{e}_2 = (\bar{e}_2)_2$$

$$\bar{e}_3 = -\mathrm{SINL}\,(\bar{e}_1)_2 + \mathrm{COSL}\,(\bar{e}_3)_2$$

$$\bar{e}_1 = -\mathrm{SINL}\ \mathrm{COS}\,\lambda\,\bar{i}_1' + \mathrm{SINL}\ \mathrm{SIN}\,\lambda\,\bar{i}_2' - \mathrm{COSL}\,\bar{i}_3' \tag{1}$$

$$\bar{e}_2 = -\mathrm{SIN}\,\lambda\,\bar{i}_1' - \mathrm{COS}\,\lambda\,\bar{i}_2' \tag{2}$$

$$\bar{e}_3 = -\mathrm{COSL}\ \mathrm{COS}\,\lambda\,\bar{i}_1' + \mathrm{COSL}\ \mathrm{SIN}\,\lambda\,\bar{i}_2' + \mathrm{SINL}\,\bar{i}_3' \tag{3}$$

The above transformation considers longitude to be measured positive to the west from some fixed reference line. Setting $\lambda = \lambda_R + \lambda_\gamma$

where:

λ_R = Spacecraft longitude measured positive to the east from the Greenwich Meridian.

λ_γ = The longitude of the Greenwich Meridian measured from a point 90° west of the vernal equinox and measured positive to the east.

Letting:

$$\mathrm{SIN}\,\Delta = \mathrm{SIN}\,(\lambda_R + \lambda_\gamma) = \mathrm{SIN}\,\lambda \tag{4}$$

$$\mathrm{COS}\,\Delta = \mathrm{COS}\,(\lambda_R + \lambda_\gamma) = \mathrm{COS}\,\lambda \tag{5}$$

The above transformation can be rewritten as:

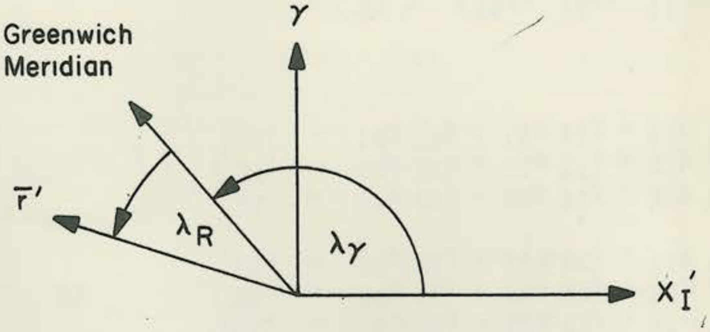
$$d_{11} = -\mathrm{SINL}\ \mathrm{COS}\,\Delta \tag{6}$$
$$d_{12} = \mathrm{SINL}\ \mathrm{SIN}\,\Delta \tag{7}$$
$$d_{13} = -\mathrm{COSL} \tag{8}$$

$$d_{21} = -\mathrm{SIN}\,\Delta \tag{9}$$
$$d_{22} = -\mathrm{COS}\,\Delta \tag{10}$$
$$d_{23} = 0 \tag{11}$$

$$d_{31} = -\mathrm{COSL}\ \mathrm{COS}\,\Delta \tag{12}$$
$$d_{32} = \mathrm{COSL}\ \mathrm{SIN}\,\Delta \tag{13}$$
$$d_{33} = \mathrm{SINL} \tag{14}$$

Where:

$\Delta = \lambda_R + \lambda_\gamma$
λ_R is measured from the Greenwich Meridian positive to the east
λ_γ is measured from the X_I' axis to the Greenwich Meridian positive to the east.



Where:

$\bar{r}$ is the vehicle's radius vector
$\bar{r}'$ is the vehicle's radius vector projected onto the equatorial plane

$\therefore \Delta$ Represents the inertial longitude of $\bar{r}$ with respect to X_I' measured positive to the east.

And

$$\mathrm{SIN}\,\Delta = \mathrm{SIN}\,\lambda_R\ \mathrm{COS}\,\lambda_\gamma + \mathrm{SIN}\,\lambda_\gamma\ \mathrm{COS}\,\lambda_R \tag{15}$$

$$\mathrm{COS}\,\Delta = \mathrm{COS}\,\lambda_R\ \mathrm{COS}\,\lambda_\gamma - \mathrm{SIN}\,\lambda_R\ \mathrm{SIN}\,\lambda_\gamma \tag{16}$$

The I-frame to E-frame matrix is called the D matrix.

$$\begin{pmatrix} \bar{e}_1 \\ \bar{e}_2 \\ \bar{e}_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{pmatrix} \begin{pmatrix} \bar{i}'_1 \\ \bar{i}'_2 \\ \bar{i}'_3 \end{pmatrix} \tag{37}$$

Utilizing the existing E-frame to B-frame matrix of the simulator:

$$\begin{pmatrix} \bar{i} \\ \bar{j} \\ \bar{k} \end{pmatrix} = \begin{pmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{pmatrix} \begin{pmatrix} \bar{e}_1 \\ \bar{e}_2 \\ \bar{e}_3 \end{pmatrix} \tag{38}$$

In order to form an I′-frame to B-frame matrix which is called the R matrix and arbitrarily denoting the elements as:

$$\begin{pmatrix} \bar{i} \\ \bar{j} \\ \bar{k} \end{pmatrix} = \begin{pmatrix} r_{13} & r_{23} & r_{33} \\ r_{12} & r_{22} & r_{32} \\ -r_{11} & -r_{21} & -r_{31} \end{pmatrix} \begin{pmatrix} \bar{i}'_1 \\ \bar{i}'_2 \\ \bar{i}'_3 \end{pmatrix} \tag{39}$$

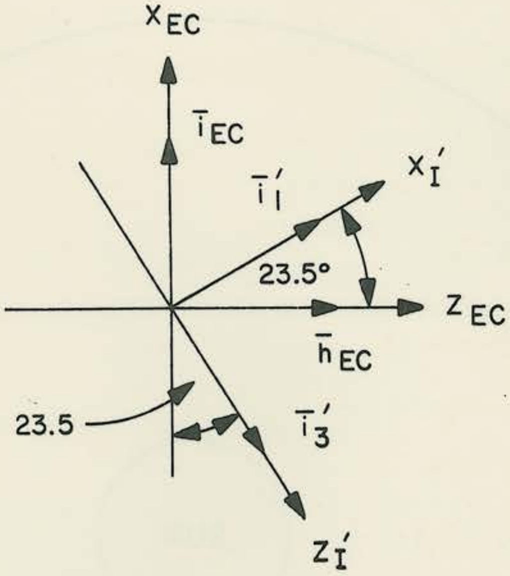
Where:

$$\left.\begin{array}{l} r_{13} = f_{11} d_{11} + f_{12} d_{21} + f_{13} d_{31} = i'_{11} \\ r_{23} = f_{11} d_{12} + f_{12} d_{22} + f_{13} d_{32} = i'_{12} \\ r_{33} = f_{11} d_{13} + f_{12} d_{23} + f_{13} d_{33} = i'_{13} \end{array}\right\} \begin{pmatrix} \bar{i} \\ \bar{j} \\ \bar{k} \end{pmatrix} = (i_{ij}) \begin{pmatrix} i'_1 \\ i'_2 \\ i'_3 \end{pmatrix} \qquad \begin{array}{r} (40) \\ (41) \\ (42) \end{array}$$

$$\left.\begin{array}{l} r_{12} = f_{21} d_{11} + f_{22} d_{21} + f_{23} d_{31} = r'_{21} \\ r_{22} = f_{21} d_{12} + f_{22} d_{22} + f_{23} d_{32} = r'_{22} \\ r_{32} = f_{21} d_{13} + f_{22} d_{23} + f_{23} d_{33} = r'_{23} \end{array}\right\} \qquad 11 \qquad \begin{array}{r} (43) \\ (44) \\ (45) \end{array}$$

$$\left.\begin{array}{l} -r_{11} = f_{31} d_{11} + f_{32} d_{21} + f_{33} d_{31} = r'_{31} \\ -r_{21} = f_{32} d_{12} + f_{32} d_{22} + f_{33} d_{32} = r'_{32} \\ -r_{31} = f_{31} d_{13} + f_{32} d_{23} + f_{33} d_{33} = r'_{33} \end{array}\right\} \qquad 11 \qquad \begin{array}{r} (46) \\ (47) \\ (48) \end{array}$$

If we now define an ecliptic frame of reference such that the X_{EC} - Y_{EC} frame of reference lies in the ecliptic plane with the Y_{EC} axis coincident with the Y_I' axis, the X_{EC} axis directed positively out the north ecliptic pole, and the Z_{EC} axis directed such that an orthogonal right handed triad is formed. The ecliptic frame differs from the inertial frame by a rotation of 23.5° about their common Y axis. This relationship is shown below:



$$\bar{i}_1' = \text{SIN } 23.5° \, \bar{i}_{EC} + \text{COS } 23.5° \, \bar{k}_{EC} \tag{49}$$

$$\bar{i}_2' = \bar{j}_{EC} \tag{50}$$

$$\bar{i}_3' = -\text{COS } 23.5° \, \bar{i}_{EC} + \text{SIN } 23.5° \, \bar{k}_{EC} \tag{51}$$

The ecliptic frame is also depicted in figure 3.1.

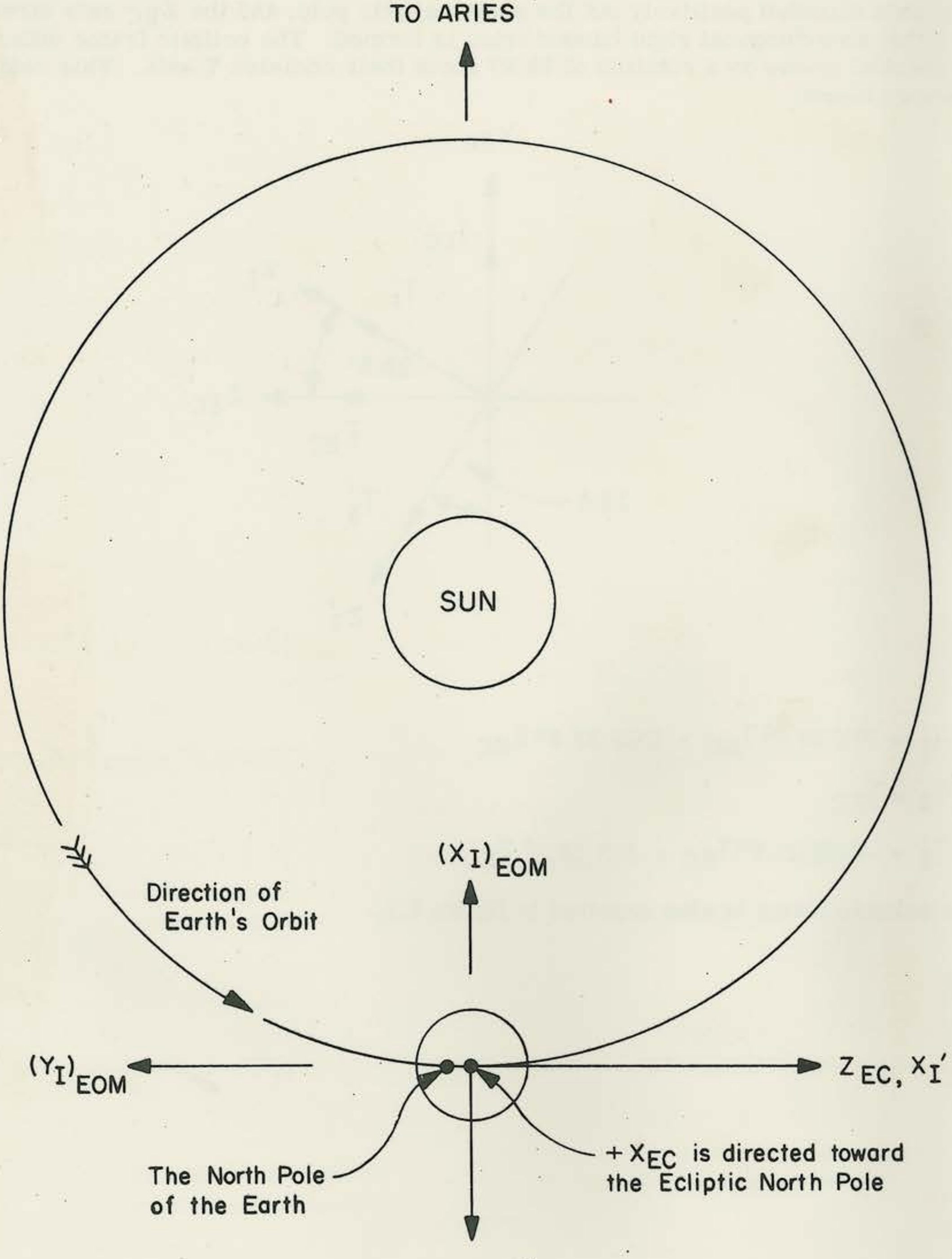


Figure 3.1 The Ecliptic Frame