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AERO-ASTRODYNAMICS CONSIDERATIONS FOR THE APOLLO TELESCOPE MCUNT

By Robert E. Lavender
Aero-Astrodynamics Laboratory

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ABSTRACT

This report presents the results of preliminary analyses which have been conducted by the Aero-Astrodynamics Laboratory relative to the Apollo Telescope Mount (ATM). The ATM is an experimental package consisting of a group of sensors in the visual, ultraviolet (UV), extreme ultraviolet (XUV), and X-ray spectral regions, and the necessary experimental support equipment to obtain scientific data by solar observations from earth orbit. The ATM package is considered to be hard-mounted to the Lunar Module (LM). Mission analysis, orbital aerodynamics, aerodynamic torque, orbital lifetime, dynamics and control are discussed. Preliminary mission timelines are included.

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Robert E. Lavender

TECHNICAL AND SCIENTIFIC STAFF
AERO-ASTRODYNAMICS LABORATORY

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DEFINITION OF SYMBOLS

Symbol	Definition
a	semi-major axis
a_o	attitude control gain
a_1	attitude rate control gain
A	reference area
C_A	axial force coefficient
C_D	drag force coefficient
C_N	normal force coefficient
E	eccentric anomaly
E_i	incident energy transported by molecules to a unit surface in unit time
E_r	energy transported by reflected molecules away from a unit surface in unit time
E_w	energy transported by reflected molecules away from a unit surface in unit time if molecules were re-emitted at the temperature of the surface
H	angular momentum of control moment gyro
I	moment of inertia
i	orbital inclination
m	molecule mass
M	aerodynamic moment
n	mean orbital angular velocity
N_i	number of molecules incident on a unit surface in unit time
q	dynamic pressure
r	circular orbit radius

DEFINITION OF SYMBOLS (Continued)

Symbol	Definition
R	gas constant
S	molecular speed ratio
T_i	temperature of incident molecules
T_r	temperature of reflected molecules
T_w	wall temperature
V_r	velocity of spacecraft relative to rotating atmosphere
x_{cp}	center-of-pressure location
x_{cg}	center-of-gravity location
α	angle of attack; also, thermal accommodation coefficient
ϵ	orbit eccentricity
ζ_c	control damping coefficient
θ	angle between velocity vector and body surface element
μ	gravitational constant for the earth, GM_e
ρ_m	atmospheric mass density
ω_c	control frequency
Ω_e	rotational rate of the earth's atmosphere

TECHNICAL MEMORANDUM X-53500

AERO-ASTRODYNAMICS CONSIDERATIONS FOR THE APOLLO TELESCOPE MOUNT

SUMMARY

Preliminary analyses have been conducted on the Apollo Telescope Mount (ATM) mission assuming the ATM to be hard-mounted on a Lunar Module (LM). The LM is assumed to be modified to accept the ATM package.

Mission analysis is discussed and several mission profiles are considered. Results are presented which show that the launch window for the second launch can be extended by the use of a phasing ellipse. Two preliminary timelines are included corresponding to docking the LM to the Command Service Module (CSM) every twelve hours or every seven days.

Results of orbital aerodynamics analyses are shown. The free-molecule flow drag and normal force coefficients and center of pressure location are shown as functions of angle of attack for both the LM alone and docked CSM-LM configurations. These results are used in subsequent analyses of aerodynamic torque disturbance and orbital lifetimes. Orbital lifetimes have been obtained for several modes of mission duration and orbital storage.

Dynamics and control are briefly discussed.

I. INTRODUCTION

The Apollo Telescope Mount (ATM) is an experimental package consisting of a group of sensors in the visual, ultraviolet (UV), extreme ultraviolet (XUV), and X-ray spectral regions, and the necessary experimental support equipment to obtain scientific data by solar observations from earth orbit. Initial NASA planning for the ATM experiments considered mounting the ATM package to the Apollo Service Module through a gimbal arrangement. More recently, consideration has been given to operation of the ATM experiments with the ATM package hard-mounted to the Lunar Module (LM) and the entire spacecraft aimed toward the sun by use of control moment gyros (CMG's).

The purpose of this report is to document the preliminary analyses which have been made by the Aero-Astrodynamics Laboratory relative to the LM-ATM mode of operation. It is intended that this report will supplement and support the Marshall Space Flight Center's project development plan for the ATM project. The preliminary analyses have been directed toward the initial ATM mission (ATM-A) considering a dual launch of AAS 211/212. Two additional missions (ATM-B, ATM-C) may follow on later flights.

The LM spacecraft used for the ATM mission consists of either an LM ascent stage and an LM descent stage which has been modified to accept the ATM experiments and experiment support equipment, or an LM ascent stage with an attached rack holding the experiments and experiment support equipment. Part of the support equipment is a series of control moment gyros for fine attitude control. Neither the ascent nor descent propulsion engines are present for the LM-ATM configuration but the LM reaction control system (RCS) remains and is used for momentum dump of the CMG's.

II. MISSION ANALYSIS

The pacing item of all missions is that of the instrument unit (IU). As long as the IU "milestones" are met, the launch can proceed with a predicted schedule. The first input to the development of the IU is the Mission Defining Document (MDD) about 15 months prior to launch. This is used to establish the basic logic for the flight computer, "size" the computer, scale the parameters, etc. The next input is that of the Final Mission Defining Document (FMDD) about eight months prior to launch. This was designed to be a fine tuning and update for the prescribed mission; however, major changes can be made at this time. The last programming input for the IU is five months prior to launch at which time minor changes (constants of the same magnitude) can be made. This time sequence is contract controlled, and any deviation from this timeline must be the result of a change board action.

To accomplish a program with the greatest degree of success requires that the mission be well defined and that mission objectives, test requirements, and constraints be known by about five months before the MDD due date (about 20 months prior to launch). This is necessary so that an acceptable flight profile can be established that will comply completely with the mission objectives and constraints. In the same time frame, propulsion and mass data (best available) are necessary to start the trajectory study.

Four months prior to the MDD due date, it is necessary to start the complete trajectory study based on best available data. This lead time is necessary as trajectory shaping must be done as well as satisfying the various mission constraints and requirements. This study can take up to eight weeks depending on the complexity and originality of the mission. Since other centers are involved, an interface must be established and close working relationship maintained such that all parties are in complete agreement and can "tie" their studies together. An output from this trajectory study is targeting parameters which are an input for the guidance equation study.

Three months prior to the MDD date, a study should be initiated to investigate all possible abort and alternate mission capabilities. With the Saturn IB, the study is limited to one engine out. The completion of this study is necessary two months before the MDD due date as it is necessary input for the guidance equation study.

Two months before the MDD due date, four studies should be started, two having a direct input to the MDD, and the other two relating to the completion of the abort and alternate mission study,as the basic information becomes available. First, the guidance equation study must be started as it has direct input to the IU. This study must include as much of the total mission logic as possible. This, then, allows the computer designers to establish how much computer space will be available for purposes other than guiding the flight. The study could last up to six weeks depending upon mission complexity. Second, the rigid body analysis must be started to see if the flight profile selected demands maneuvers beyond the structural capability of the vehicle. This also has a direct influence on the IU design. Third, with the completion of the trajectory study, it is possible to establish an experiment timeline. Fourth, at this same time, a complete study of lift-off and separation can be initiated. This will signify any recontact problems which could exist and the probability level lowered by retro maneuvers of spent stages if any problem is detected. Once the experiment timeline has been established, it is necessary to verify that the vehicle has the capability to perform these experiments. Therefore, it is necessary to determine what power sources are available and to what extent they can be used to fulfill the desired mission. Another study which logically follows the experiment timeline is that of the transmittal of accumulated data. This can be somewhat of a problem since the vehicle is in radio contact with a given station for a given time duration. A time priority base must be established for each receiving station such that collected data can be properly transmitted and received.

This completes the basic analysis which must be performed on any mission. The rest of the time is spent on refinement of data, the updating of studies, and simplification of methods used. The only unrelated study is the flexible body study which is initiated at the FMDD due date. This study includes bending dynamics and filter design check.

A typical data flow is presented in Figure 1. It should be noted that at launch minus three months the IU is to be delivered to KSC for final flight checkout. The timeline is referenced in months prior to launch.

The mission analysis for the initial ATM (ATM-A) considering the dual launch of AAS 211/212 is similar to that of the AS 207/208 mission in that both are dual launches and require a rendezvous of the Command Service Module (CSM) with an unmanned Lunar Module (LM). The two missions have basically the same launch vehicle powered flight profile so that much of the AS 207/208 studies can be applied to the initial ATM mission. One major difference is that the ATM mission is currently planned for a near-circular 200 n.m. orbit. This is to be accomplished with the use of the CSM after rendezvous at lower earth orbit.

Three mission profiles have been considered for the dual launch. The profiles are summarized in Figures 2 through 4. All three cases have considered that the CSM would be launched first (AAS 211), followed approximately 24 hours later by the launch of the unmanned LM payload with AAS 212. The first profile, Figure 2, considers the CSM is launched into a 120 n.m. circular orbit followed by launch of the LM into an ellipse with 80 n.m. perigee and variable apogee depending on launch time. After one or more orbits, the CSM transfers to the LM ellipse and docks. Table 1 shows the time to achieve rendezvous position as a function of the number of phasing orbits. The remaining docking time, considering a 7 1/2 hour S-IVB stabilization lifetime, is also shown. The LM off-load versus launch window data shows the decrease in payload weight required for increase in launch window time. After docking, the CSM circularizes into a 200 n.m. orbit using Service Propulsion System (SPS) burns.

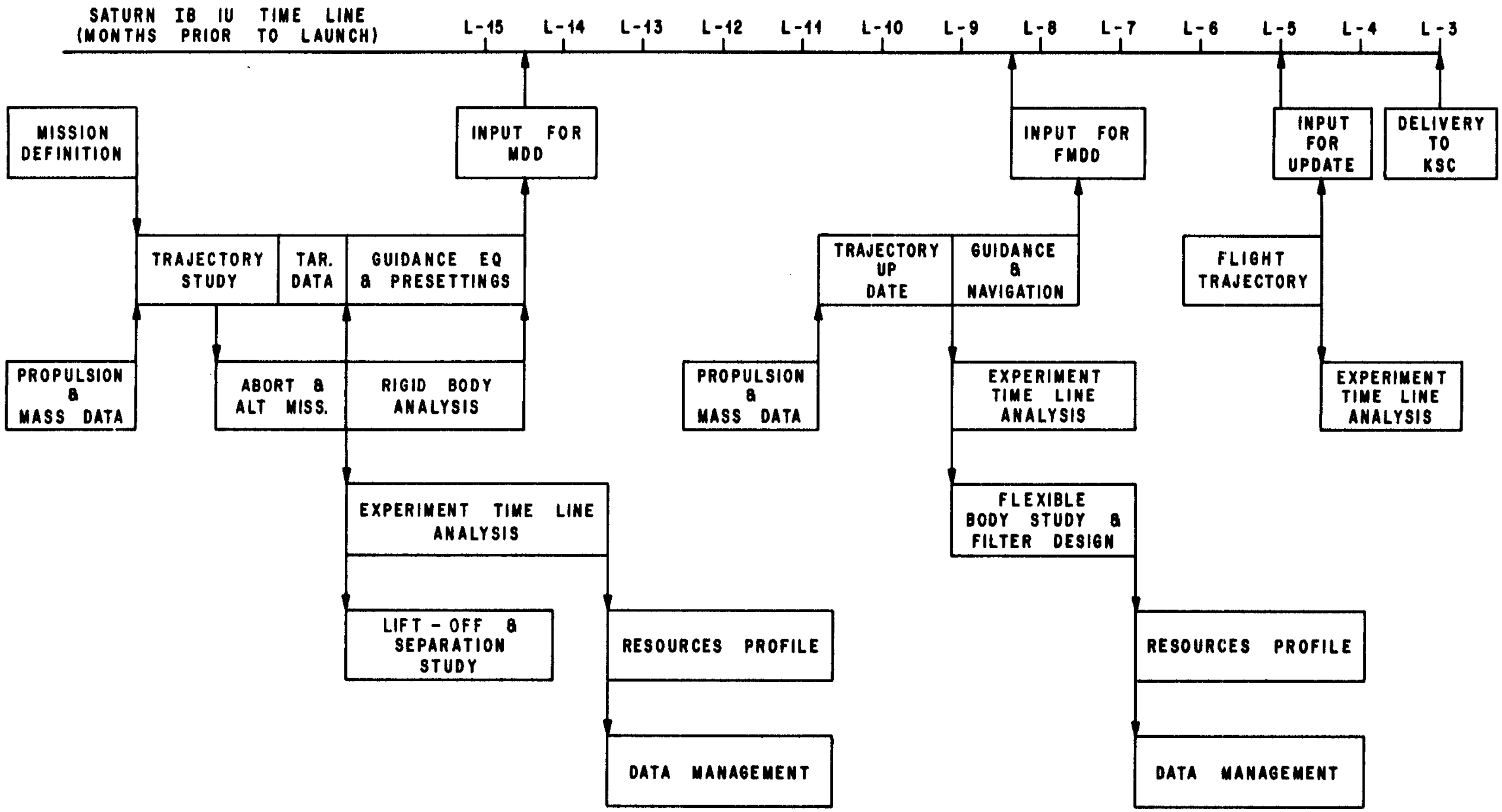


FIG. 1. MISSION ANALYSIS DATA FLOW TIMELINE

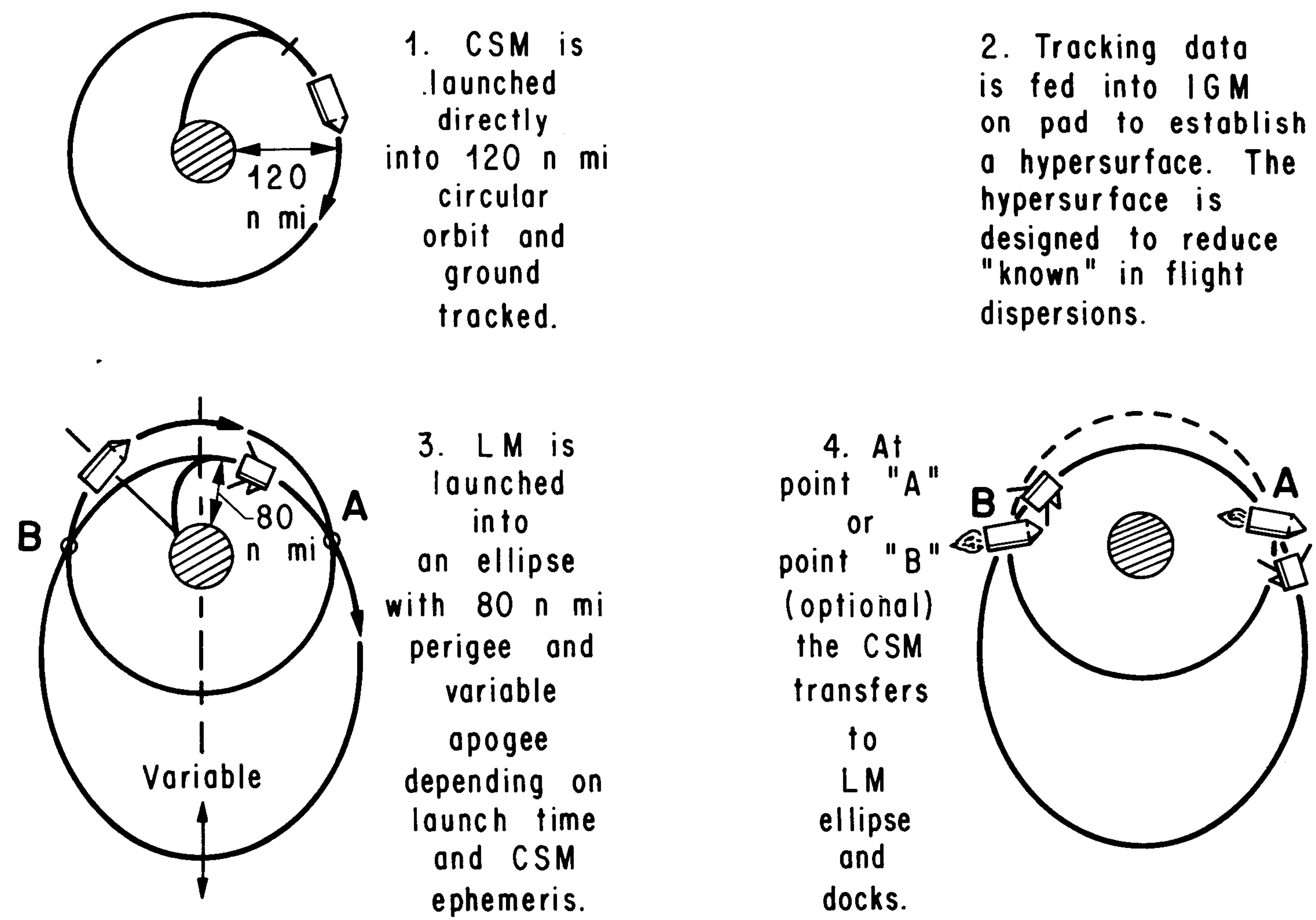


FIG. 2. MISSION PROFILE WITH LM PHASING ELLIPSE

TABLE 1

Summary Table for LM Phasing Ellipse

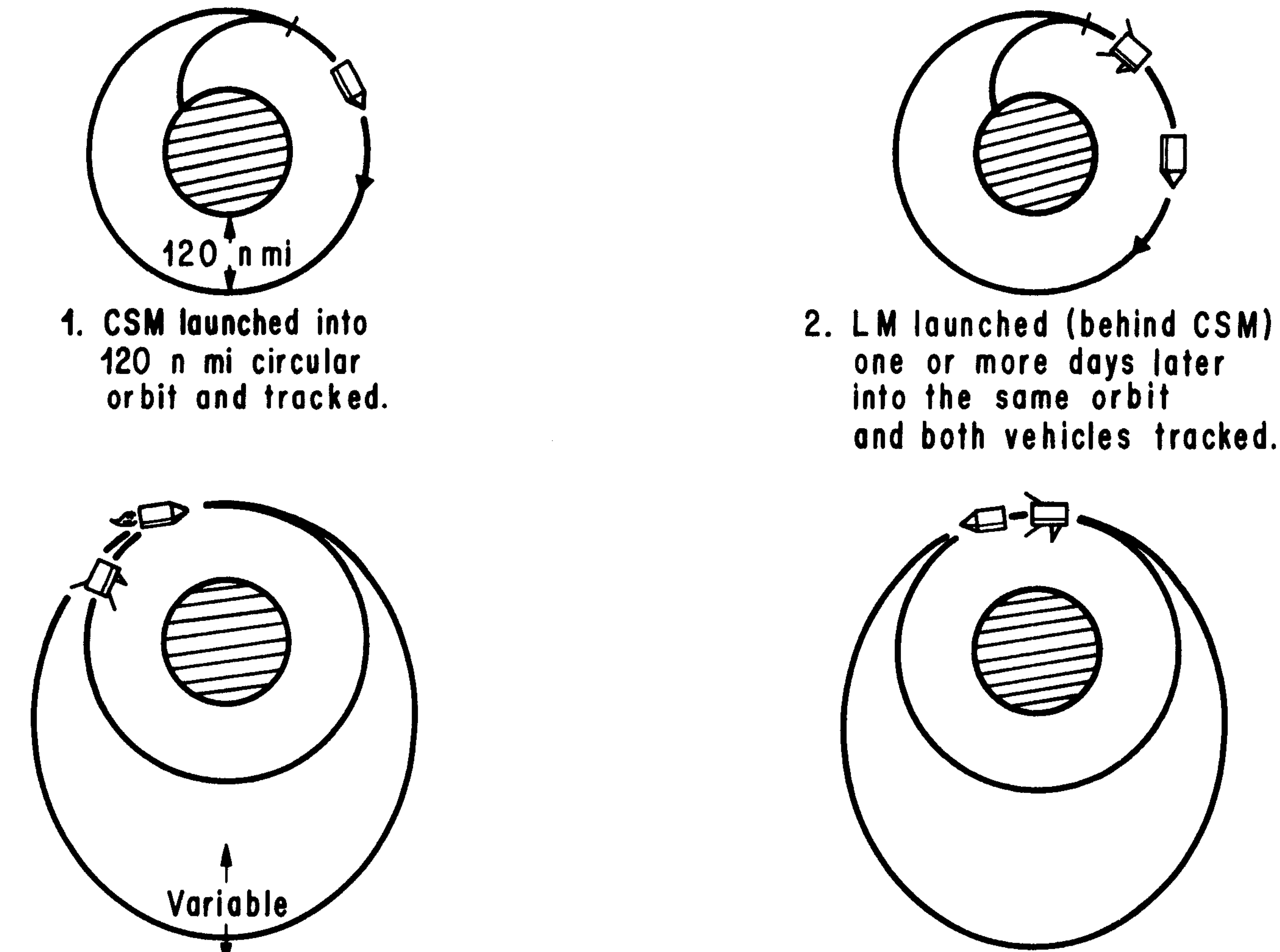
Number of Orbits	Time to Achieve Rendezvous Position (hrs)	Payload vs Launch Window		Docking Time Remaining (hrs)
		LM OFF Load (lbs)	Launch Window (min)	
1 1/4	1.87	0	3.6	5.63
		300	4.7	
		1000	6.8	
1 3/4	2.63	0	7.2	4.87
		300	9.1	
		1000	13.1	
2 1/4	3.37	0	7.3	4.13
		300	9.2	
		1000	13.2	
2 3/4	4.13	0	11.0	3.37
		300	13.8	
		1000	19.3	
3 1/4	4.88	0	11.1	2.62
		300	13.3	
		1000	19.6	
3 3/4	5.63	0	14.5	1.87
		300	18.2	
		1000	25.3	

The second profile, Figure 3, considers the CSM is launched into a 120 n.m. circular orbit followed by launch of the LM into the same orbit. The CSM then burns into a variable apogee to phase with LM. The CSM then brakes at perigee in phase with LM and docks. After docking, the CSM circularizes into a 200 n. m. orbit using SPS burns. Table 2 shows the launch window available as a function of CSM phasing orbit apogee. Time to achieve rendezvous and remaining docking time for a 7 1/2 hour S-IVB stabilization lifetime are also shown as a function of the number of orbits for the phasing maneuver.

The third profile, Figure 4, considers the CSM to be launched into a 100 n.m. circular orbit followed by the LM launched into an orbit with 120 n.m. perigee and variable apogee depending on launch time. The CSM then initiates the transfer maneuver, matches the velocity of LM in the ellipse,and docks. After docking, the CSM circularizes into a 200 n.m. orbit. Table 3 shows the corresponding launch window and docking time data for this profile. Of these profiles, the first one discussed with LM elliptical phasing appears most attractive at this time since the LM in its ATM configuration is not at all weight critical and considerable flexibility can be maintained in choosing the LM phasing ellipse apogee. The LM-ATM configuration is estimated to be 11,500 to 19,000 pounds from References 1 and 2, respectively.

The CSM has been considered to be launched first because of the limited S-IVB stabilization lifetime for the unmanned LM payload and the assumption that the CSM will dock to the LM and effect the LM/S-IVB separation. For the ATM mission,however, there may be valid reasons for launching the unmanned payload first, activating LM subsystems and effecting separation from the S-IVB prior to the manned launch. The operation of the LM-ATM spacecraft, including proper attitude hold capability for the CMG system, may be desired before committing the manned launch. Of course, if the LM-ATM payload is separated from the S-IVB stage before CSM docking, then the short S-IVB stabilization lifetime is no longer a problem. It is recommended that consideration be given to this mode of operation.

Two preliminary timelines for the Apollo Telescope Mount mission are presented in Appendices A and B, reflecting the assumption of crew transfer every twelve hours or every seven days,respectively. Shown in the timelines are crew scheduling of experiment and housekeeping duties, and the geometric considerations of ascending and descending node positions, major land masses, day-night periods, and tracking. The list of assumptions accompanies the timelines in Appendix A. Another possible mode of operation is in the docked CSM-LM configuration during the entire 14 days. This mode has several advantages and disadvantages relative to the undocked mode and will require analysis.



1. CSM launched into 120 n mi circular orbit and tracked.

2. LM launched (behind CSM) one or more days later into the same orbit and both vehicles tracked.

3. CSM burns into a varible apogee to phase with LM.

4. CSM brakes at perigee in phase with LM and docks.

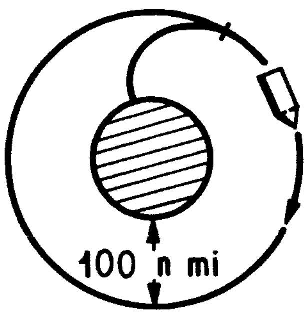
FIG. 3. MISSION PROFILE WITH CSM PHASING ELLIPSE

TABLE 2

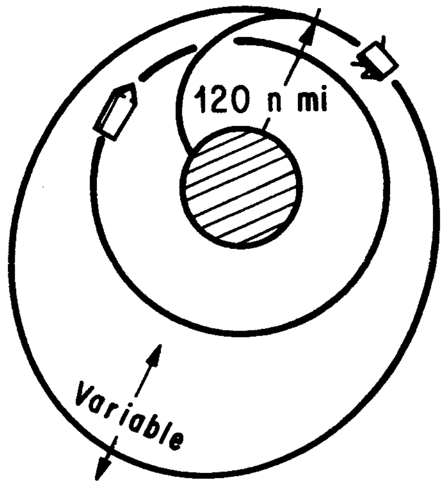
Summary Table for CSM Phasing Ellipse

Number of Orbits	Time to Achieve Rendezvous Position (hrs)	Altitude of Apogee (H_A) vs Launch Window		Docking Time Remaining (hrs)
		H_A (n.m.)	Launch Window (min)	
1 1/2*	2.25	350	4.5	5.25
		400	5.6	
		520	7.6	
2 1/2	3.75	350	8.8	3.75
		400	11.3	
		520	15.3	
3 1/2	5.25	350	13.3	2.25
		400	17.1	
		520	23.3	

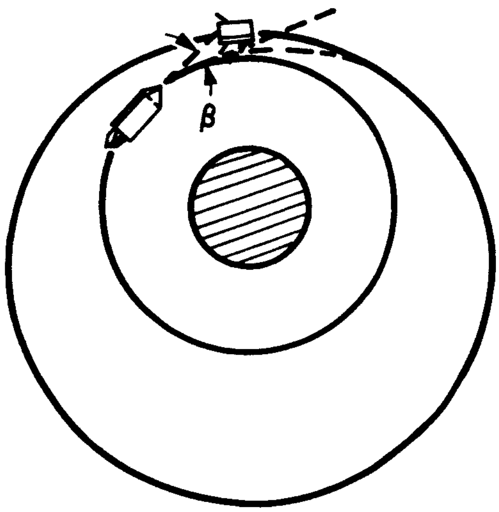
*1/2 orbit allocated for orbit determination.



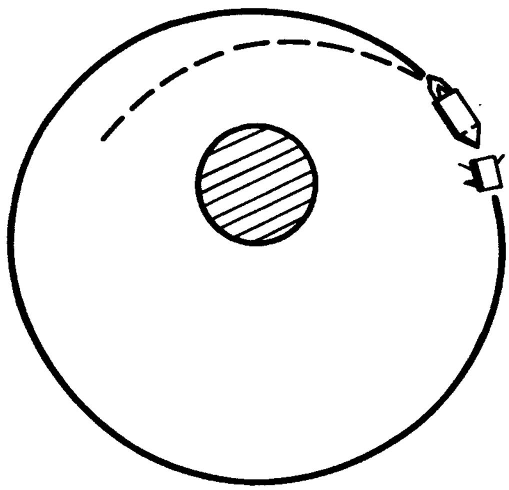
1. CSM launched into a 100 n mi circular orbit and tracked.



2. LM launched into a 120 n mi perigee and variable apogee ellipse, depending on the launch time.



3. CSM optically tracks LM and initiates transfer manuever.



4. CSM matches velocity of LM in ellipse and docks.

FIG. 4. MISSION PROFILE WITH LM PHASING ELLIPSE AND CSM TRANSFER MANEUVER

TABLE 3

Summary Table for LM Phasing Ellipse and CSM Transfer Maneuver

Number of Orbits	Time to Achieve Rendezvous Position (hrs)	Payload vs Launch Window		Docking Time Remaining (hrs)
		LM Off Load (lbs)	Launch Window (min)	
1	2.25*	300	1.5	5.25
		1000	2.8	
		1700	5.1	
		2100	6.2	
		2800	8.3	
2	3.75	300	3.0	3.75
		1000	5.6	
		1700	10.1	
		2100	12.3	
		2800	16.6	
3	5.25	300	4.4	2.25
		1000	8.5	
		1700	15.3	
		2100	18.4	
		2800	24.8	

*An additional 1/2 orbit has been allocated for the transfer maneuver.

III. ORBITAL AERODYNAMICS

The orbital aerodynamic characteristics of the orbiting vehicles to be considered in the ATM program have been determined by standard calculations. The approach and assumptions used for this analysis are explained in this section.

A spacecraft passes through the atmosphere at orbital altitudes. The aerodynamic characteristics of this craft depend on factors such as shape, size, speed, and surface conditions as well as the properties of the atmosphere such as density, temperature, and composition. The most notable feature of this flight is that the density is so low that corpuscular behavior occurs. This means that the incoming molecules (relative to the spacecraft) which collide with the body are not influenced by molecules which have already collided and are rebounding. This type of flow is called free molecule flow and occurs normally when the mean free path of the molecule (the average distance that a molecule travels between successive collisions with other molecules) is 10 or more times greater than the characteristic body dimension. The basic parameter used to describe various flow regimes is the Knudsen number, K_n, which is the ratio of the mean free path to the characteristic dimension.

Since the incident flow to a body in the free molecule regime is undisturbed by the presence of that body, the equilibrium velocity distribution of the incident molecule is changed only by molecule-body collisions. Therefore, the effects of the incident and reflected molecules can be analyzed separately.

In free molecule flow, the forces and moments on a body are functions of only three parameters and the geometric configuration of that body. One parameter, the molecular speed ratio, is defined as,

$$S = \frac{V_r}{\sqrt{2RT_i}} \tag{1}$$

where V_r is the velocity of the body of interest, T_i is the average temperature of the incident molecules and is the second parameter; R is the gas constant of the particular gas of interest. The third parameter, T_r, is the average temperature of the molecules reflected from the body surface. T_r and T_i are commonly used as the reflected-to-incident molecular temperature ratio, T_r/T_i.

The forces and moments acting on a body in free molecule flow are a function of the molecule-surface interaction. This interaction is considered in two parts, the momentum transferred to the surface and the energy transferred to the surface. The momentum which is imparted to the surface depends on the type of reflection; either specular (when the angle of reflection equals the angle of incidence) or diffuse (when the molecule strikes the surface and is re-emitted in a random direction). The fraction of the incident molecules which are diffusely reflected is known as the reflection coefficient. Specular reflection is not considered in present calculations since molecule-surface interaction experiments conducted to date on orbital vehicle type surfaces indicate an almost completely diffuse reflection. Thus, the assumption of completely diffuse reflection in the flow field model introduces only a slight error in the force coefficient values. In the case of diffusely reflected molecules, momentum is transferred to the body surface only in a normal direction (zero tangential momentum).

The degree of thermal equilibrium attained between the molecule and body surface before re-emission of the molecule is measured by the energy or thermal accommodation coefficient, α, defined as

$$\alpha = \frac{E_i - E_r}{E_i - E_w} \qquad (2)$$

where

E_i is the total incident energy transported by the molecules to a unit surface area in unit time,

E_r is the total energy transported by the reflected molecules away from a unit surface area in unit time, and

E_w is the total energy the reflected molecules would transport away from a unit surface area in unit time if they were re-emitted at the temperature of the surface.

It will be shown later that T_r/T_i enters into the resultant force coefficient equations as a measure of this energy effect. The assumption of complete thermal accommodation, where $T_r = T_w$ and $\alpha = 1.0$, is not as well founded as the assumption of diffuse reflection. The thermal accommodation coefficient must be obtained experimentally or estimated based on previous data for similar surfaces and incident molecular properties. It is a function of molecule weight, surface temperature, the material, finish, age, and history of the surface, and, when the molecules possess a large mass motion, the history of the molecular speed ratio and the direction cosines between the surface and the direction of mass flow. Experimental values of the thermal accommodation coefficient obtained to date for surfaces and impinging molecules typical of those at orbital altitudes have the range $0.7 \leq \alpha \leq 1.0$. The error introduced in free molecule force coefficient values by assuming $\alpha = 1.0$ will be discussed later.

The equation for the force on an element of area in free molecule flow may be computed using kinetic theory relationships and a Maxwellian velocity distribution. Since the effects of the incident and reflected molecules can be analyzed separately, the total force on the element of area is obtained by summing the force due to the incident molecules and that due to the reflected molecules. A geometric assumption made here is that the element of area is located on a flat or convex surface. A concave surface would produce a force on the element of area due to the molecules that have been reflected from other parts of the body, which is not taken into account in the following equation. The force equation is derived in Reference 3. The nondimensional free molecule force coefficient equation resulting from this derivation is

$$\frac{dC}{dA} = \frac{1}{A} \left\{ (\epsilon k + \gamma \ell + \eta t) \left[\gamma(1 + \operatorname{erf} \gamma S) + \frac{1}{S\sqrt{\pi}} e^{-\gamma^2 S^2} \right] + \frac{\ell}{2S^2} (1 + \operatorname{erf} \gamma S) \right.$$

$$\left. + \frac{\ell}{2} \sqrt{T_r/T_i} \left[\frac{\gamma\sqrt{\pi}}{S} (1 + \operatorname{erf} \gamma S) + \frac{1}{S^2} e^{-\gamma^2 S^2} \right] \right\}, \qquad (3)$$

where

- k, ℓ, t are direction cosines between the local x, y, and z (with respect to an element of surface, y is the inward directed normal and x and z are tangent to the surface) axes and the desired force direction,
- ϵ, γ, η are direction cosines between the local x, y, and z axes and the relative velocity vector.

This equation is exact within the physical assumptions of kinetic theory, free molecule flow, diffuse reflection, and non-concave surfaces. Shadowing on one portion of a particular shape by another portion of that shape and the effect of the random thermal motion of the molecules are included in the equation. Shadowing by one body on another is not included.

To examine the effect of thermal accommodation coefficients, we look at equation (2), where one may write for diffusely reflected molecules

$$E_r = 2m\ N_i\ RT_r \tag{4}$$

$$E_w = 2m\ N_i\ RT_w \tag{5}$$

and

$$E_i = (1/2)m\ N_i \left\{V_r^2 + RT_i \left[4 + \frac{1}{(\emptyset + 1)}\right]\right\}, \tag{6}$$

where

$$\emptyset = \emptyset(S,\theta) = \frac{e^{-S^2 \sin^2\theta}}{\sqrt{\pi}\ S \sin\theta(1 + \operatorname{erf} S \sin\theta)} .$$

Solving equation (2) for E_r gives

$$E_r = (1 - \alpha)\ E_i + \alpha\ E_w.$$

Substituting for E_i, E_r, and E_w gives

$$2m\ N_i\ RT_r = (1/2)(1 - \alpha)m\ N_i \left\{V_r^2 + RT_i \left[4 + \frac{1}{(\emptyset + 1)}\right]\right\} + 2\alpha m\ N_i\ RT_w. \tag{7}$$

Simplifying and introducing equation (1) gives

$$T_r = (1/2)(1 - \alpha)\ T_i \left\{S^2 + \left[2 + \frac{1}{2(\emptyset + 1)}\right]\right\} + \alpha T_w \tag{8}$$

and

$$\frac{T_r}{T_i} = \frac{(1 - \alpha)}{2} \left\{S^2 + \left[2 + \frac{1}{2(\emptyset + 1)}\right]\right\} + \alpha\ \frac{T_w}{T_i} . \tag{9}$$

For a body surface normal to the relative velocity, V_r, and with $S > 5$, which is the case for orbital altitudes of at least 1000 km or less, $\theta = 90°$ and $\phi(S,\theta) \to 0$; then

$$\frac{T_r}{T_i} = \frac{(1 - \alpha)}{2}\left[S^2 + \frac{5}{2}\right] + \alpha\frac{T_w}{T_i} . \tag{10}$$

For a body surface parallel to the relative velocity, V_r, and for any value of S, $\theta = 0°$ and $\phi(S,\theta) \to \infty$; then,

$$\frac{T_r}{T_i} = \frac{(1 - \alpha)}{2}\left[S^2 + 2\right] + \alpha\frac{T_w}{T_i} . \tag{11}$$

It is seen, therefore, that for practical orbital altitudes ($S > 5$), equations (10) and (11) have essentially the same value. This indicates that the reflected-to-incident temperature ratio, T_r/T_i, is practically unaffected by surface orientation.

Now, what is the effect of body surface temperature, T_w, on T_r/T_i? Consider a body in a 200 n.m. orbit, T_i = 1470°K, with a surface temperature of 300°K (the surface temperature presently assumed for all orbiting bodies when determining the aerodynamic force coefficients for that body). For a temperature variation over the surface of ±50°K, the ratio of T_w/T_i varies from 0.170 to 0.238. Then, for $\alpha = 1$, the assumption in the present flow field model, $T_w/T_i = T_r/T_i$, and the ratio is directly affected by the surface temperature variation. The assumed ±50°K variation will then produce a 40 percent variation in T_r/T_i. However, the contribution of the reflected molecules to the force coefficient values is an order of magnitude less than that of the incident molecules so that the actual effect of surface temperature variation on the force coefficient magnitudes is less than 2 percent. With $\alpha < 1$ and $S > 5$, as is the actual case, the effect of surface temperature variation on T_r/T_i is considerably less, becoming less than 1 percent as α decreases below a value of 0.75. The effect on force coefficient magnitudes is then negligible.

Finally, what is the effect of the thermal accommodation coefficient, α, on T_r/T_i, thus, on the force coefficient magnitudes? Looking again at equations (10) and (11), we see that as α varies from 1 to 0, T_r/T_i is radically affected and will vary from less than 0.2 to a value of 50 or greater, depending upon the value of S. Since the contribution of the reflected molecules is multiplied by $(T_r/T_i)^{1/2}$, this contribution to the force coefficient magnitudes can be increased from an order of magnitude less than that of the incident molecules to the same order of magnitude as $\alpha \to 0$. Therefore, variations in α can significantly alter the force coefficient magnitudes.

Using the approach outlined above, orbital aerodynamic characteristics for the CSM docked with the LM and for the LM alone have been calculated. Figures 5 through 12 present the axial force coefficient, normal force coefficient, drag coefficient, and center of pressure for these configurations for a 200 nautical mile orbit. Figure 13 shows the reference positions for the center of pressure data. The coefficients are based upon a reference area of 33.47 square meters. These results were computed assuming that batteries supply power for the 14-day mission in a "brute force" approach. The use of solar cell arrays complicates the determination of the free molecule flow aerodynamic characteristics which has not been performed at this time pending more definite information concerning the solar array designs. For the case where ATM is placed in orbital storage at the end of the 14-day mission and then reactivated at a later time, the battery approach is not acceptable.

IV. AERODYNAMIC TORQUE

The free-molecule drag and normal force coefficients presented in the previous section have been used for orbital lifetime analyses and aerodynamic torque considerations. The orbital lifetime results are discussed in the next section. This section presents the aerodynamic torque analysis necessary for control analyses and CMG angular momentum considerations.

The mass density of the upper atmosphere can be computed from a series of equations given by Smith [4]. The maximum mass density, ρ_m, that can be expected at 200 n.m. altitude in the late '68 or early '69 time frame is obtained as 1.58×10^{-10} kg/m^3. This value for mass density is subsequently used for the calculation of dynamic pressure.

Neglecting terms of the order $(\Omega_e/n)^2$, Sterne [5] shows that the relative velocity of the spacecraft with respect to the rotating atmosphere can be expressed by

$$V_r = \left(\frac{\mu}{a} \cdot \frac{1 + \epsilon \cos E}{1 - \epsilon \cos E}\right)^{1/2} \left[1 - \frac{\Omega_e (1 - \epsilon^2)^{1/2}}{n} \cos i \, \frac{1 - \epsilon \cos E}{1 + \epsilon \cos E}\right] . \quad (12)$$

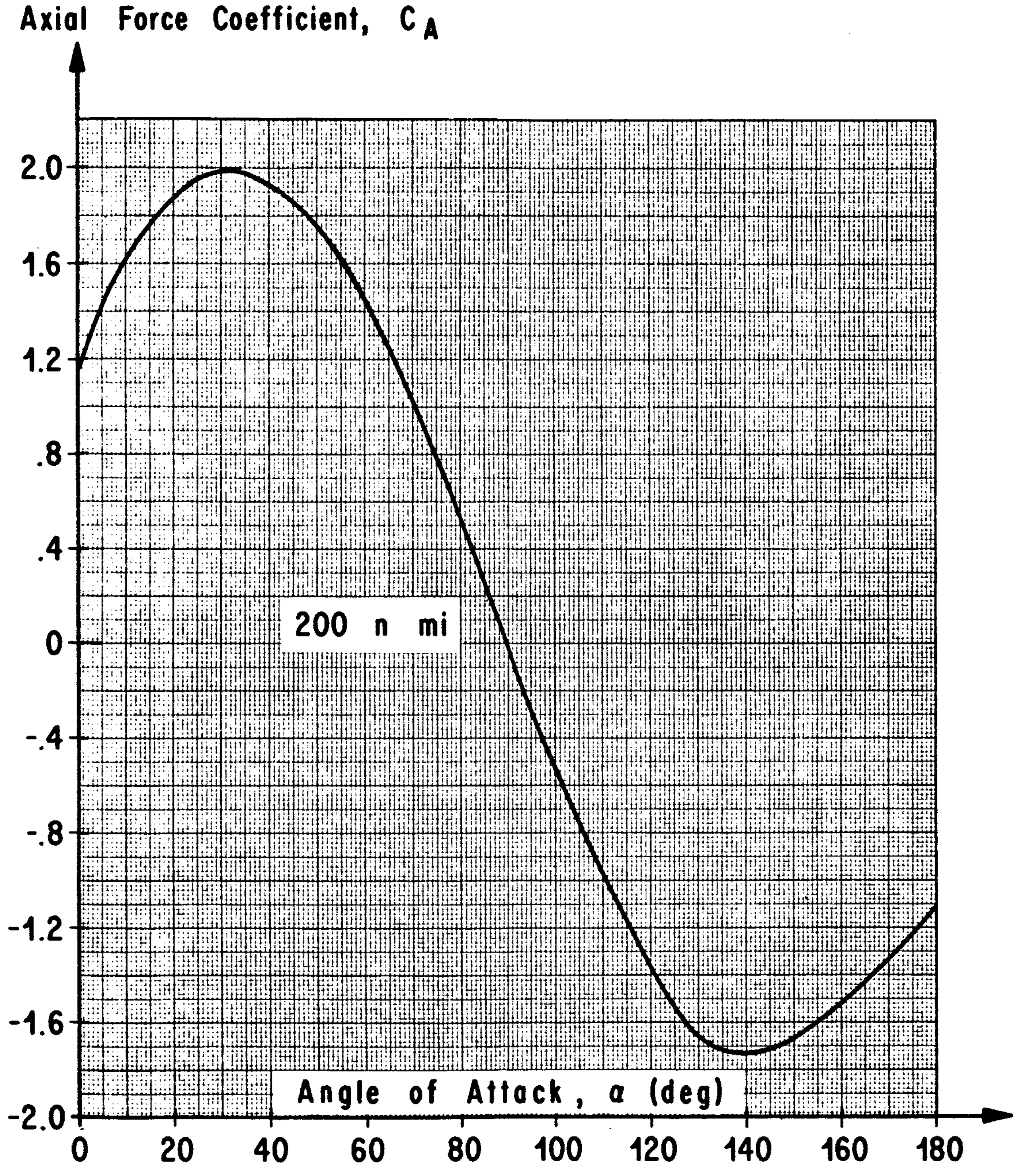


FIG. 5. DOCKED LM/CSM AXIAL FORCE COEFFICIENT

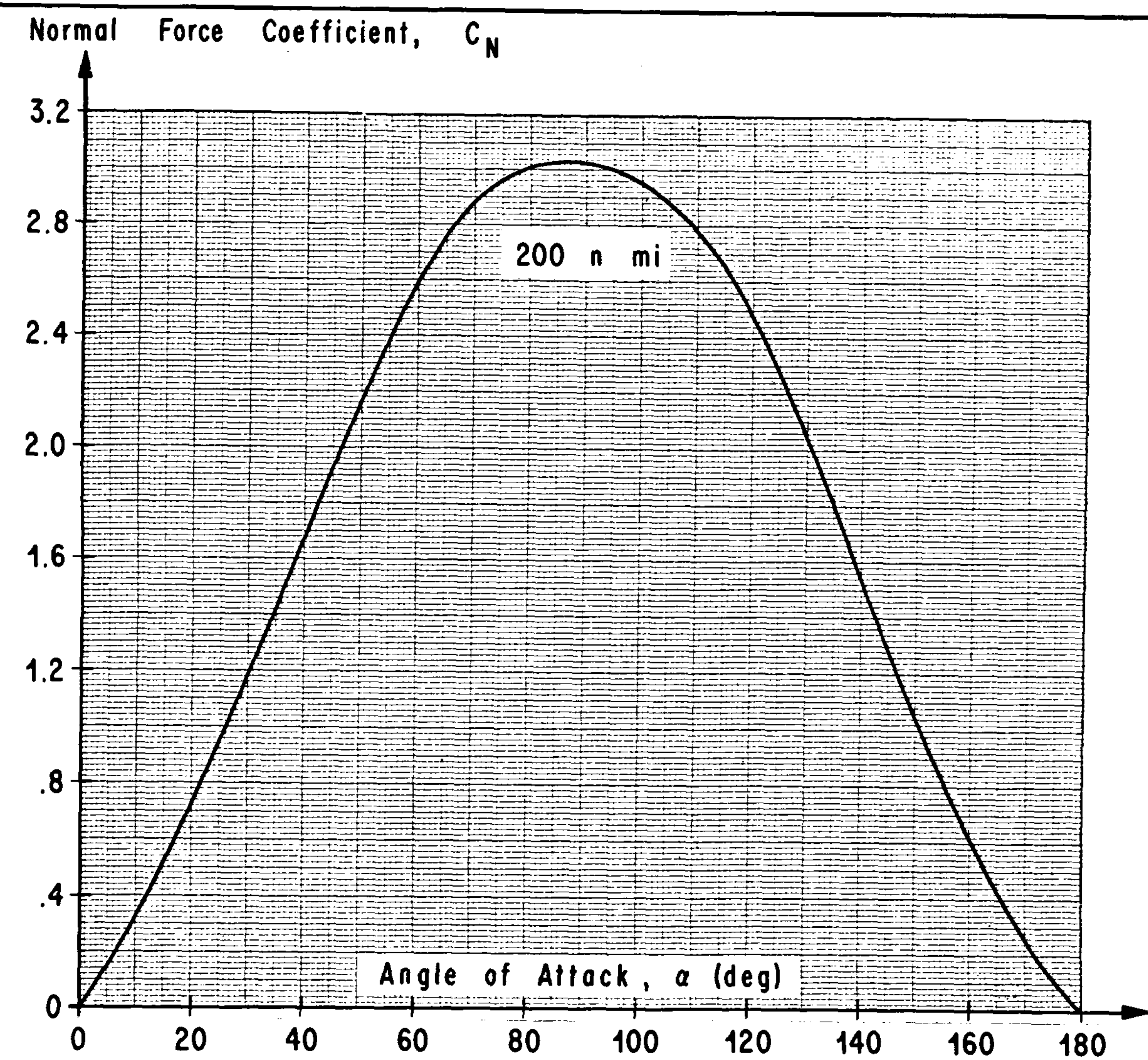


FIG. 6. DOCKED LM/CSM NORMAL FORCE COEFFICIENT

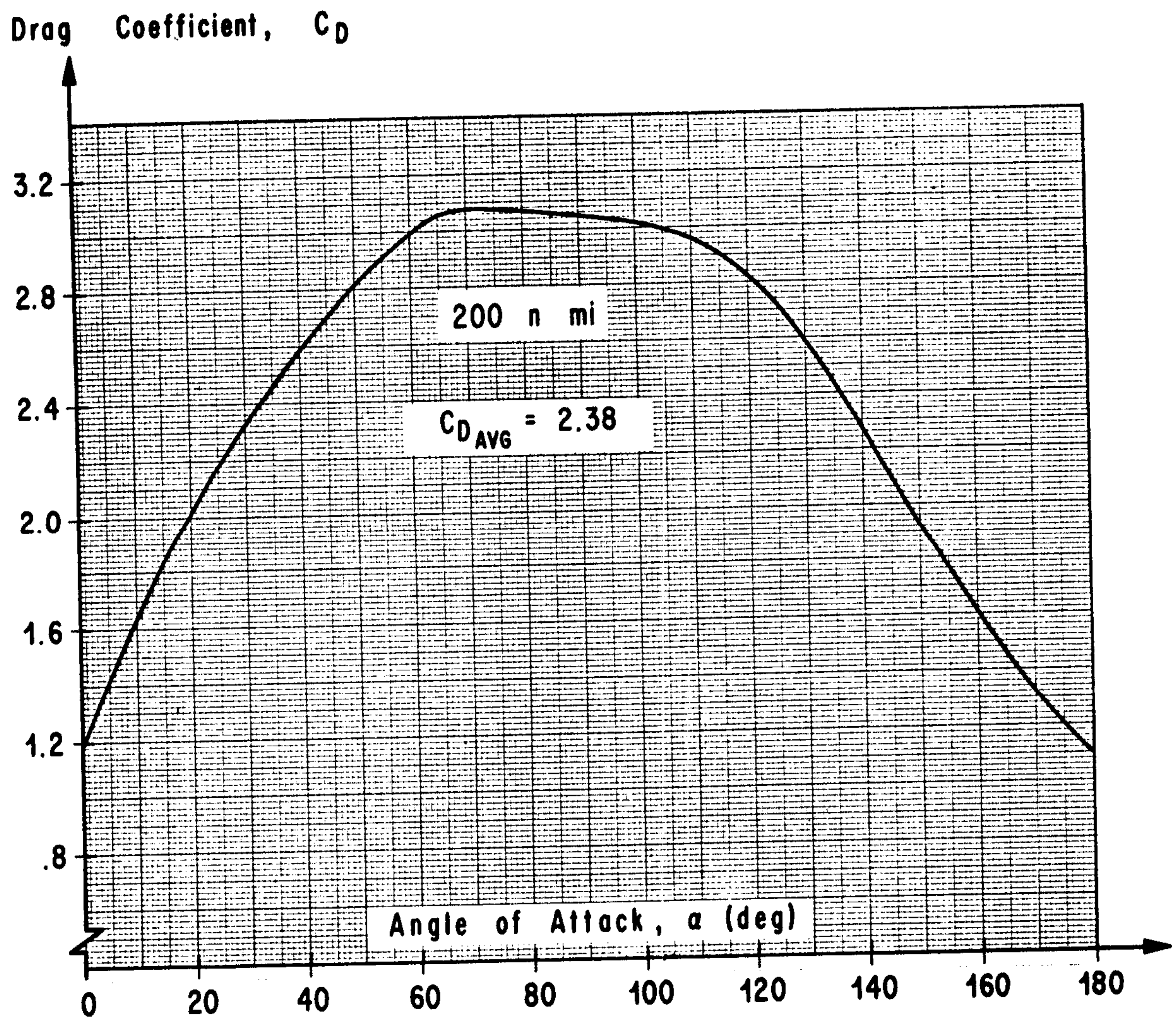


FIG. 7. DOCKED LM/CSM DRAG COEFFICIENT

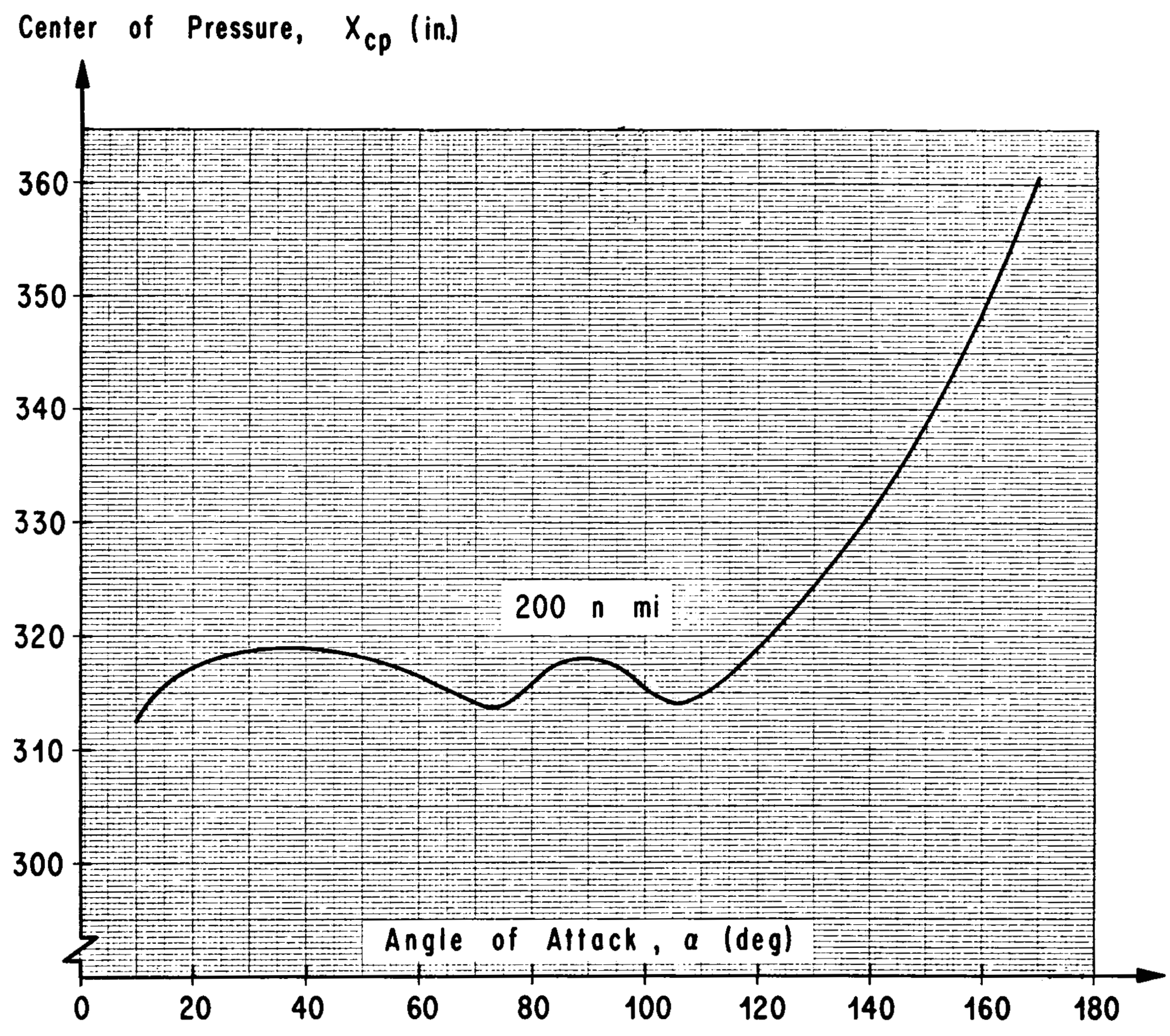


FIG. 8. DOCKED LM/CSM CENTER OF PRESSURE

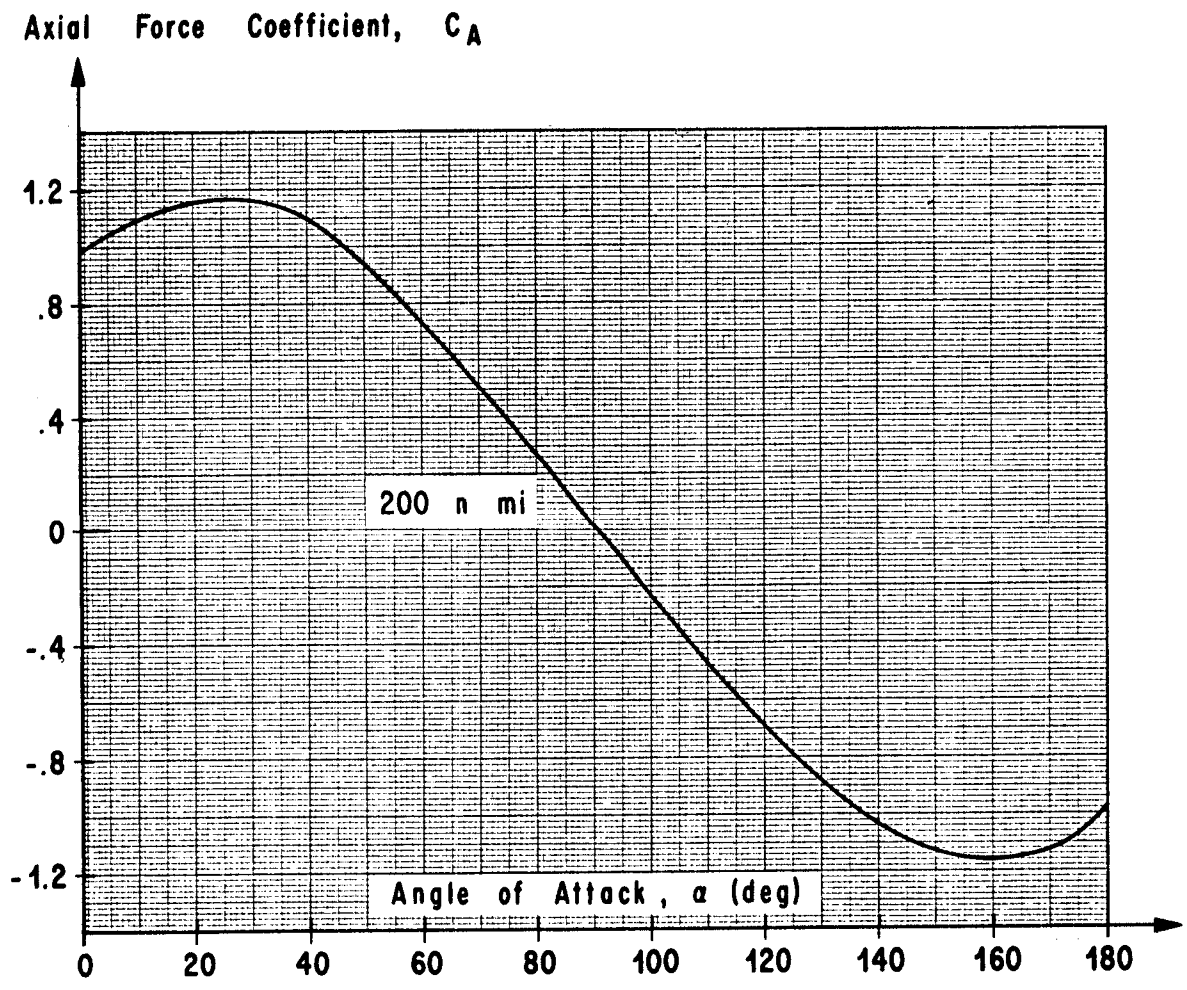


FIG. 9. LM AXIAL FORCE COEFFICIENT

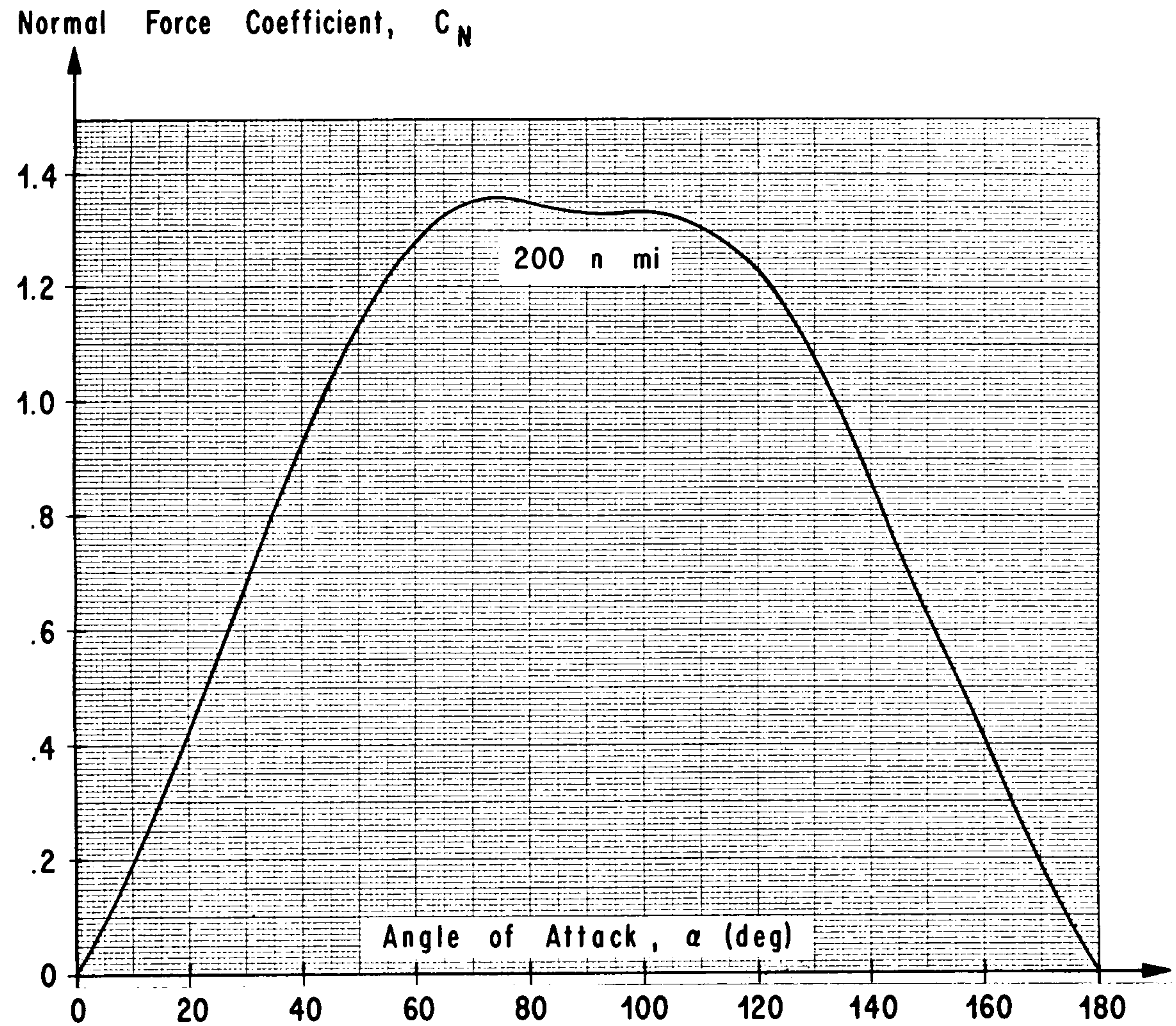


FIG. 10. LM NORMAL FORCE COEFFICIENT

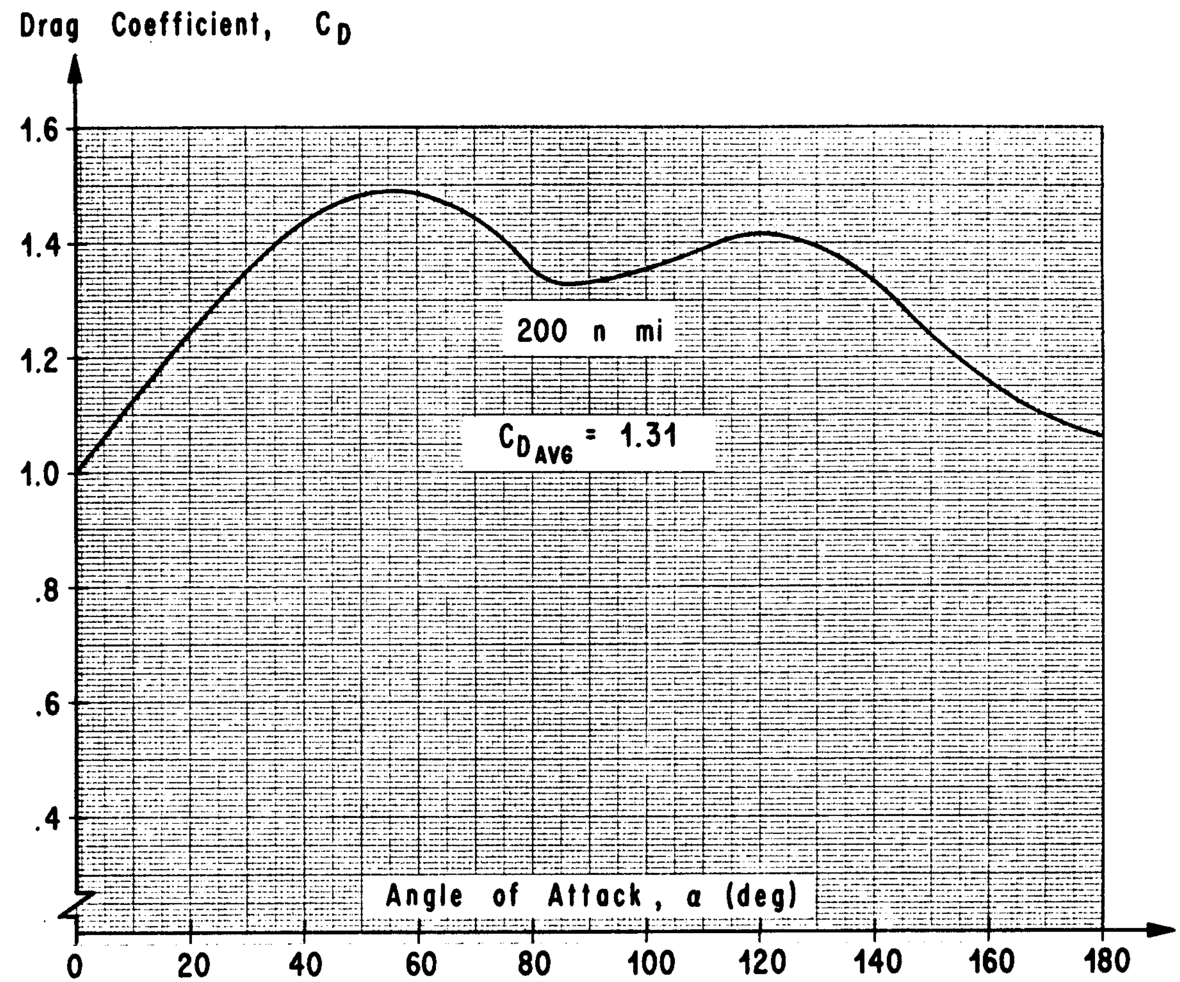


FIG. 11. LM DRAG COEFFICIENT

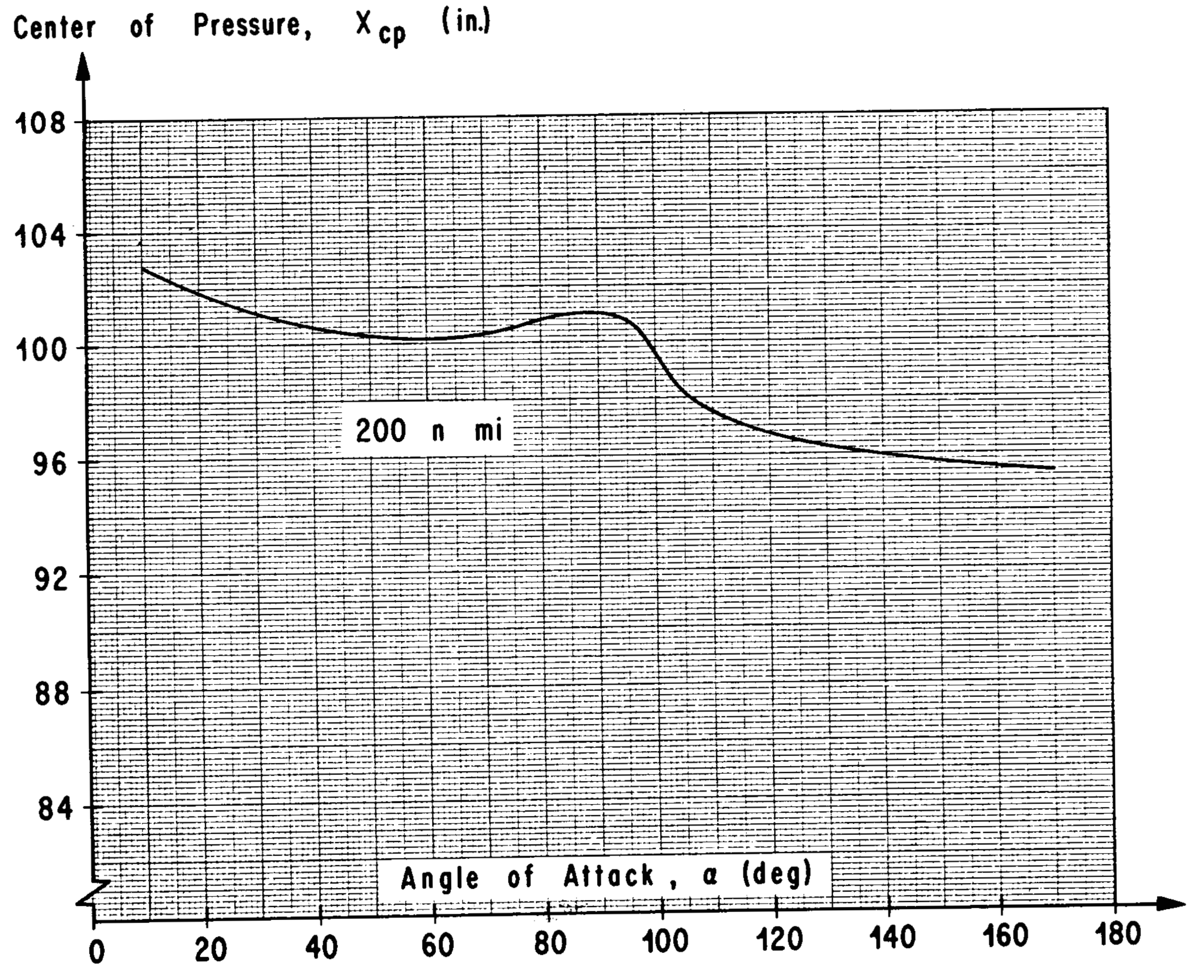


FIG. 12. LM CENTER OF PRESSURE

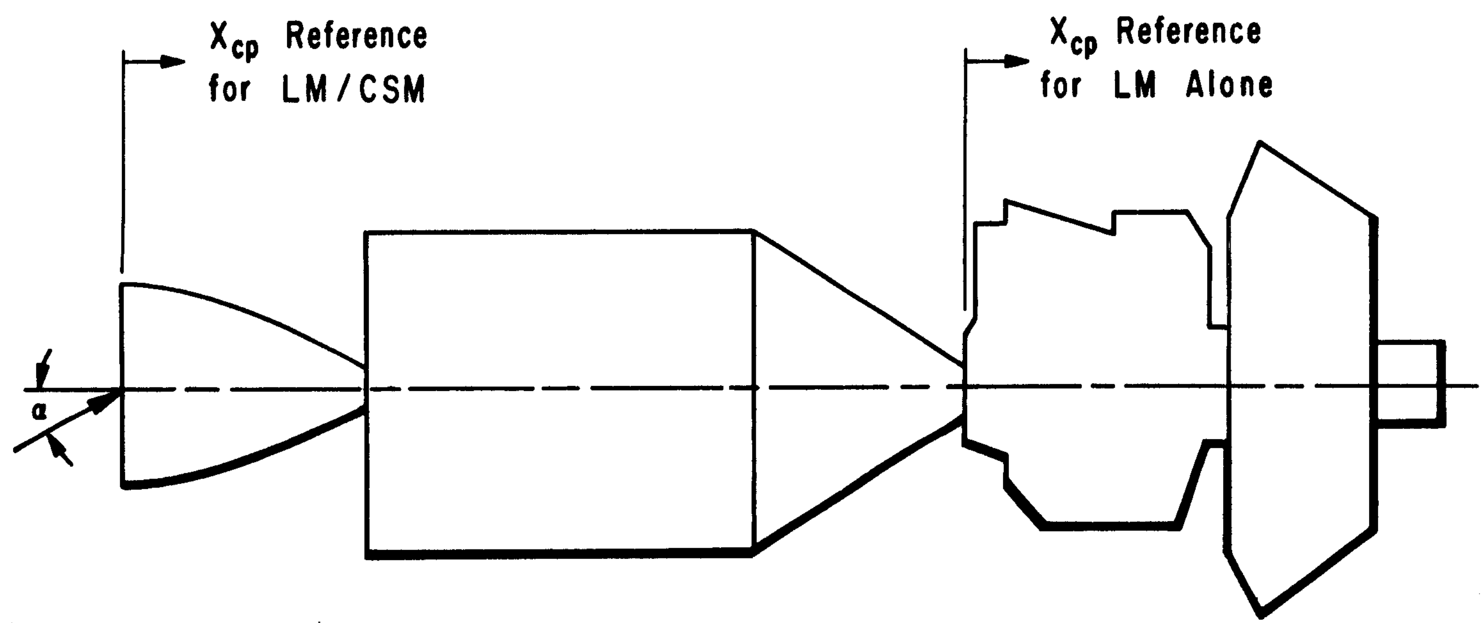


FIG. 13. REFERENCE STATIONS FOR CENTER OF PRESSURE DATA

For a circular orbit, this reduces to

$$V_r = (\mu/r)^{1/2}\left[1 - \frac{\Omega_e \cos i}{n}\right], \tag{13}$$

where the first term is the inertial velocity for a circular orbit.

The relative velocity has been obtained for a 200 n.m. altitude and found to be 7260 km/sec from the above equation, where

μ = GMe = 0.3986×10^6 km^3/sec^2

r = 6378 + 370 = 6748 km

$\Omega_e = 7.292 \times 10^{-5}$ rad/sec

$n = (\mu/r^3)^{1/2} = 1.139 \times 10^{-3}$ rad/sec

cos i = cos 29.5° = 0.8704.

The dynamic pressure, q, is then obtained:

$$q = (1/2)\ \rho_m V_r^2 = 4.164 \times 10^{-3}\ \mathrm{N/m^2}\ (8.697 \times 10^{-5}\ \mathrm{lb/ft^2}).$$

From the previous section, the maximum normal force coefficient is 1.36 for LM alone and 3.04 for the docked CSM-LM configuration. The corresponding center of pressure is 101 inches from the LM docking collar for LM alone and 318 inches from the SM nozzle exit plane for the CSM-LM vehicle.

Current estimates from Propulsion and Vehicle Engineering Laboratory place the center of gravity at LM Station 187 for LM alone and at LM Station 390 for the CSM-LM docked configuration. In the docked configuration, the nozzle exit plane of the SM is 387 inches from the docking collar where the docking collar corresponds to LM Station 312.5. From these results, the center of pressure is 24.5 inches closer to the docking collar than the center of gravity for the LM alone. For the docked CSM-LM vehicle, the center of pressure is 8.5 inches closer to the docking collar than the center of gravity. Considering the "nose" to be the opposite end from the SM nozzle and a "nose-up" moment as positive, the aerodynamic torque from these results would be positive (nose-up) for the CSM-LM vehicle and negative (nose-down) for the LM alone configuration. The magnitude of the maximum aerodynamic moment is as follows:

LM Alone

$$M = C_N qA |x_{cp} - x_{cg}|$$

$$= (1.36)(4.164 \times 10^{-3} \text{ N/m}^2)(33.47 \text{ m}^2)(0.62 \text{ m})$$

$$= 0.118 \text{ N-m } (0.087 \text{ ft-lb}).$$

CSM-LM

$$M = C_N qA |X_{cp} - X_{cg}|$$

$$= (3.04)(4.164 \times 10^{-3} \text{ N/m}^2)(33.47 \text{ m}^2)(0.22 \text{ m})$$

$$= 0.093 \text{ N-m } (0.069 \text{ ft-lb}).$$

Thus, it is observed that the aerodynamic disturbance torque is about the same magnitude for both configurations.

V. ORBITAL LIFETIME

The orbital lifetime for proposed configurations and modes of operation are presented in this section. In considering the lifetimes associated with the various orbiting configurations and modes of operation, the masses, drag coefficients, altitudes, and atmospheric density are the most critical parameters. All the lifetimes are therefore presented as a function of altitude. The atmospheric density, which is probably the most critical of parameters associated with predicting orbital lifetime, is directly associated with solar activity. That is, as solar activity increases, the density of the atmosphere increases, and hence, the higher the solar activity the lower the orbital lifetime. The lifetime studies were based on a late 1968 launch which is predicted to be the period of maximum solar activity. The statistical deviations, $\pm 2\sigma$, are based on predicted variations in the present solar cycle which will attain its maximum in late 1968 or early 1969.

The four modes of operation which were investigated are as follows:

(a) Fourteen days broadside, three month tumbling.

(b) Fourteen days broadside, six month tumbling.

(c) Twenty-eight days broadside, three month tumbling.

(d) Twenty-eight days broadside, six month tumbling.

These modes represent cycles of operation time during which there occur fourteen or twenty-eight days of orbital experimentation and three or six months of LM orbital storage. These cycles of operation were assumed to recur throughout the orbital lifetime. Although the results have been obtained for the broadside mode during the active mission periods, the vehicle will actually be inertially oriented toward the sun. As the vehicle emerges from the earth's shadow, it will be aligned fairly well with the velocity vector. At noon the vehicle is traveling broadside, and at dusk it is essentially aligned again with the velocity vector. This assumes that the ATM spar is along the vehicle's centerline. The broadside assumption for lifetime analysis gives conservative results for the LM and CSM-LM configurations without solar cell arrays. With solar cells, the drag coefficient will increase appreciably at low angle of attack. The broadside drag will not increase since the solar panels are edge on to the velocity vector.

Figures 14 through 17 present results of the lifetime studies for the LM configuration. Since the broadside drag coefficient is 1.34 and the tumbling drag coefficient is 1.31, the lifetimes for the four orbiting modes are essentially the same. The configuration mass assumed is 8182 kg (18,000 lbm). These results are based upon the previous drag data presented which do not include solar panels.

Figures 18 through 21 show the corresponding results for the CSM-LM configuration. The broadside drag coefficient is 3.04, and a mass of 18,182 kg (40,000 lbm) was assumed. For the orbital storage periods, the LM tumbling drag of 1.31 and LM mass were used. These results can be considered quite applicable for the CSM-LM vehicle with solar panels since it is estimated that the vehicle drag at low angle of attack (with solar panels broadside) is less than the vehicle broadside drag used. For orbital storage, the panels are stored about the LM vehicle in such a way that the tumbling drag with panels may not exceed the tumbling drag without panels.

More extensive analysis is needed relating to orbital aerodynamics with solar panels since these panels will shade other portions of the vehicle at various angles of attack and sideslip and complicate the analysis. When these more detailed aerodynamic characteristics are available, more detailed aerodynamic torque disturbance and orbital lifetime analyses can be conducted.

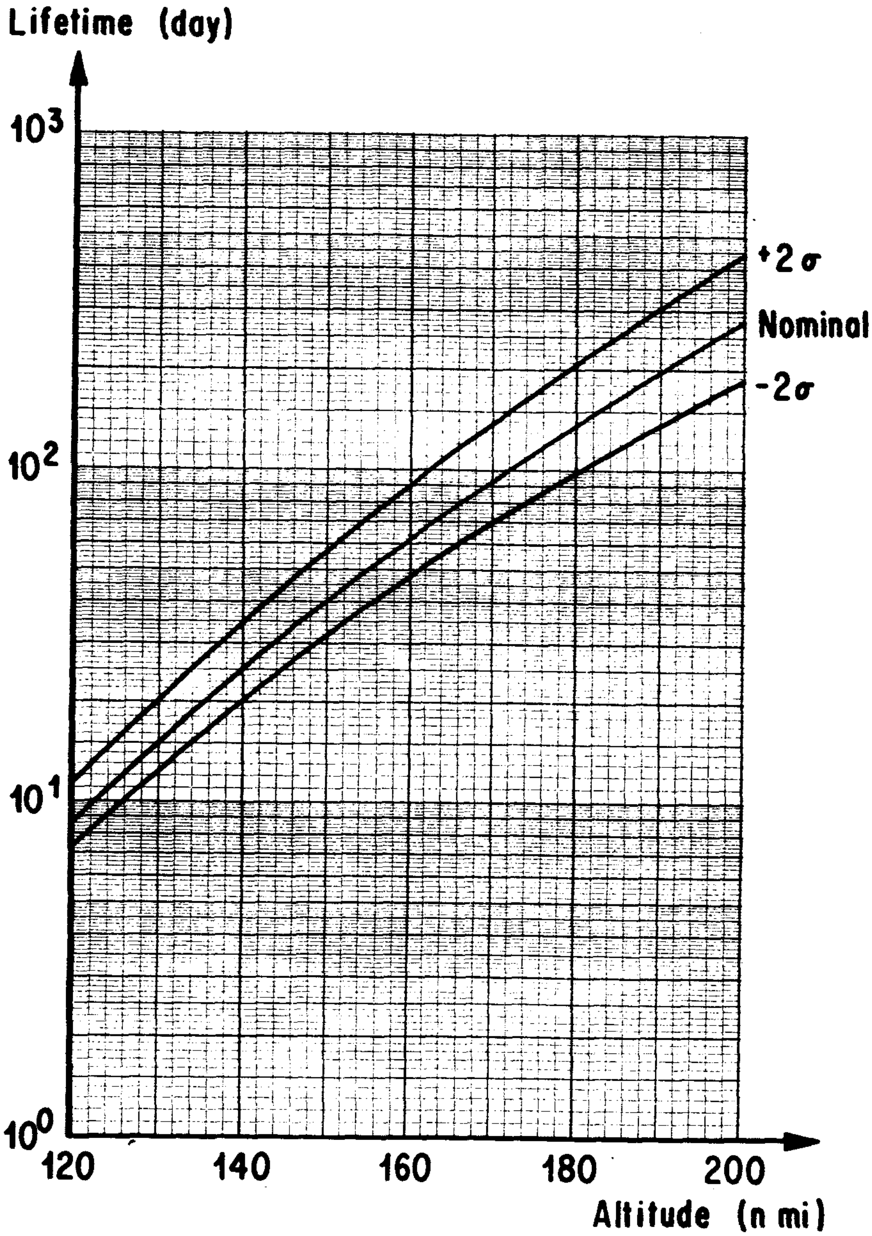


FIG. 14. ATM LIFETIME VS ALTITUDE FOR THE 14 DAY BROADSIDE, 3 MONTH TUMBLING MODE

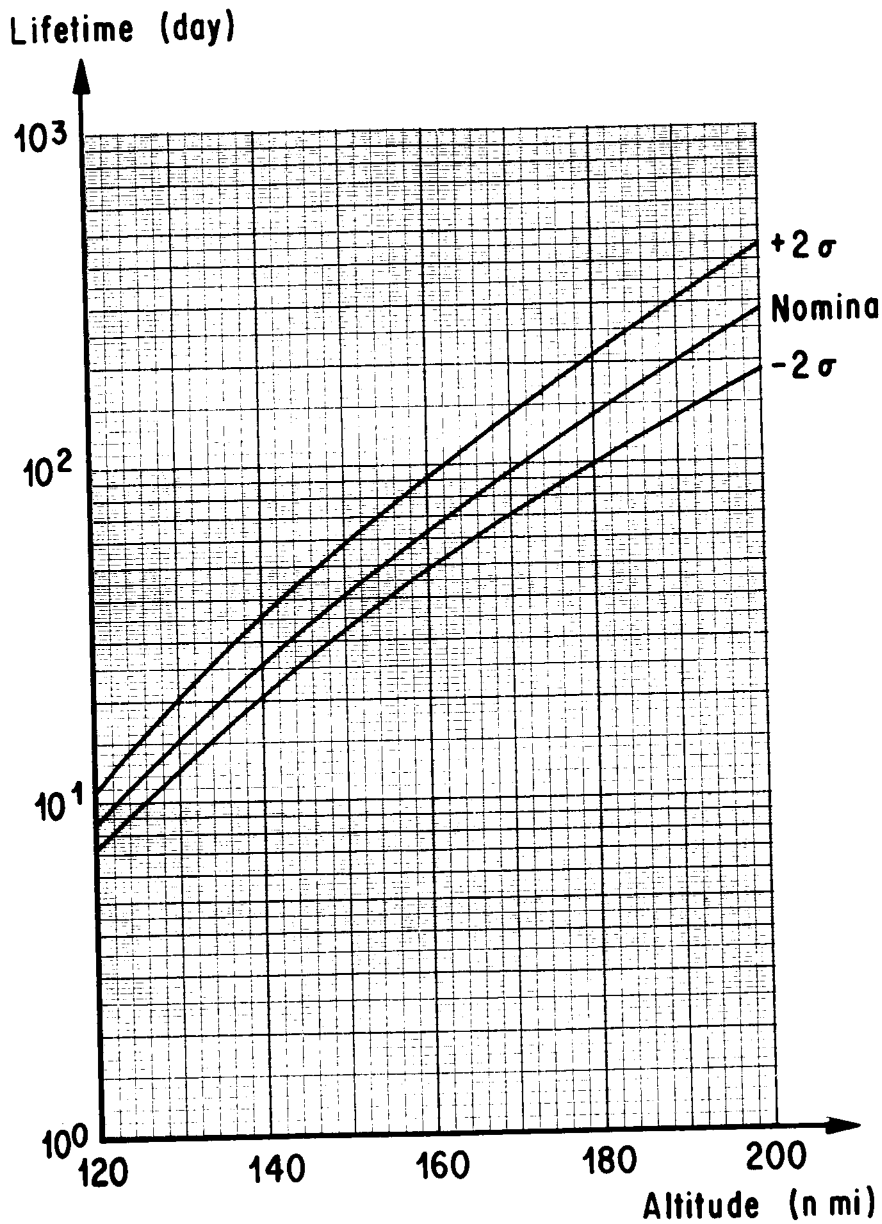


FIG. 15. ATM LIFETIME VS ALTITUDE FOR THE 14 DAY BROADSIDE, 6 MONTH TUMBLING MODE

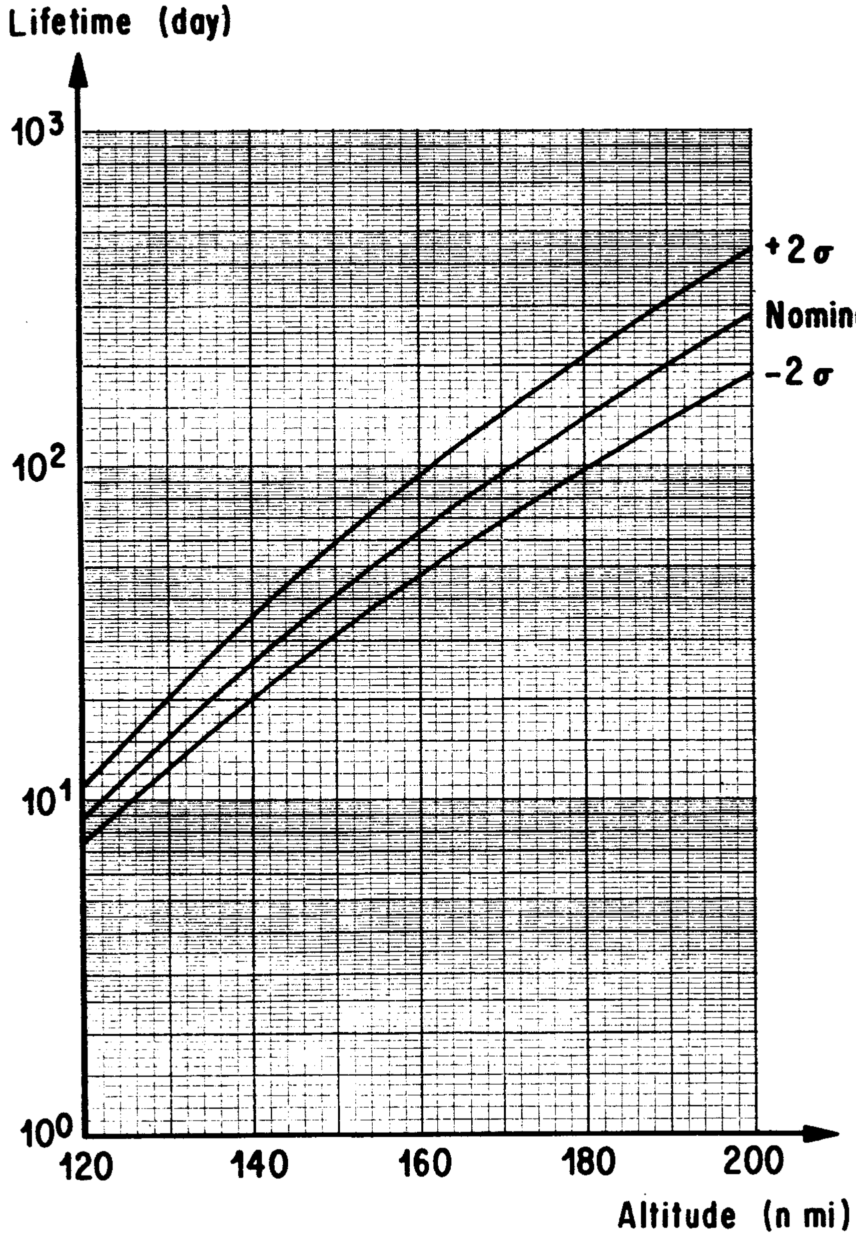


FIG. 16. ATM LIFETIME VS ALTITUDE FOR THE 28 DAY BROADSIDE, 3 MONTH TUMBLING MODE

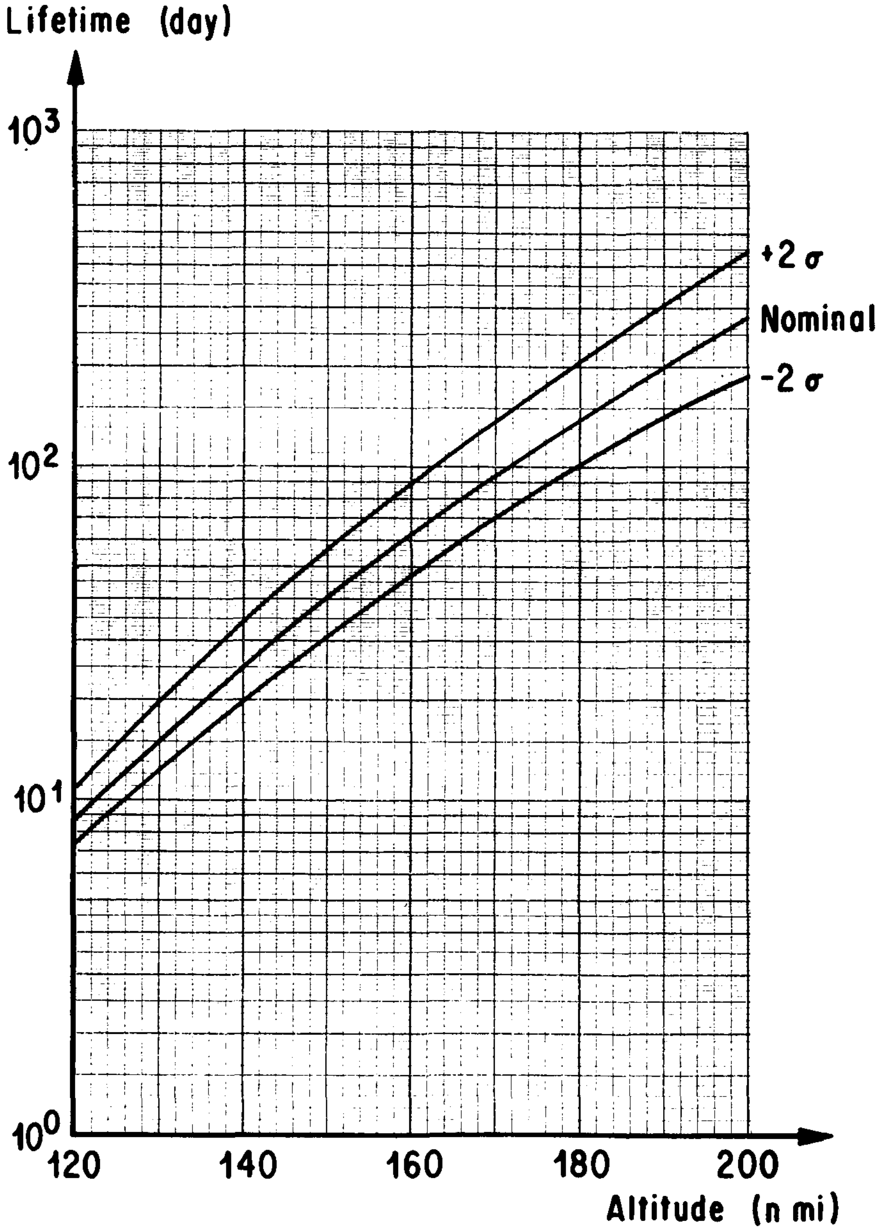


FIG. 17. ATM LIFETIME VS ALTITUDE FOR THE 28 DAY BROADSIDE, 6 MONTH TUMBLING MODE

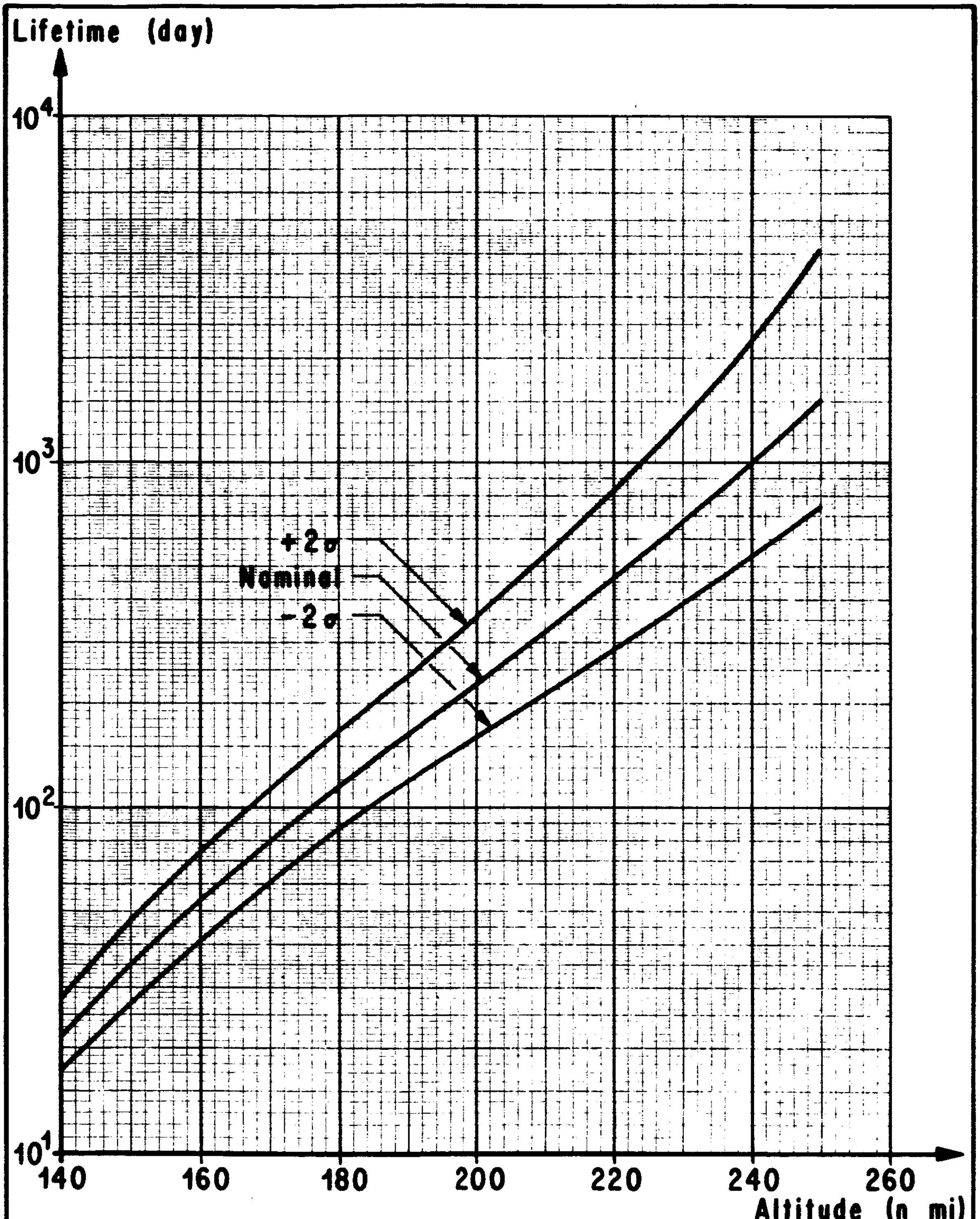


FIG. 18. ATM (LM/CSM) LIFETIME VS ALTITUDE FOR THE 14 DAY BROADSIDE, 3 MONTH TUMBLING MODE

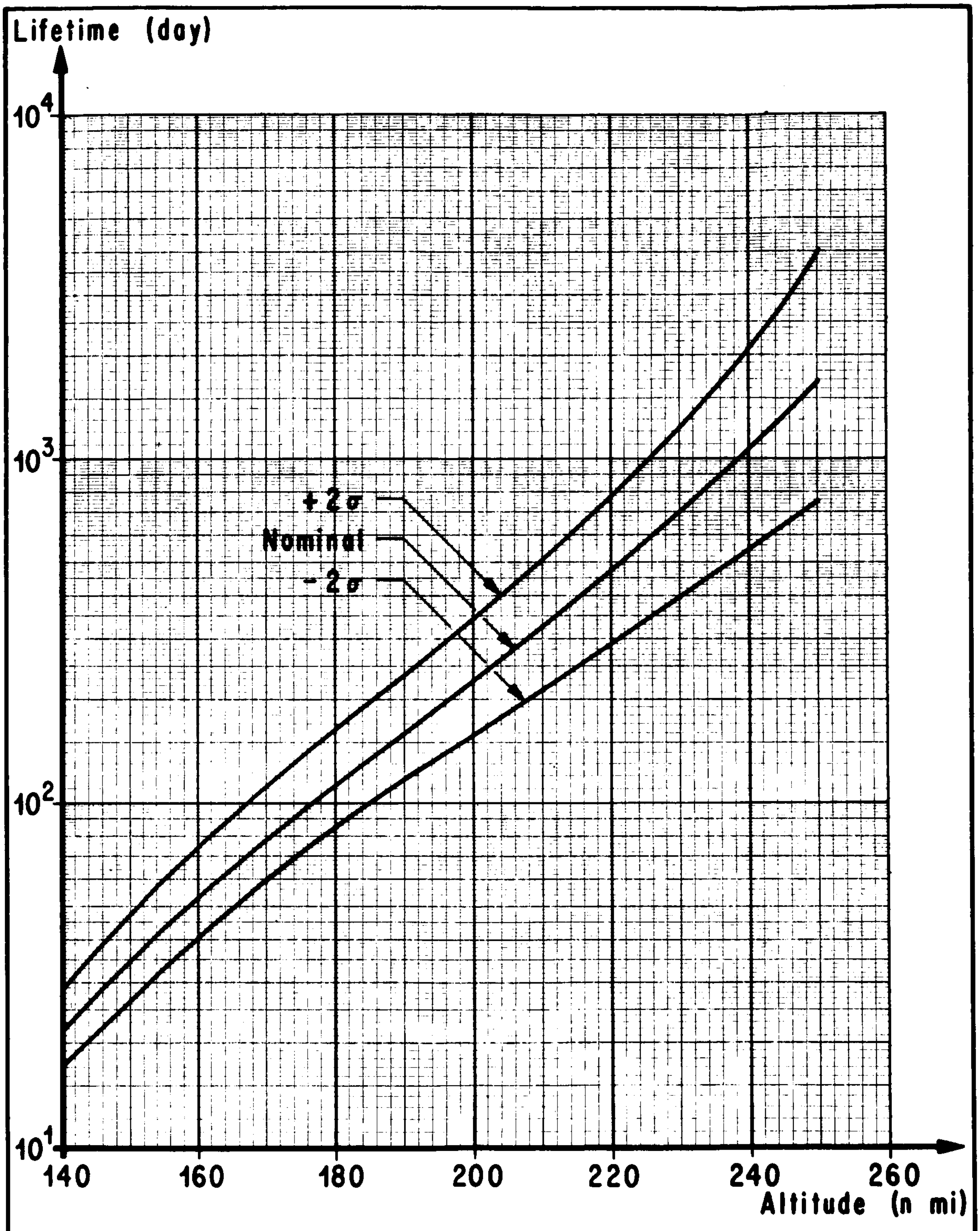


FIG. 19. ATM (LM/CSM) LIFETIME VS ALTITUDE FOR THE 14 DAY BROADSIDE, 6 MONTH TUMBLING MODE

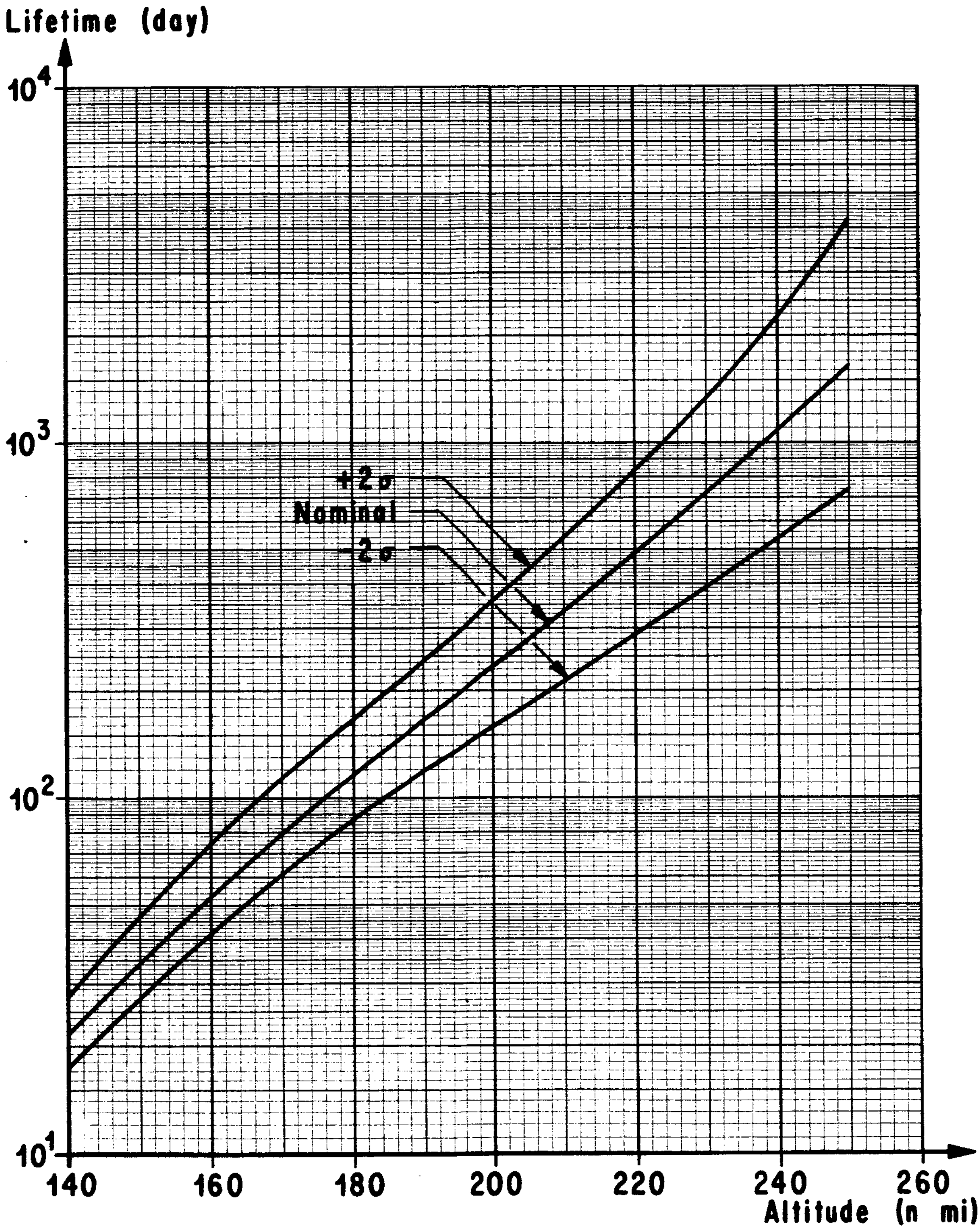


FIG. 20. ATM (LM/CSM) LIFETIME VS ALTITUDE FOR THE 28 DAY BROADSIDE, 3 MONTH TUMBLING MODE

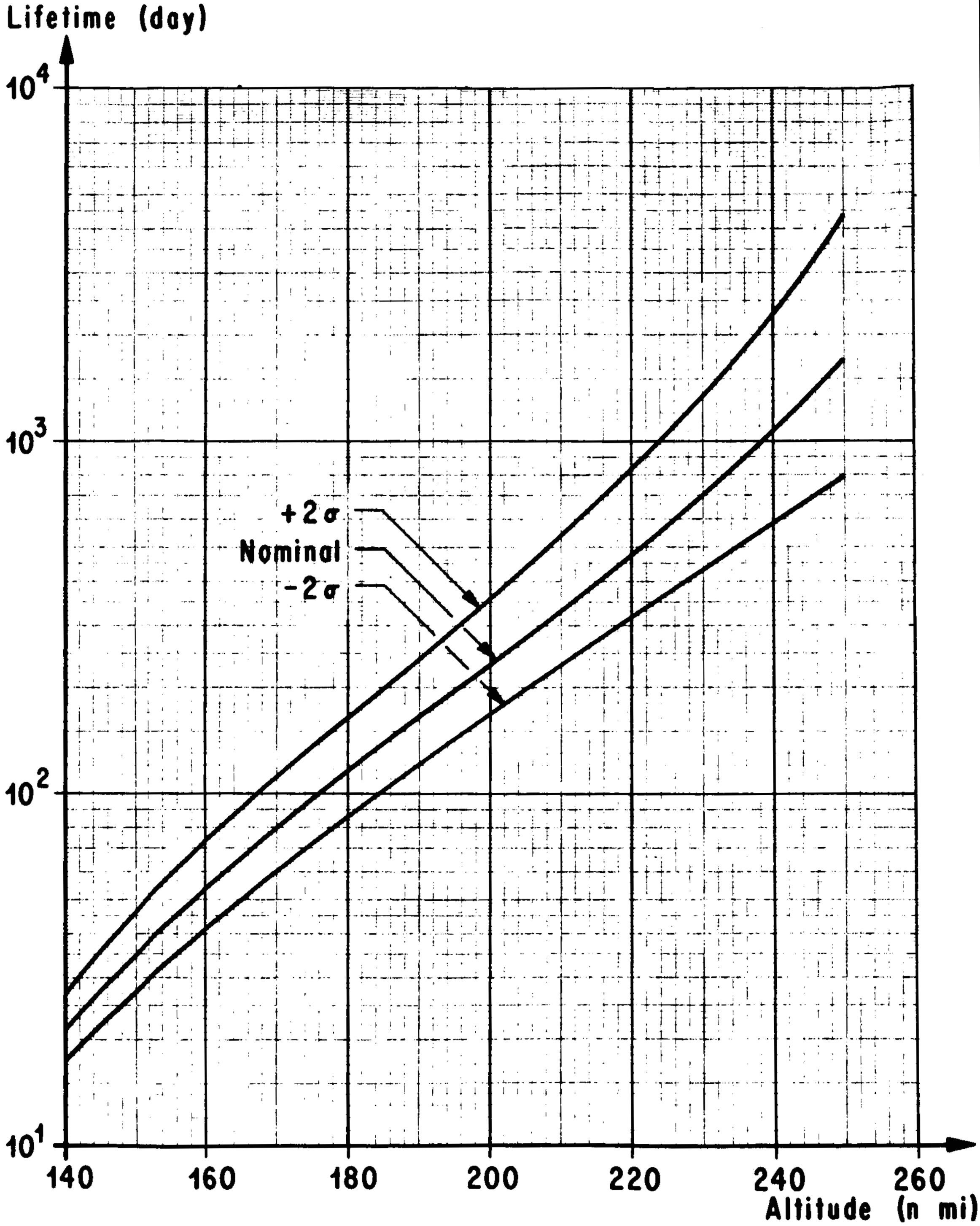


FIG. 21. ATM (LM/CSM) LIFETIME VS ALTITUDE FOR THE 28 DAY BROADSIDE, 6 MONTH TUMBLING MODE

VI. DYNAMICS AND CONTROL

Several of the dynamic, stability, and control problems and the analytical methods for their solution are outlined below. These problems, in general, are very similar to those for the Saturn vehicles and other spacecraft analyzed previously. The methods now used should be sufficient, with few exceptions, for analysis of the ATM. Some of the specific computer programs now used are, of course, highly specialized for greater efficiency. The amount of specialized methods to be developed for the ATM would depend on the number of configurations to be analyzed and possibly the need to include effects now neglected.

The free vibration analysis would probably be straightforward but could require a moderately large manpower effort if a detailed structural model is needed. An energy method would be most likely, probably something similar to the VISA program now used for the uprated Saturn I vehicle. This superimposed normal mode technique has been found to be accurate, convenient, and economical. Of course, the exact technique cannot be determined until after a study of the structure. The present knowledge of part of the structure should be very useful and reduce the total effort required.

The above discussion has considered the structure to be linear. This would need to be verified. The presence of large nonlinearities would greatly complicate the analysis. An analysis would probably need to be specially developed.

The structural damping would probably be very similar to that of present vehicles for earth environment. The changes due to space environment would need to be carefully examined, especially since a long lifetime is desired. This laboratory has sponsored damping studies in the past and is currently examining literature on space environmental effects.

Propellant slosh dynamics would need to be analyzed. Low-g slosh analysis methods are now fairly well developed and progress toward better understanding of the phenomenon is good. A useful slosh analysis for the ATM should be possible.

Current control system stability and response analyses should be totally adequate for the ATM system if no nonlinearities occur. Present equations would require very little or no change. A system with nonlinearities would require more analysis. Presently, a system of computer programs is used for these analyses. The first generates the coefficient of the matrices for the system. This program may need some minor modification since the input format could depend on the method of structural vibration analysis. The stability program could probably be used without alteration. The response program may require addition of a different forcing function to simulate crew movements. The crew movements and the crew's physical movement reactions to vehicle motions would be part of the feedback loop and their random movements would need to be known. These programs are used as a system,and data handling is done by magnetic tape to reduce chance of human error.

One of the first items to be studied should be docking dynamics. This would include rigid and flexible body stability analysis of the control system during coupling, slosh dynamics, and coupling forces. Analyses for these items are now under development. Dynamics and control analyses while in the docked configuration also will require extensive study if a docked mode of ATM operation is choosen.

It is easily shown that if the control frequency and damping of the LM with CMG control is 1.3 cycles per second and 0.7, respectively, then when the CSM docks, the control frequency and damping are reduced about one-half with the LM holding the control gains constant. For example, the approximate equations [2] for the control frequency and damping are

$$\omega_c = \frac{4}{3}\sqrt{\frac{a_o H}{I}} \tag{14}$$

$$\zeta_c = (2/3)\ (a_1/a_o)\sqrt{\frac{a_o H}{I}} = \frac{a_1\ \omega_c}{2a_o}\ . \tag{15}$$

When the CSM docks, the total configuration moment of inertia, I, may increase by a factor of about four, thus effecting the reduction of control frequency and damping. If the first mode structural frequency of the combined vehicle is at least 1.3 cycles per second, then there will be a one octave or more frequency difference between the first structural mode and the control frequency. No additional stability problems would be anticipated that were not already inherent in the LM-CMG system. However, the response time of the docked vehicle would be twice as long, and the disturbances would require a longer time to damp out compared to the LM configuration.

If the control sensors are located near the sources of applied moment, then the structural bending modes are usually phase stabilized. Although the bending itself is stable, the system with flexible dynamics will no longer possess the same desired dominant root characteristics as the simplified rigid body system. Usually the system must be analyzed by root locus, and the control gains adjusted to produce the desired results. The control system of the docked LM and CSM with sensors located near the CMGs will produce phase stable structural modes without additional compensation by filters. However, as in booster control with point-of-force sensing, the system with flexible dynamics must be analyzed and the control gains adjusted to produce the desired dominant root location in the complex plane.

In conclusion, analysis programs have already been developed in the areas of structural-free vibration, vehicle stability, and vehicle response. The docking dynamics mode is a straightforward extension of these methods. The damping and low-g slosh problems may still require some state-of-the-art development. Progress is now being made in these areas, especially in low-g slosh, where much advanced work is being sponsored by this laboratory. The presence of nonlinearities would complicate but would not basically change the solution of the problem.

VII. CONCLUSIONS

1. More detailed mission analysis is necessary to firmly define the mission. This report assumes a dual launch with the CSM launched first, rendezvous at low earth orbit with use of the CSM for transfer to the higher orbit, and operation of the LM in an undocked mode.

2. More detailed timeline analyses must be performed when better information is available relative to experiment requirements. This report assumes four experiments, several of which may not be compatible with the flight schedule. Early selection of experiments for the first ATM mission must be made.

3. More detailed analysis of the aerodynamic disturbance torques about all three body axes is needed as the vehicle orbits about the earth in an inertially fixed attitude pointing toward the sun. These data will then provide time histories of the aerodynamic disturbance to be considered with gravity gradient disturbances for analysis of the control moment gyro dumping requirements.

4. Detailed free-molecule flow analysis is needed throughout the entire pitch and yaw angle-of-attack regions using the flight configuration to be used for the ATM mission. If solar panels are to be used, they must be included in the analysis. Whether or not the mission is performed in a docked or undocked mode will influence these results.

5. Additional lifetime studies may be required, especially if the LM with solar panels is used in the undocked mode. These studies cannot be performed, however, until the free-molecule drag characteristics are computed for this configuration.

6. Extensive dynamics and control analyses will be required to properly assess the capability of the spacecraft to perform the ATM fine attitude control requirements. This is especially true if the mission is performed in the docked mode.

7. Many areas of interest to this laboratory have not been touched upon. The proper processing and disposition of telemetered data are an example. The MSFC Flight Evaluation Working Group will provide post-flight engineering evaluation support for the mission. More detailed planning of experimental data retrieval can be made when the requirements are better defined.

APPENDIX A

Preliminary Timeline Analysis for Crew Transfer Every Twelve Hours

A preliminary timeline is presented herein for the ATM mission to investigate specific solar features in detail with a complement of instruments measuring in the white light, ultraviolet, extreme ultraviolet, and X-ray regions of the spectrum. The major emphasis of such experiments would be to investigate activity regions on the solar disk or in the corona to determine the characteristics of specific phenomena. Four experiments are considered for this mission:

a. Ultraviolet Spectrometer, Harvard College Observatory, (HCO).

b. Ultraviolet Spectrograph, Naval Research Laboratory, (NRL).

c. Extreme UV/X-ray Spectroheliographs, Goddard Space Flight Center (GSFC).

d. White Light Coronagraph, High Altitude Observatory, (HAO).

The timelines reflect the following assumptions:

a. Mission duration of 14 days.

b. Launch was selected to be from Cape Kennedy in the early morning into a 200 n.m. orbit with an inclination of 29.5°.

c. The vehicle model consists of the CSM and the LM in which the telescopes are mounted. The LM is released from the CSM during the experiments; the CSM must rendezvous and dock with the LM for change of crew. A total of 1 1/2 hours was allotted for rendezvous, docking and crew transfer.

d. Two crew members remain in the CSM while the other performs the experiments in the LM for a 12-hour duration. All crew members rotate. No astronaut will remain in the LM for a period of longer than 12 hours.

e. Observing requirements for the four study experiments conducted in the LM are presented in Table 1A. Three modes of experiment observing are defined by these requirements.

(1) Patrol mode: Experiments in standby condition with course-sun orientation, and astronaut may monitor solar activity. No data acquisition performed. This mode is represented in the timelines as $\boxed{//////////}$.

(2) Standard mode: Scheduled observations of solar regions for data acquisition periods of 1 to 10 minutes.

(3) Activity mode: Observations of active solar regions for data acquisition periods of 20 minutes or greater. This mode is designated in the timelines by the AM in the upper right of the experiment scheduled.

f. An EVA, Extra-Vehicular Activity, occurs on the seventh and final days for data retrieval.

g. Sleep periods precede and follow a LM tour of duty. A nap may occur in the LM. Astronauts do not necessarily sleep simultaneously. Astronauts are scheduled at least seven and one-half hours of sleep per day.

h. There will be two hot meals of 45 minute duration each, and one snack of 30 minutes each day. A transfer of a food supply into the LM occurs each third day as snacks may occur in the LM.

i. Two personal hygiene periods per day for each astronaut is assumed.

j. There will be a CSM system check of 30 minute duration each 12 hour ±1 hour, with a total of 3 checks per day. A CSM system check is designated by CSM.

k. The LM requires a 10 minute systems check performed six times each day. A LM check occurs as each astronaut enters the LM, another during the shutdown procedure following an operational laboratory period. A LM systems check is designated by LM.

l. Thirty minutes is assumed for LM checkout and axis alignment upon entering the LM.

m. Each astronaut will perform a five-minute safety check of his personal equipment each 13 hours or less.

The timelines contain the following information:

a. Mission time in hours from launch is marked on top of the timeline.

b. C1, C2, and C3 lines represent the activities of each crew member.

c. Following the crew activities is a row designated "node." The "D" and "A" signify the descending nodal crossing and ascending nodal crossing, respectively, at the times shown.

d. This mission is independent of a strict launch time; however, a representative day-night scale is given.

e. The row designated "land" shows when the spacecraft is over major land masses and specifies which land mass by the code referenced in the list of symbols.

f. Tracking station coverage is shown on the last line. The individual stations are abbreviated and are defined in the list of symbols.

TABLE 1A

EXPERIMENT OBSERVING REQUIREMENTS

Study Experiments	Standard Mode				Activity Mode				Patrol Mode	Total Time
	Duration of Data Sampling Sequences (min)	Number of Data Sampling Sequences	Number of Orbits Between Sequences	Cumulative Observing Time (hr)	Duration of Data Sampling Sequences (min)	Number of Data Sampling Sequences	Number of Orbits Between Data Sequences	Cumulative Observing Time (hr)	Cumulative Observing Time (hr)	(Hr.)
HCO	8.5	100	2	14.1	25.5	13	15	5.5	--	19.6
NRL	10	50	4	8.3	20	13	15	4.3	--	12.6
GSFC	5[(a)]	50	4	4.1	20 100	13 1	15 200	4.3 1.7	50[(b)] --	58.4[(b)] 1.7
HAO	5[(a)]	50	4	4.1	20	13	15	4.3	--	8.4
Totals				30.6				20.1	50	100.7

(a) Assumes 5 data samples (approximately 1 minute each) for each sequence distributed over one orbit at 12 minute intervals.

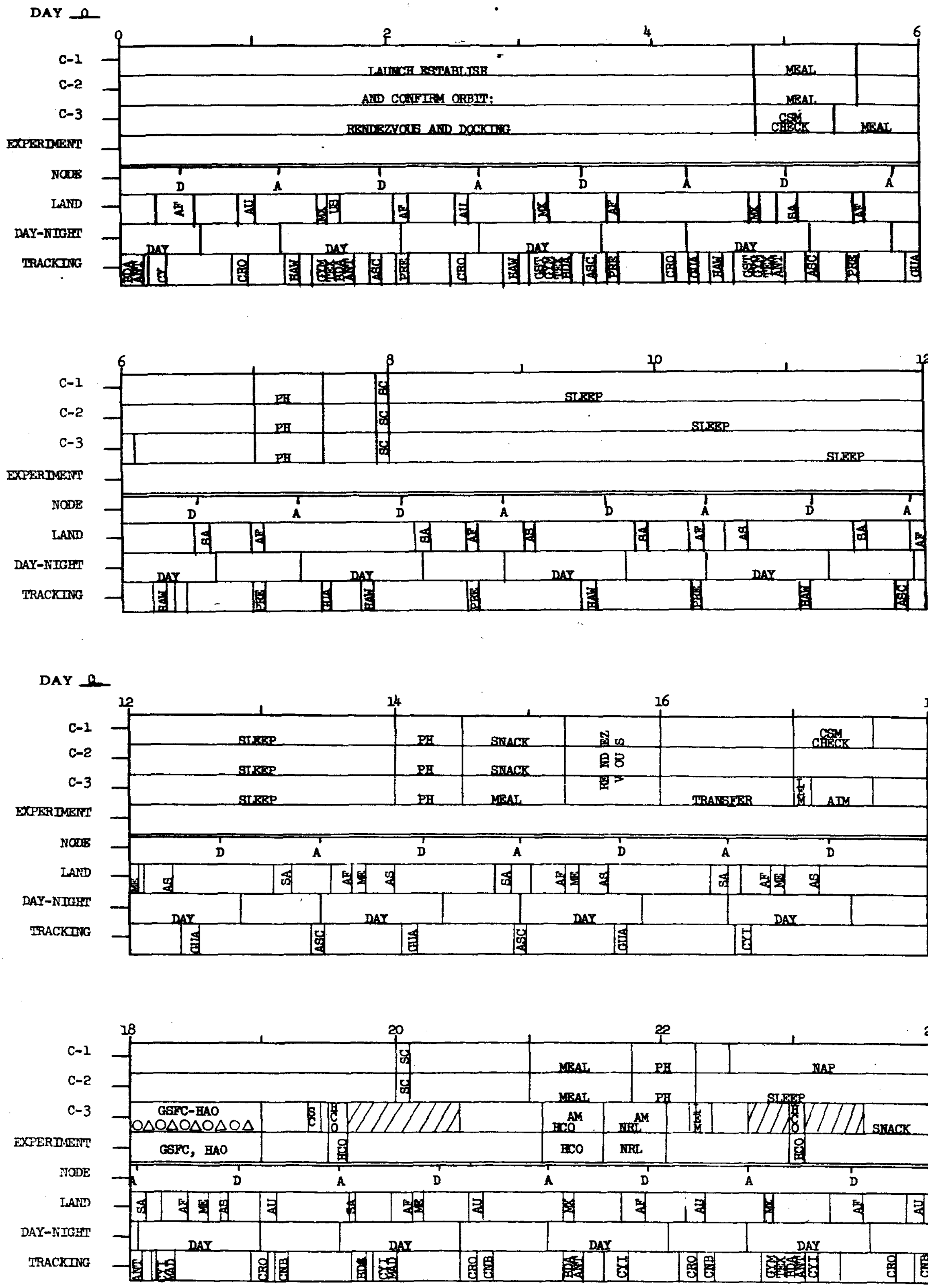
(b) GSFC experiment in standby operation as activity detector.

LIST OF SYMBOLS

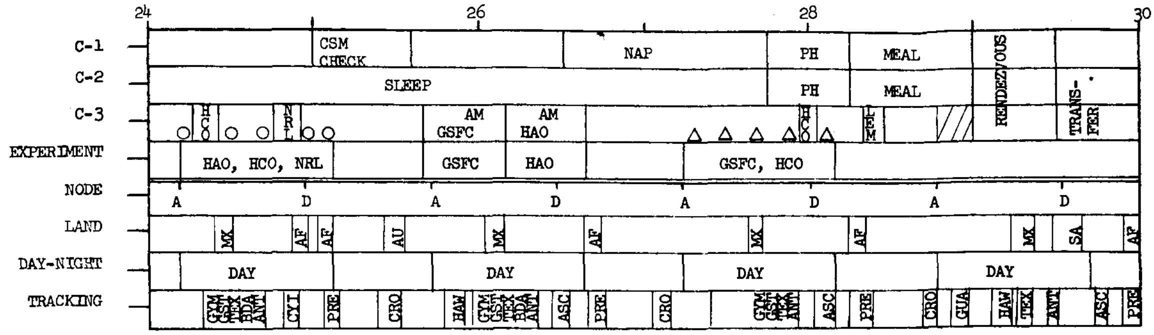
1.	C1	Crew member 1
2.	C2	Crew member 2
3.	C3	Crew member 3
4.	D	Descending node
5.	A	Ascending node
6.	Day	Means vehicle in sunlight
7.	P. H.	Personal hygiene
8.	SC	Safety package check
9.	SA	South America
10.	US	United States
11.	AF	Africa
12.	AU	Australia
13.	AS	Asia
14.	MX	Mexico
15.	ME	Middle East
16.	BDA	Bermuda
17.	ANT	Antigua
18.	ASC	Ascension
19.	CYI	Canary
20.	MAD	Madrid
21.	CRO	Carnarvon
22.	CNB	Canberra
23.	GUA	Guam
24.	HAW	Hawaii
25.	GYM	Guaymas
26.	GST	Goldstone
27.	TEX	Texas
28.	PRE	Pretoria
29.	LEM	LEM System check
30.	AIM	Vehicle & camera alignment
31.	HCO	Harvard College Observatory

32.	HAO	High Altitude Observatory
33.	GSFC	Goddard Space Flight Center
34.	AM	Activity Mode
35.	NRL	Naval Research Laboratory
36.	Transfer	Astronauts go from LEM to CSM and vice versa
37.	Δ	GSFC experiment operating
38.	O	HAO experiment operating
39.	///	Patrol mode: Standby condition with course sun orientation and astronaut monitoring solar activity. No data activity performed.
40.	EVA	Extravehicular activity
41.	CMG spin up	Control moment gyro spin up

NOTE: Madrid, Canberra, and Goldstone have 85-foot dishes and cannot track in earth orbit. They are for deep space tracking. Other available tracking sites not included here are White Sands, Patrick, Eglin, KSC, Pt. Arguello, Grand Bahama Island, and Grand Turk Island. Future updating of these timelines will take this into account.


DAY 0
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
LAUNCH ESTABLISH
AND CONFIRM ORBIT:
RENDEZVOUS AND DOCKING
MEAL
CSM CHECK
PH
SC
SLEEP
DAY 0
SNACK
RENDEZVOUS
TRANSFER
ATM
GSFC-HAO
GSFC, HAO
HCO
AM
NRL
NAP
DAY

DAY 1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C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
CSM CHECK
NAP
PH
MEAL
SLEEP
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TRANS-FER
AM GSFC
AM HAO
HAO, HCO, NRL
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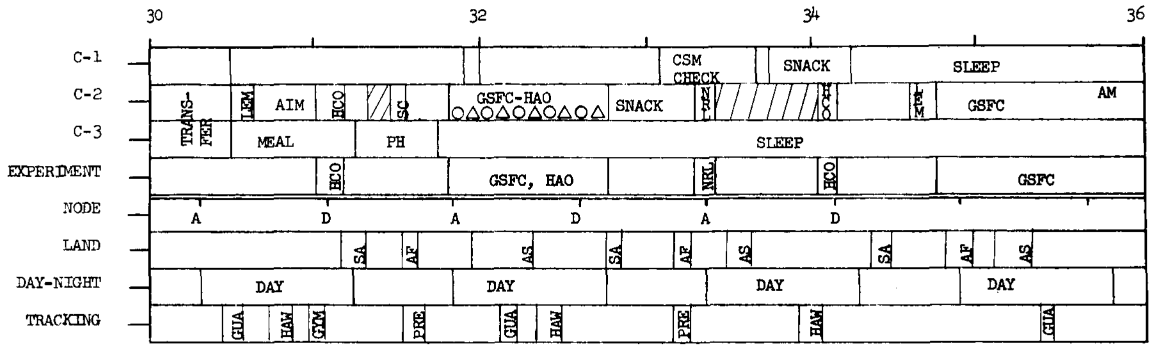
HAO
GSFC, HCO
DAY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C-1
C-2
C-3
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DAY-NIGHT
TRACKING
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SLEEP
TRANS-FER
AIM
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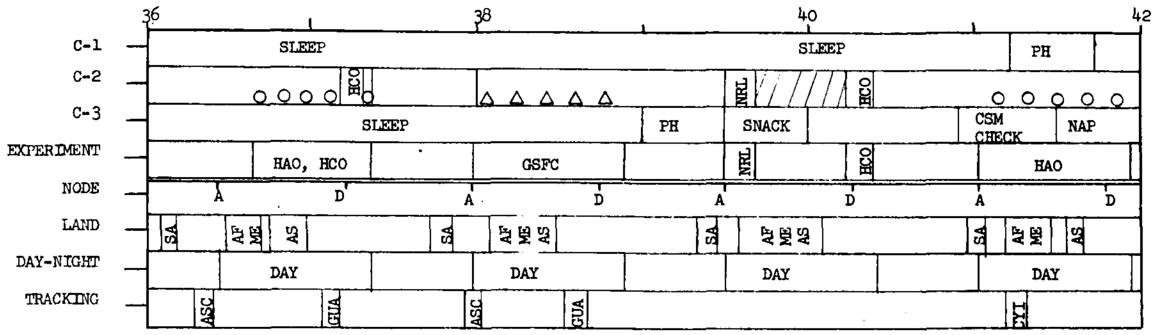
GSFC
AM
MEAL
PH
GSFC, HAO
DAY

DAY 1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C-2
C-3
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CSM CHECK
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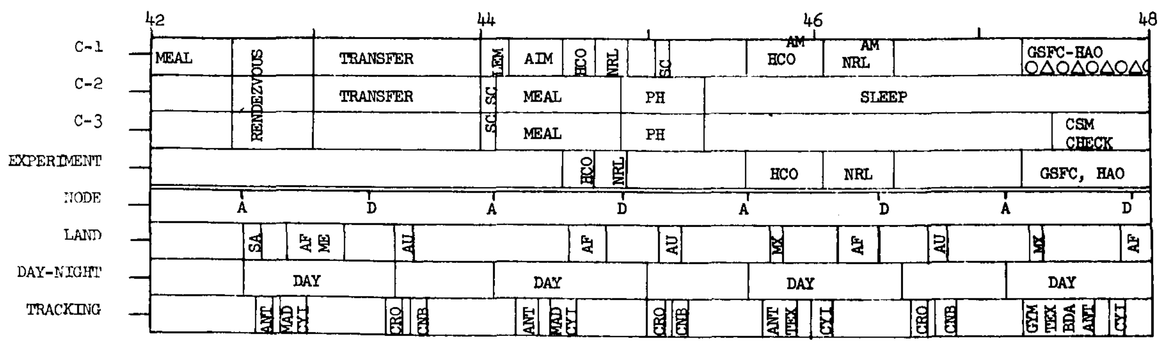
GSFC
HAO
DAY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44
46
48
C-1
C-2
C-3
EXPERIMENT
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DAY-NIGHT
TRACKING
MEAL
RENDEZVOUS
TRANSFER
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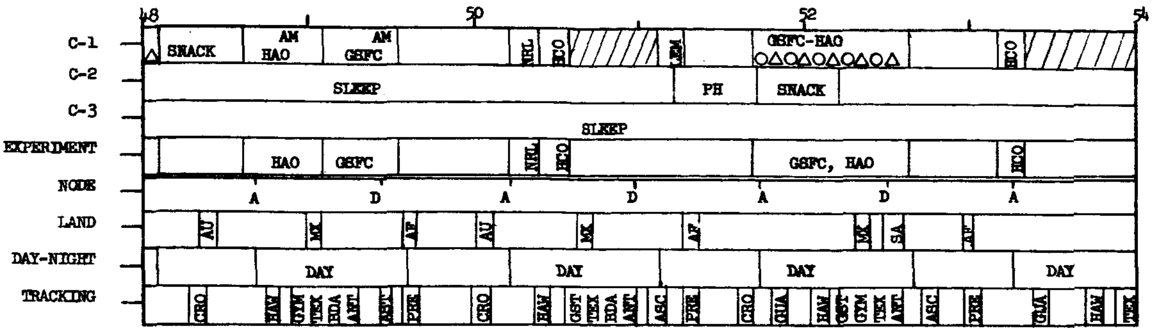
AM NRL
GSFC-HAO
MEAL
PH
SLEEP
CSM CHECK
HCO
NRL
GSFC, HAO
DAY

DAY 2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C-2
C-3
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DAY-NIGHT
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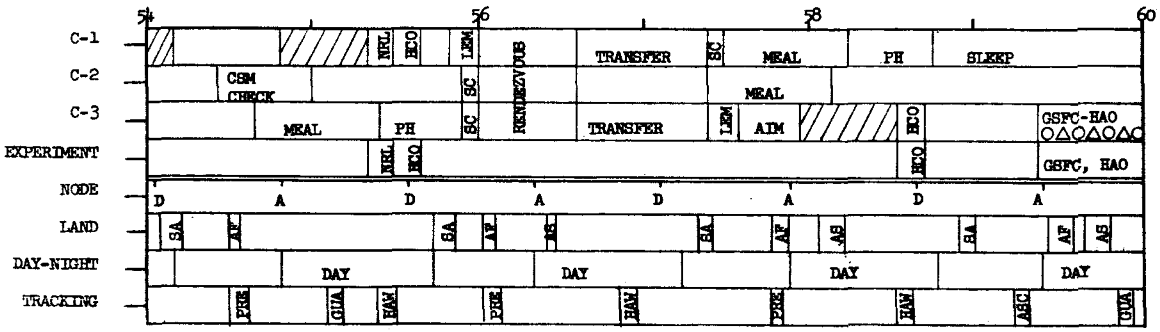
AM GSFC
GSFC-HAO
SLEEP
PH
SNACK
SLEEP
HAO
GSFC
GSFC, HAO
DAY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58
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C-2
C-3
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DAY-NIGHT
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TRANSFER
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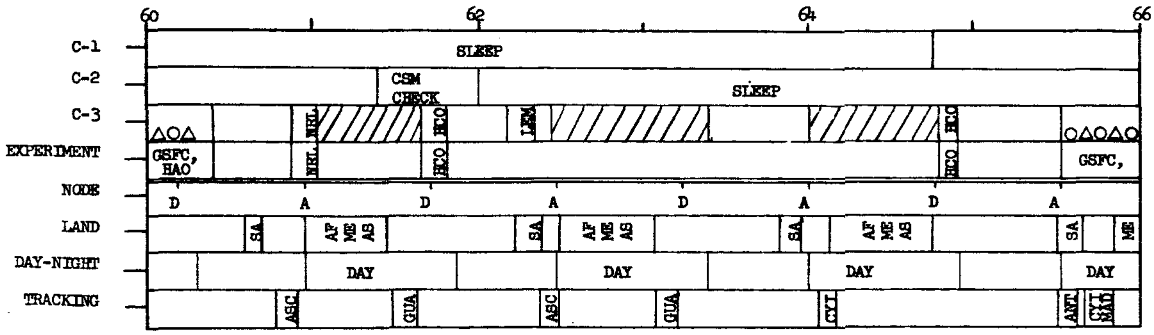
RENDEZVOUS
TRANSFER
AIM
GSFC-HAO
GSFC, HAO
DAY

DAY 2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TRACKING
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CSM CHECK
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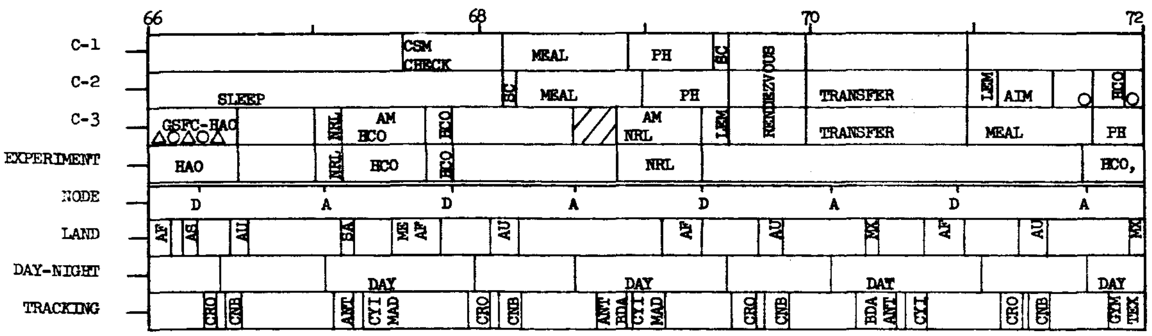
GSFC,
DAY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C-2
C-3
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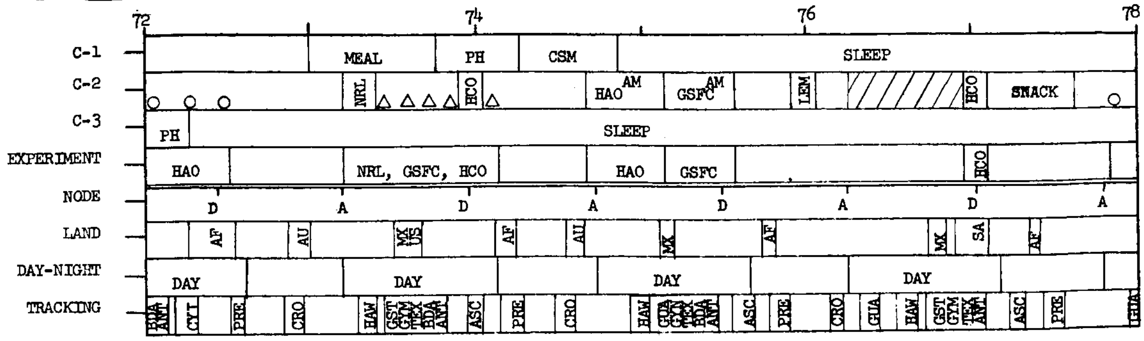
DAY-NIGHT
TRACKING
CSM CHECK
MEAL
PH
RENDEZVOUS
SLEEP
MEAL
PH
TRANSFER
AIM
GSFC-HAO
AM HCO
AM NRL
TRANSFER
MEAL
PH
HAO
HCO
NRL
HCO,
DAY

DAY 3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C-3
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TRACKING
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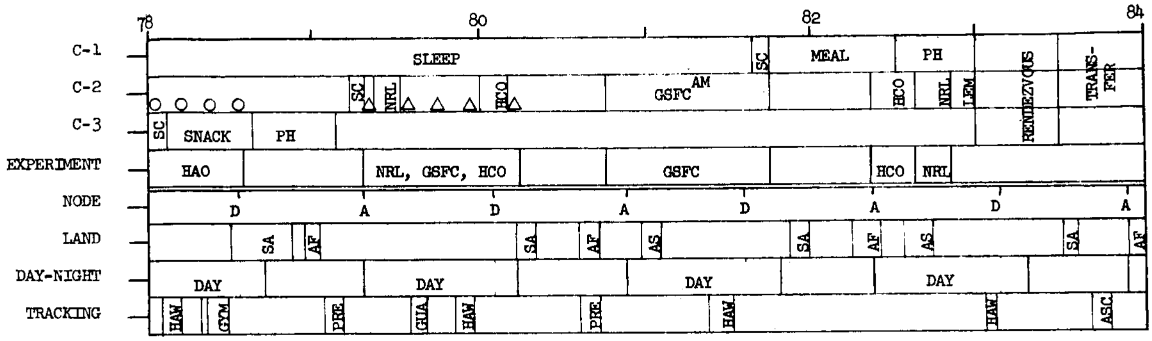
CSM
SLEEP
SNACK
HAO
NRL, GSFC, HCO
GSFC
DAY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82
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C-1
C-2
C-3
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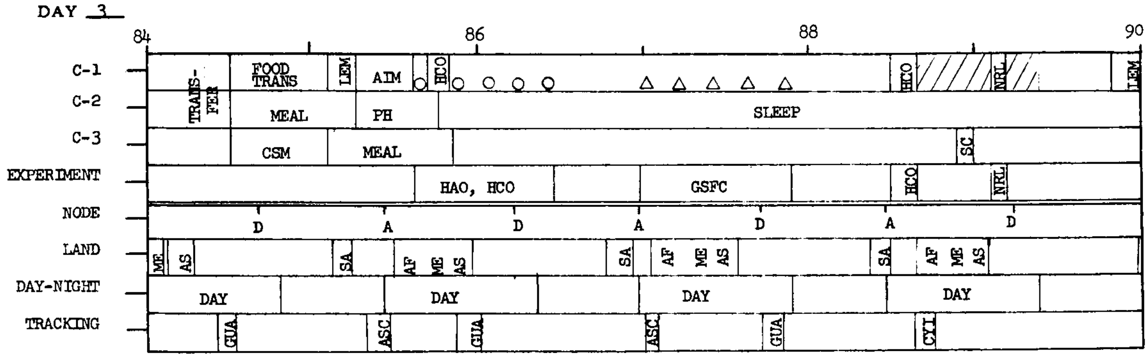
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP
MEAL
PH
SNACK
RENDEZVOUS
TRANS-FER
HAO
NRL, GSFC, HCO
GSFC
DAY

DAY 3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88
90
C-1
C-2
C-3
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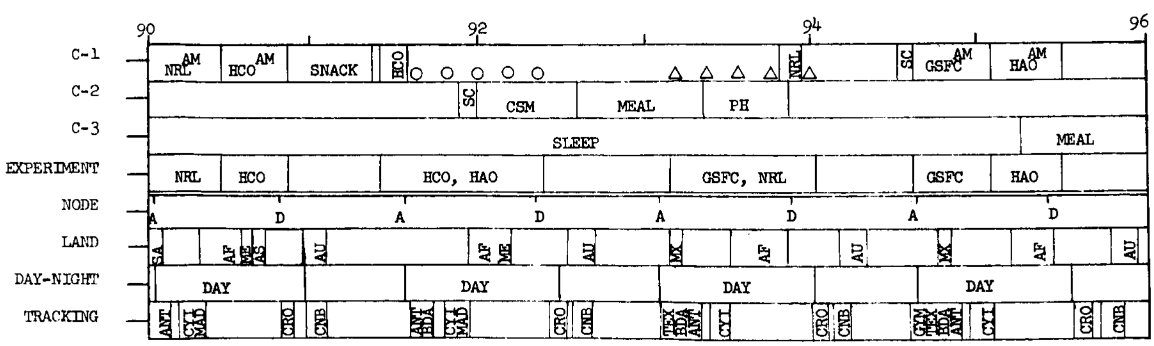
DAY-NIGHT
TRACKING
TRANS-FER
FOOD TRANS
AIM
MEAL
PH
SLEEP
CSM
HAO, HCO
GSFC
DAY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94
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C-2
C-3
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LAND
DAY-NIGHT
TRACKING
SNACK
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MEAL
PH
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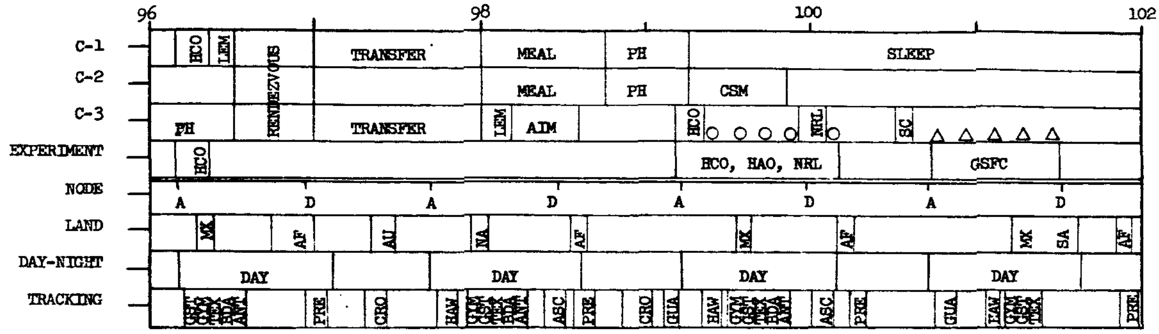
NRL
HCO
HCO, HAO
GSFC, NRL
GSFC
HAO
DAY

DAY 4



96
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102
C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
HCO LEM TRANSFER MEAL PH SLEEP
RENDEZVOUS
MEAL PH CSM
PH TRANSFER LEM AIM HCO NRL SC
HCO HCO, HAO, NRL GSFC
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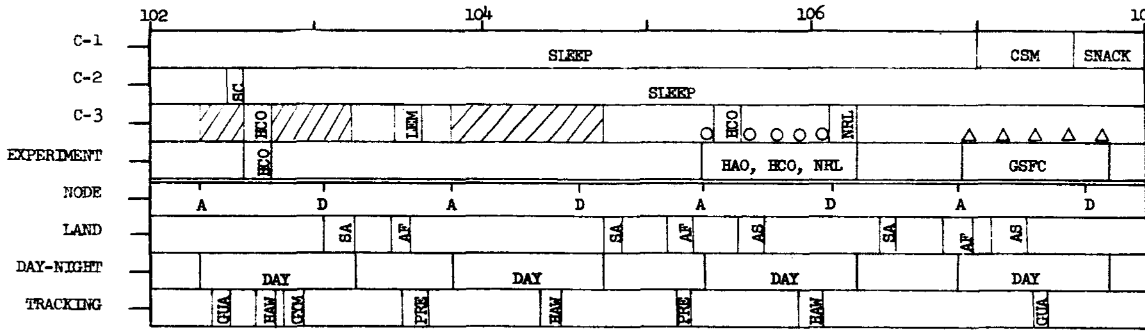

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C-2
C-3
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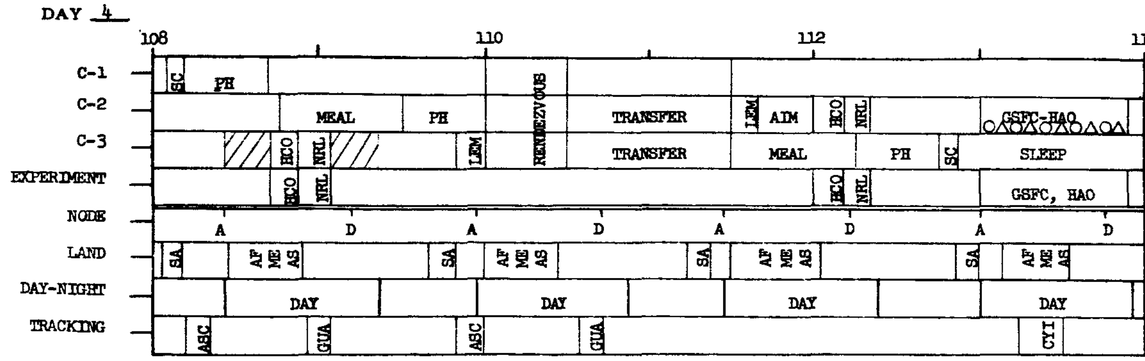
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP CSM SNACK
SC SLEEP
HCO LEM HCO NRL
HCO HAO, HCO, NRL GSFC
A D A D A D A D
SA AF SA AF AS SA AF AS
DAY DAY DAY DAY
GUA HAW GYM PRE HAW PRE HAW GUA

DAY 4



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C-2
C-3
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LAND
DAY-NIGHT
TRACKING
SC PH
MEAL PH RENDEZVOUS TRANSFER LEM AIM HCO NRL GSFC-HAO
HCO NRL LEM TRANSFER MEAL PH SC SLEEP
HCO NRL HCO NRL GSFC, HAO
A D A D A D A D
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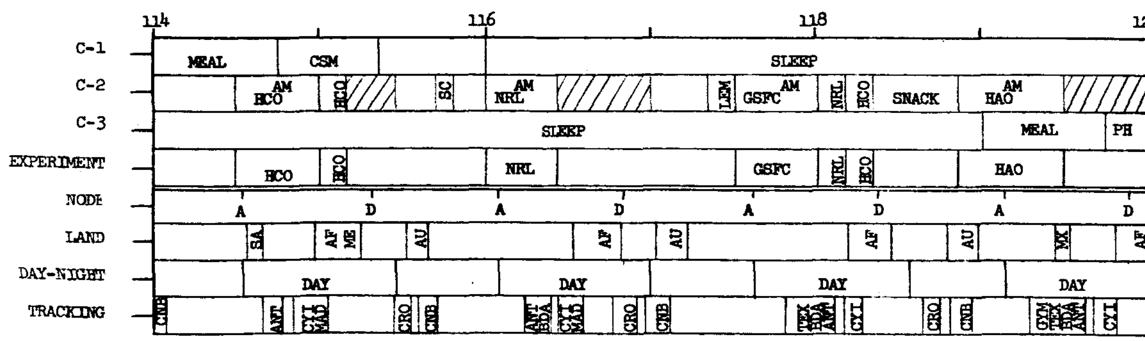
ASC GUA ASC GUA CYI



114
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118
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C-1
C-2
C-3
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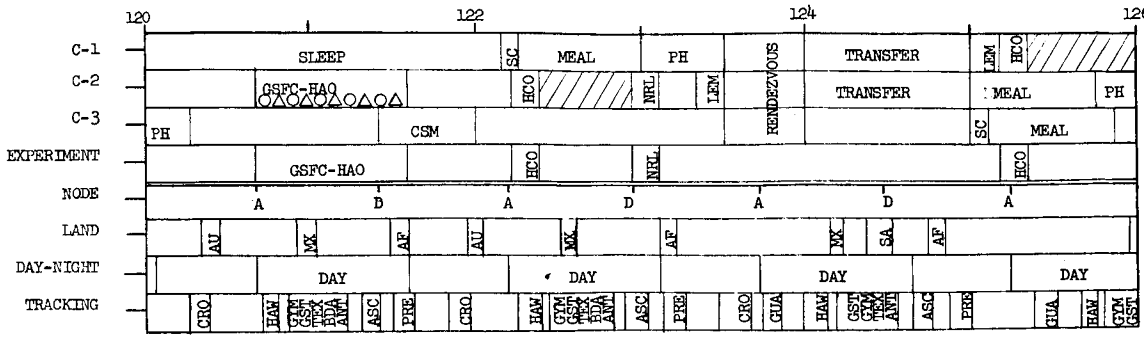
LAND
DAY-NIGHT
TRACKING
MEAL CSM SLEEP
AM HCO HCO SC AM NRL LEM AM GSFC NRL HCO SNACK AM HAO
SLEEP MEAL PH
HCO HCO NRL GSFC NRL HCO HAO
A D A D A D A D
SA AF ME AU AF AU AF AU MX AF
DAY DAY DAY DAY
CNB ANT CYI MAD CRO CNB ANT BDA CYI MAD CRO CNB TEX BDA ANT CYI CRO CNB GYM TEX BDA ANT CYI

DAY 5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124
126
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP
SC
MEAL
PH
RENDEZVOUS
TRANSFER
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HCO
GSFC-HAO
NRL
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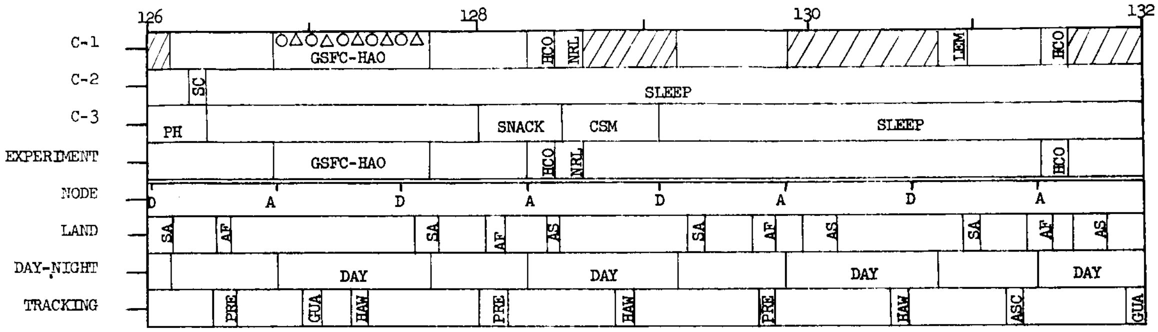
CSM
SC
MEAL
DAY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130
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C-1
C-2
C-3
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TRACKING
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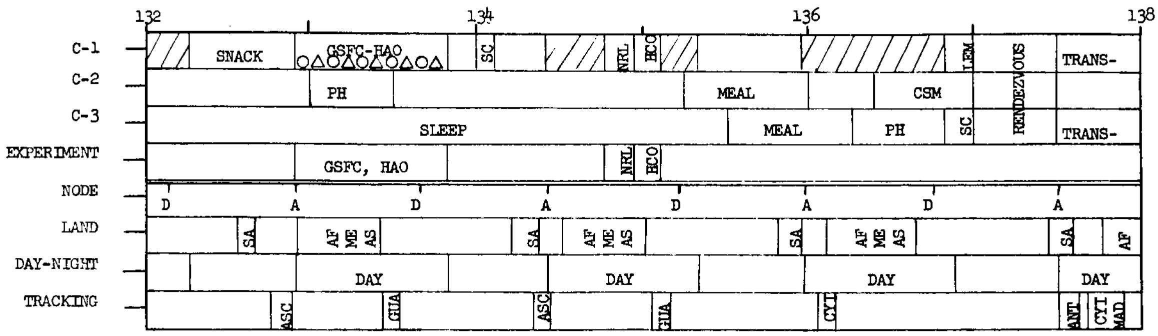
HCO
NRL
LEM
SC
SLEEP
PH
SNACK
CSM
SLEEP
DAY

DAY 5


132
134
136
138
C-1
C-2
C-3
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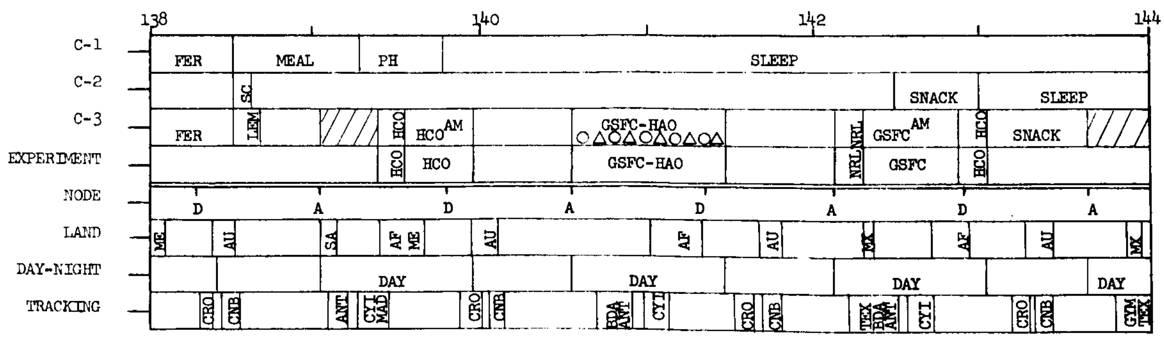
NODE
LAND
DAY-NIGHT
TRACKING
SNACK
GSFC-HAO
SC
NRL
HCO
LEM
RENDEZVOUS
TRANS-
PH
MEAL
CSM
SLEEP
MEAL
PH
SC
TRANS-
GSFC, HAO
DAY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142
144
C-1
C-2
C-3
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DAY-NIGHT
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MEAL
PH
SLEEP
SC
SNACK
SLEEP
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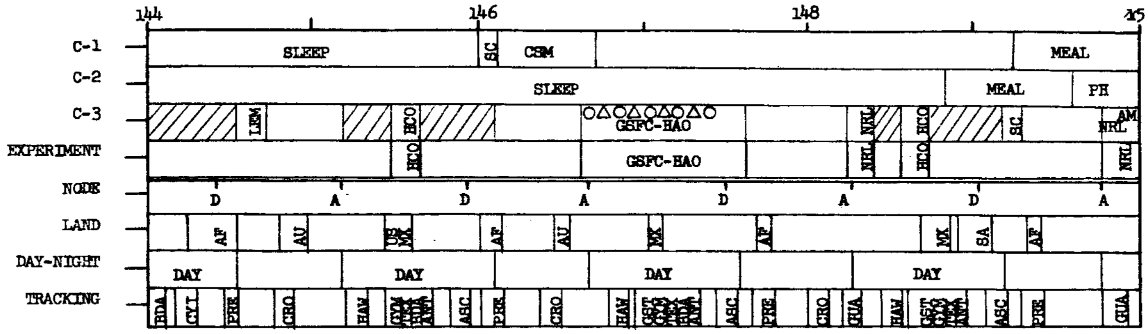
LEM
HCO
HCO AM
GSFC-HAO
NRL
GSFC AM
SNACK
HCO
GSFC
DAY

DAY 6



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C-2
C-3
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LAND
DAY-NIGHT
TRACKING
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CSM
MEAL
SLEEP
MEAL
PH
LEM
HCO
GSFC-HAO
NRL
SC
AM
HCO
GSFC-HAO
NRL
D
A
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PRE
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HAW
GYM
HUA
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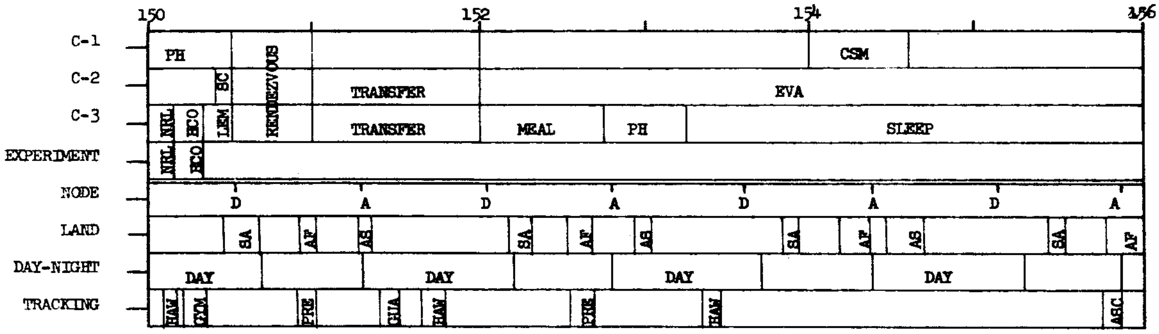
GUA
GST



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C-1
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C-3
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TRACKING
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RENDEZVOUS
CSM
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TRANSFER
EVA
NRL
HCO
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TRANSFER
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PH
SLEEP
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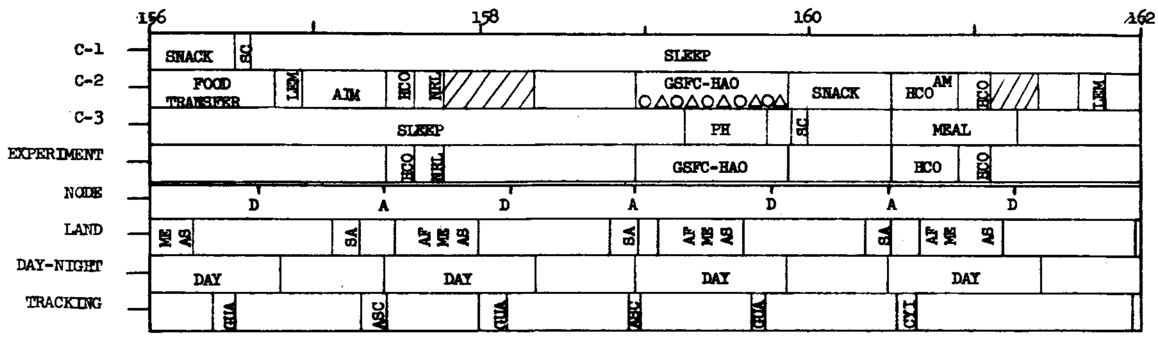
GYM
PRE
GUA
ASC

DAY 6



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C-1
C-2
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SC
SLEEP
FOOD TRANSFER
LEM
AIM
HCO
NRL
GSFC-HAO
SNACK
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AS
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ASC
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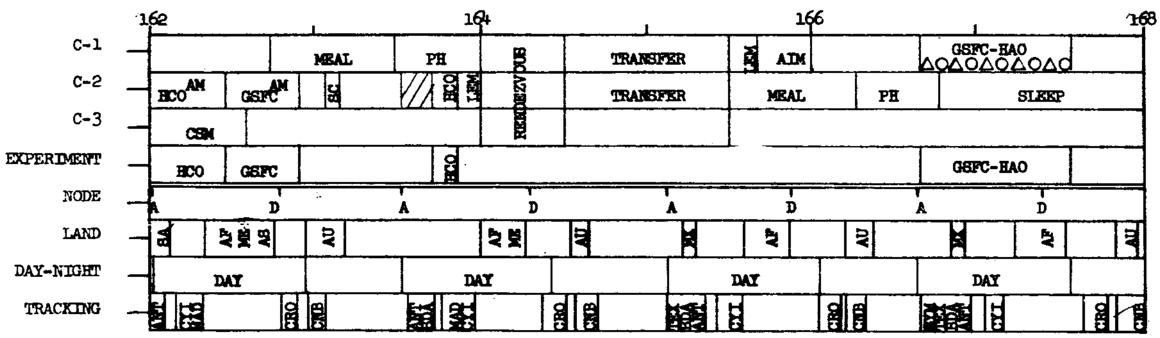

162
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C-1
C-2
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RENDEZVOUS
TRANSFER
LEM
AIM
GSFC-HAO
HCO
AM
GSFC
SC
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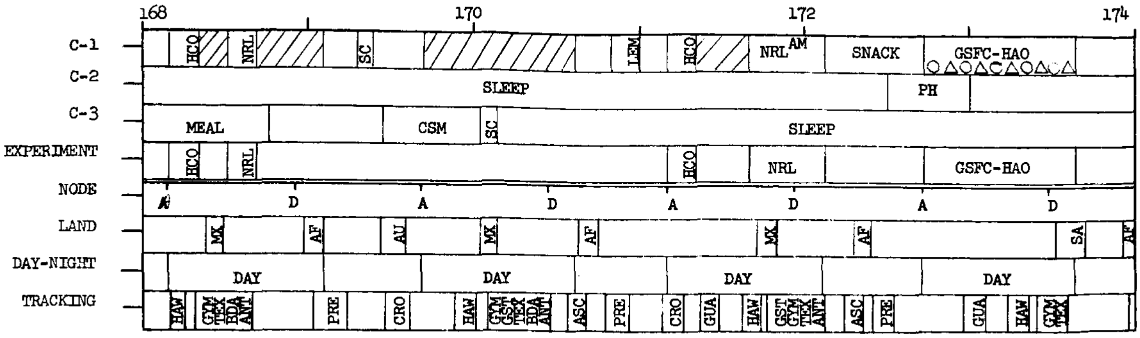
CNB
CYI

DAY 7



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C-1
C-2
C-3
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LEM
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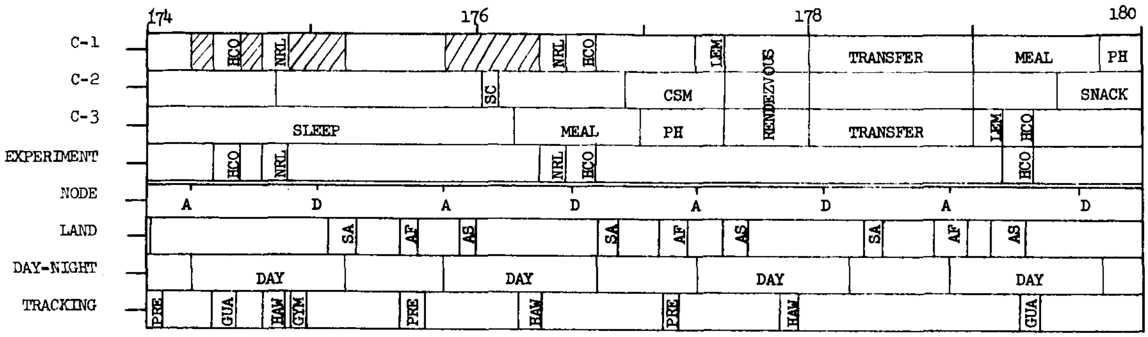
SNACK
GSFC-HAO
SLEEP
PH
MEAL
CSM
DAY



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C-1
C-2
C-3
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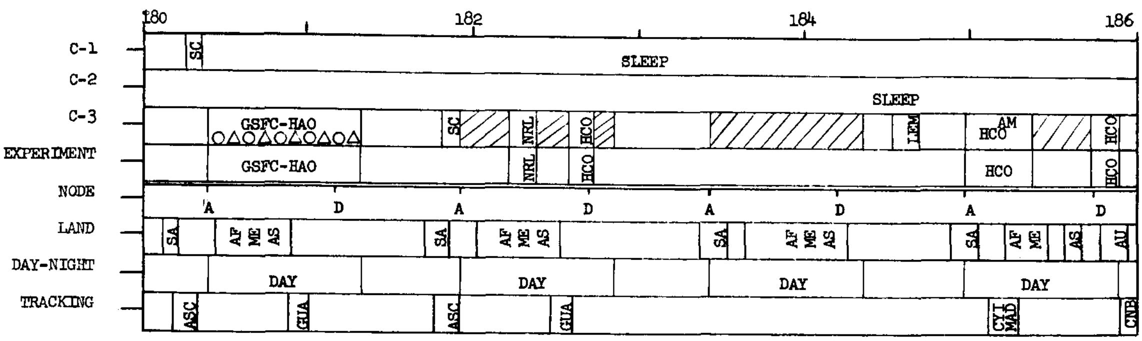
SNACK
SLEEP
DAY

DAY 7



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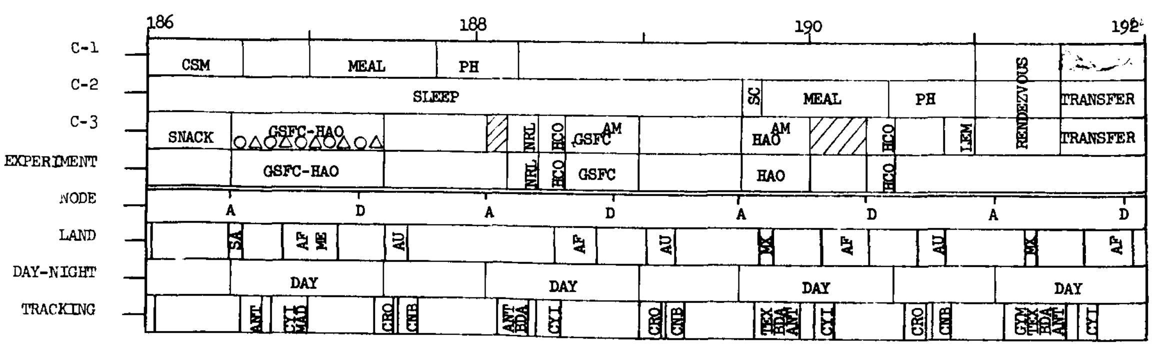
GSFC-HAO
HCO
DAY



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C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
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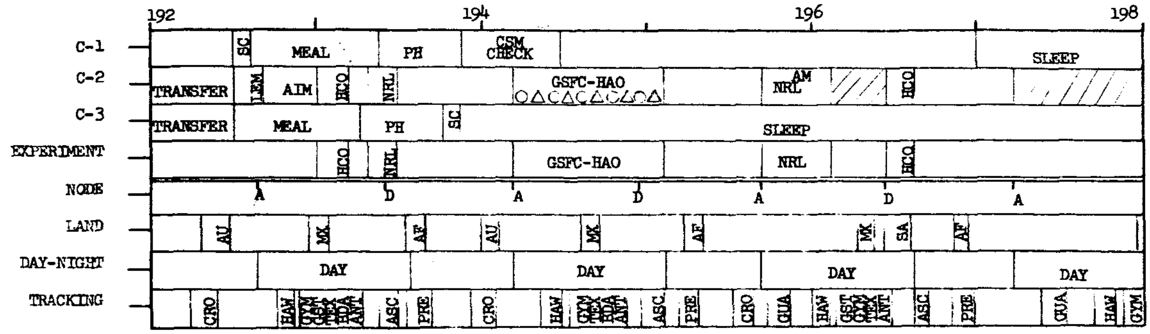
MEAL
PH
SLEEP
SNACK
GSFC-HAO
GSFC
HAO
RENDEZVOUS
TRANSFER
DAY

DAY 8



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C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
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TRANSFER LEM AIM HCO NRL GSFC-HAO NRL AM HCO
TRANSFER MEAL PH SC SLEEP
HCO NRL GSFC-HAO NRL HCO
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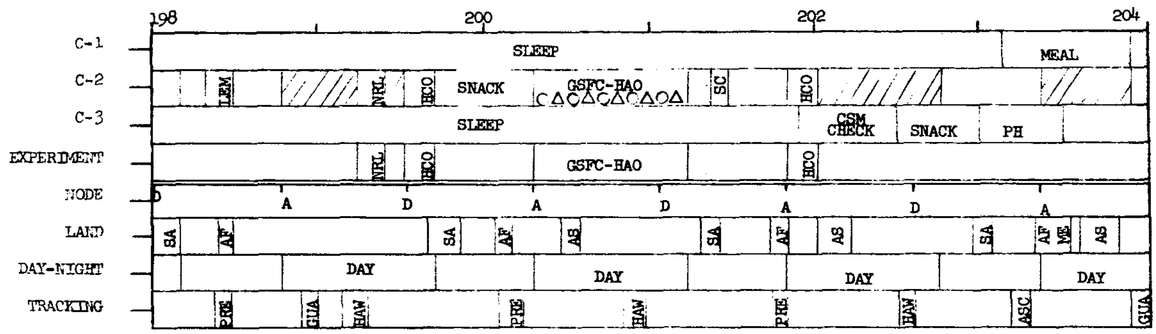
AU MX AF AU MX AF MX SA AF
DAY DAY DAY DAY
CRO HAW ASC PRE CRO HAW ASC PRE CRO GUA HAW ASC PRE GUA HAW GYM



198 200 202 204
C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
SLEEP MEAL
LEM NRL HCO SNACK GSFC-HAO SC HCO
SLEEP CSM CHECK SNACK PH
NRL HCO GSFC-HAO HCO
D A D A D A D A
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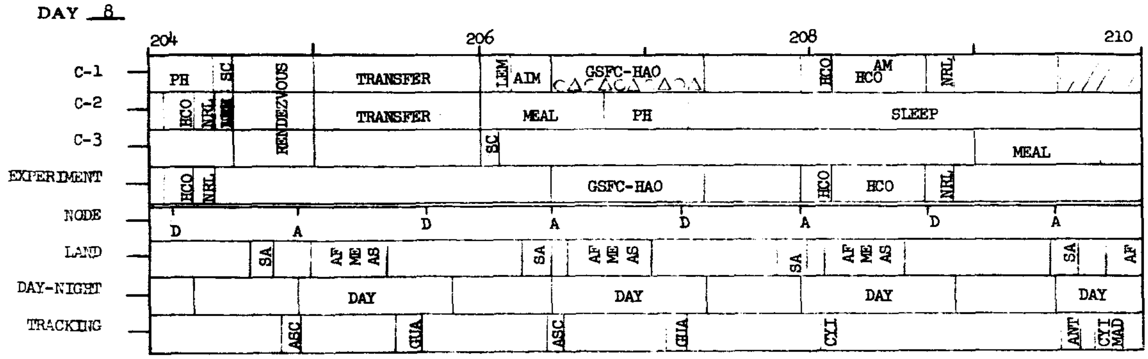
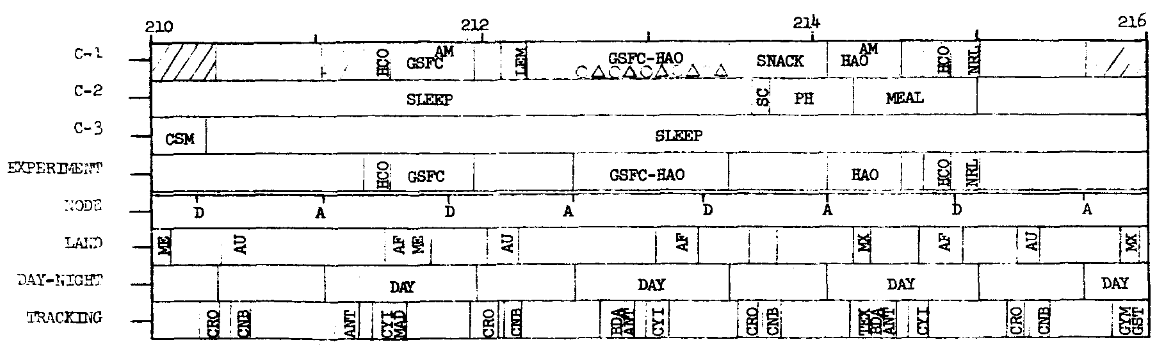
DAY DAY DAY DAY
PRE GUA HAW PRE HAW PRE HAW ASC GUA

DAY 8

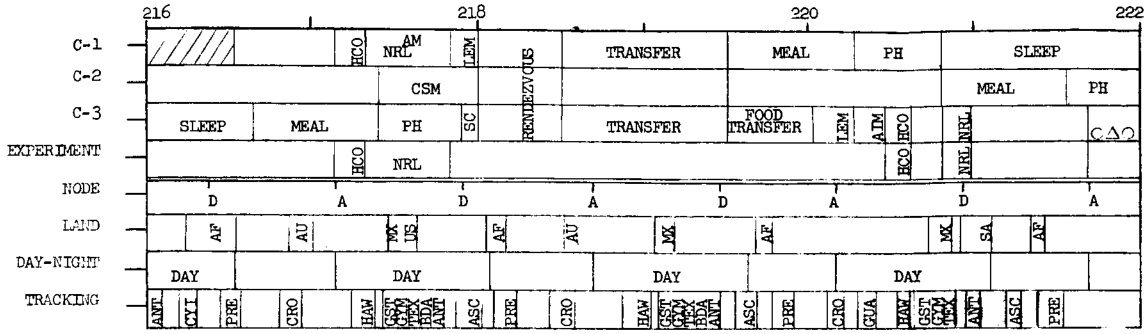


204 206 208 210
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
PH SC RENDEZVOUS TRANSFER LEM AIM GSFC-HAO HCO AM HCO NRL
HCO NRL TRANSFER MEAL PH SLEEP
SC MEAL
HCO NRL GSFC-HAO HCO HCO NRL
D A D A D A D A
SA AF ME AS SA AF ME AS SA AF ME AS SA AF
DAY DAY DAY DAY
ASC GUA ASC GUA CYI ANT CYI MAD



210 212 214 216
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
HCO GSFC AM LEM GSFC-HAO SNACK HAO AM HCO NRL
SLEEP SC PH MEAL
CSM SLEEP
HCO GSFC GSFC-HAO HAO HCO NRL
D A D A D A D A
ME AU AF ME AU AF MX AF AU MX
DAY DAY DAY DAY
CRO CNB ANT CYI MAD CRO CNB HDA ANT CYI CRO CNB TEX HDA ANT CYI CRO CNB GYM GST

DAY 9


216
218
220
222
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
HCO
NRL
AM
LEM
RENDEZVOUS
TRANSFER
MEAL
PH
SLEEP
CSM
SC
FOOD TRANSFER
ATM
DAY
ANT
CYI
PRE
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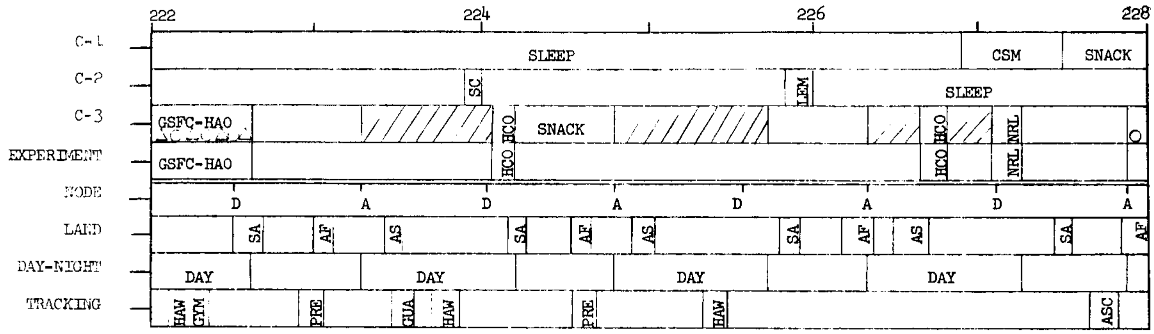
GST
GYM
TEX
BDA
ASC
GUA
AF
AU
MX
US
SA


222
224
226
228
C-1
C-2
C-3
EXPERIMENT
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DAY-NIGHT
TRACKING
SLEEP
CSM
SNACK
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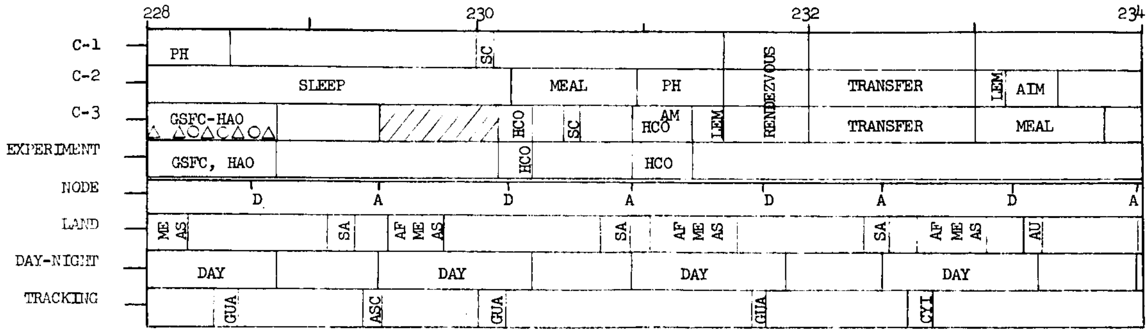
GSFC-HAO
HCO
NRL
DAY
SA
AF
AS
HAW
GYM
PRE
GUA
ASC

DAY 9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SLEEP
MEAL
TRANSFER
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AM
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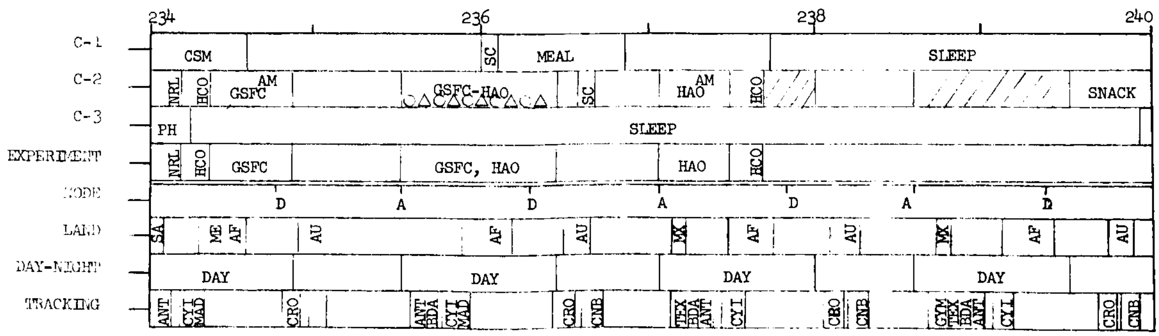
AS
SA
AF
AU
GUA
ASC
CYI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GSFC
AM
GSFC-HAO
HAO
SNACK
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MAD
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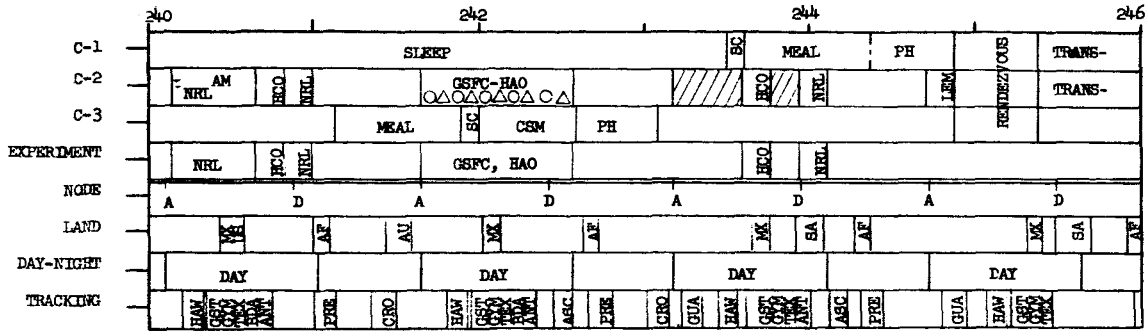
CNB
TEX
GYM

DAY 10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MEAL
PH
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GSFC-HAO
RENDEZVOUS
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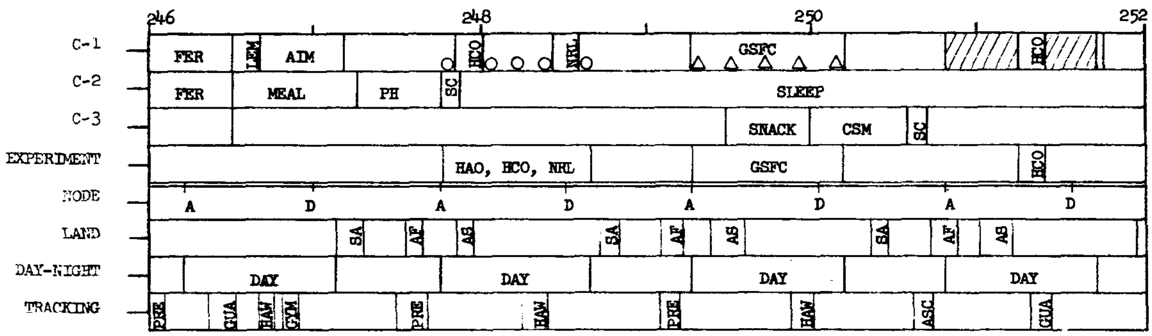
NRL
GSFC, HAO
DAY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SNACK
CSM
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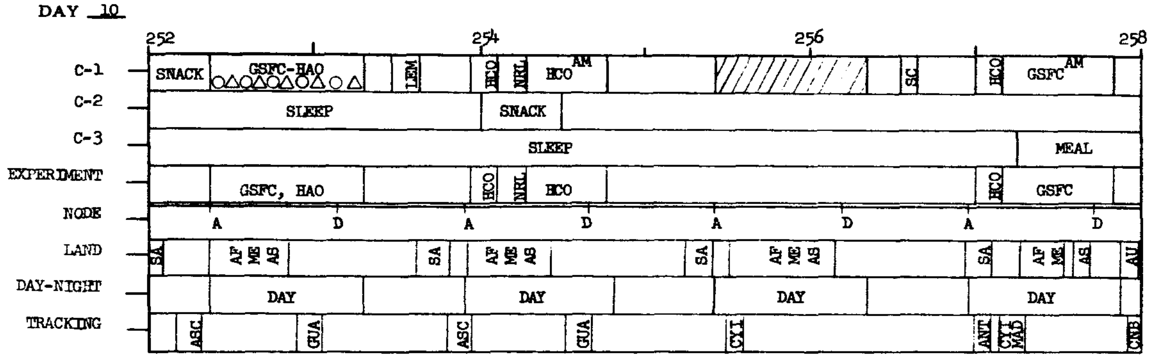
DAY

DAY 10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GSFC AM
SLEEP
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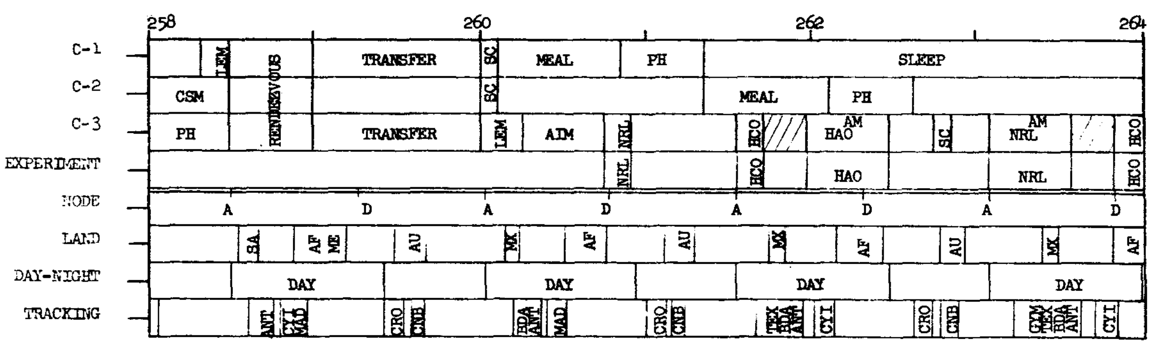
GSFC
DAY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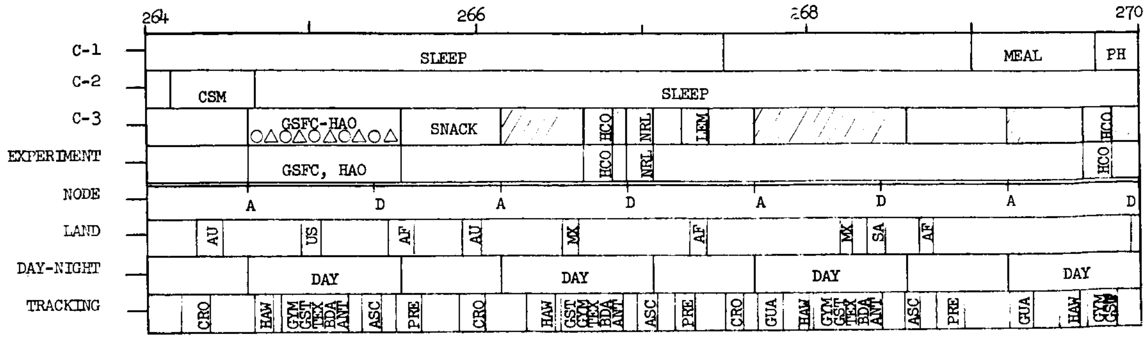
HCO
HAO AM
NRL AM
HAO
DAY

DAY 11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GSFC-HAO
SNACK
HCO
NRL
LEM
GSFC, HAO
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GST
TEX
BDA
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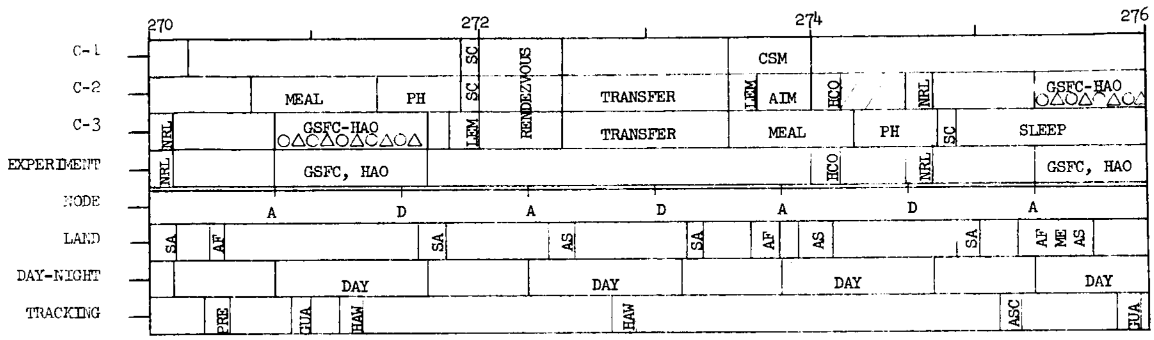
ASC
PRE
GUA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DAY-NIGHT
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CSM
MEAL
PH
TRANSFER
LEM
AIM
HCO
NRL
GSFC-HAO
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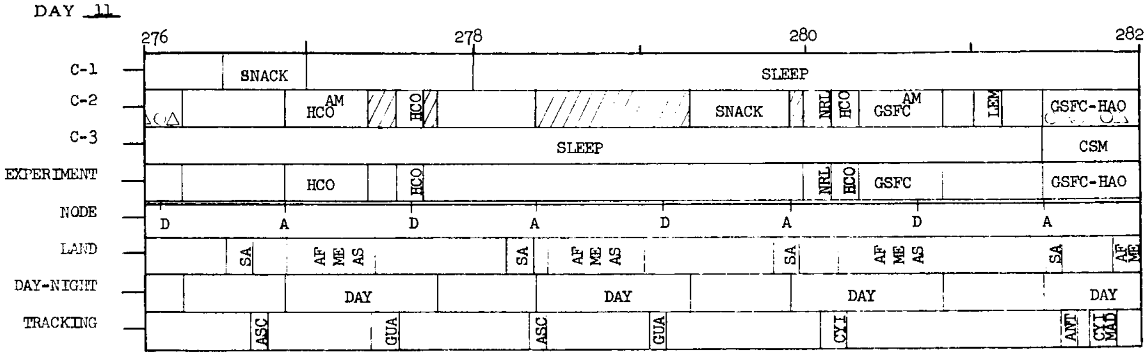
AS
ME
DAY
PRE
GUA
HAW
ASC

DAY 11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HCO
SNACK
NRL
GSFC AM
LEM
GSFC-HAO
SLEEP
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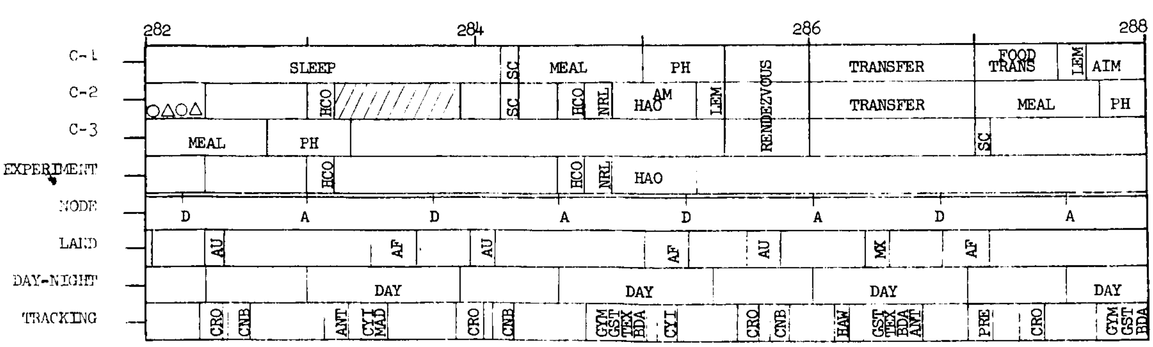
GSFC
SA
AF
ME
AS
DAY
ASC
GUA
CYI
ANT
MAD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C-1
C-2
C-3
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DAY-NIGHT
TRACKING
SLEEP
SC
MEAL
PH
RENDEZVOUS
TRANSFER
FOOD TRANS
LEM
AIM
HCO
NRL
HAO AM
MEAL
PH
SC
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DAY
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CNB
ANT
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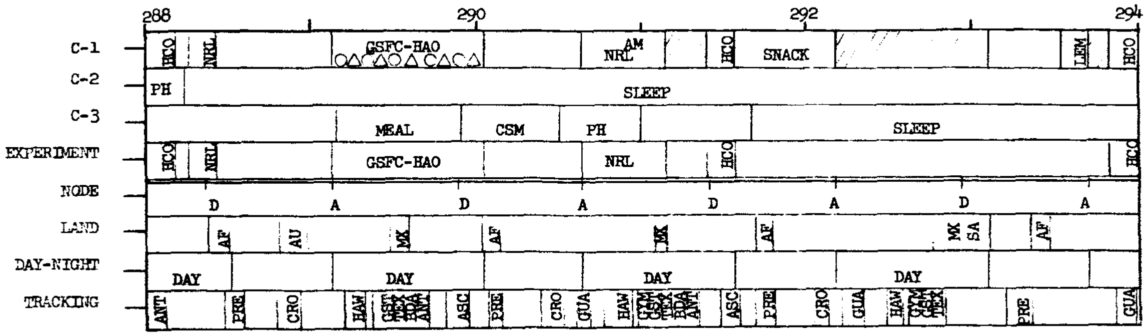
MAD
GYM
GST
TEX
BDA
HAW
PRE

DAY 12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294
C-1
C-2
C-3
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LAND
DAY-NIGHT
TRACKING
HCO NRL GSFC-HAO NRL AM HCO SNACK LEM HCO
PH SLEEP
MEAL CSM PH SLEEP
HCO NRL GSFC-HAO NRL HCO HCO
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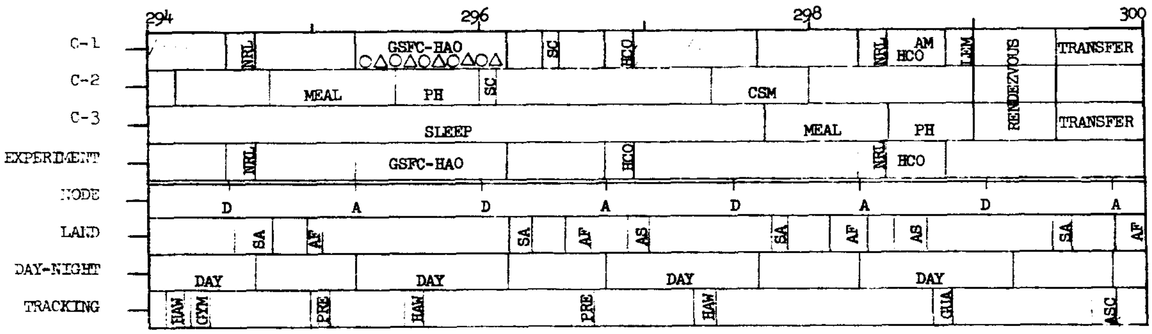
AF AU MX AF MX AF MX SA AF
DAY DAY DAY DAY
ANT PRE CRO HAW ASC PRE CRO GUA HAW ASC PRE CRO GUA HAW PRE GUA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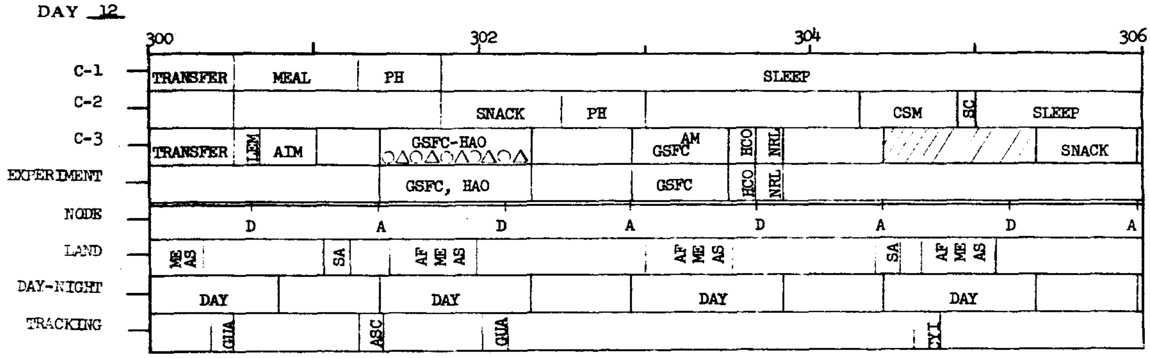
300
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
NRL GSFC-HAO SC HCO NRL AM HCO LEM RENDEZVOUS TRANSFER
MEAL PH SC CSM
SLEEP MEAL PH TRANSFER
NRL GSFC-HAO HCO NRL HCO
D A D A D A D A
SA AF SA AF AS SA AF AS SA AF
DAY DAY DAY DAY
HAW GYM PRE HAW PRE HAW GUA ASC

DAY 12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C-1
C-2
C-3
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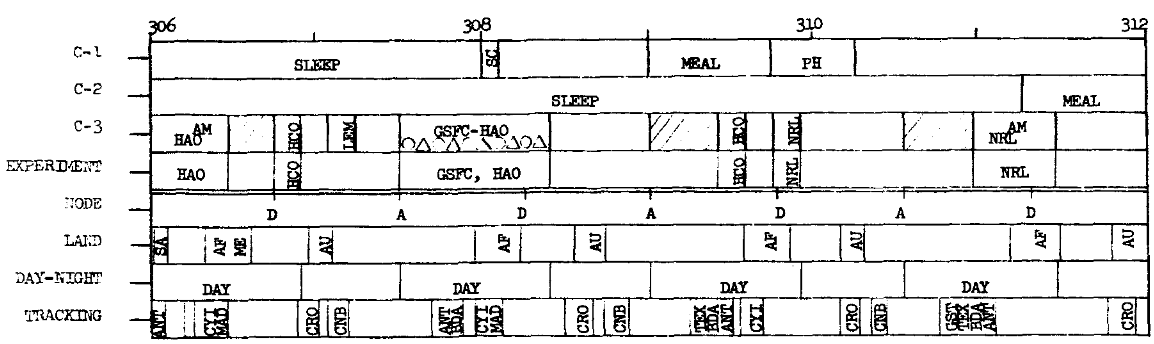
NODE
LAND
DAY-NIGHT
TRACKING
TRANSFER MEAL PH SLEEP
SNACK PH CSM SC SLEEP
TRANSFER LEM AIM GSFC-HAO GSFC AM HCO NRL SNACK
GSFC, HAO GSFC HCO NRL
D A D A D A D A
ME AS SA AF ME AS AF ME AS SA AF ME AS
DAY DAY DAY DAY
GUA ASC GUA CYI


306
308
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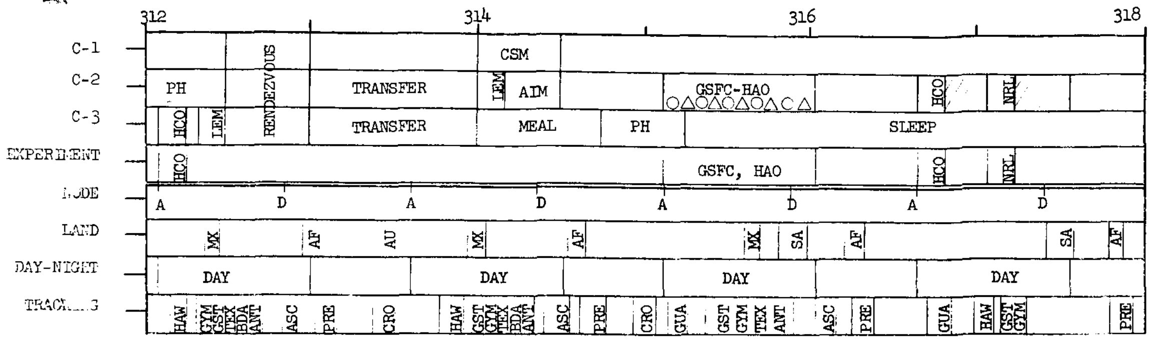
312
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP SC MEAL PH
SLEEP MEAL
HAO AM HCO LEM GSFC-HAO HCO NRL NRL AM
HAO HCO GSFC, HAO HCO NRL NRL
D A D A D A D
SA AF ME AU AF AU AF AU AF AU
DAY DAY DAY DAY
ANT CYI MAD CRO CNB CYI MAD CRO CNB CYI CRO CNB CRO

DAY 13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C-1
C-2
C-3
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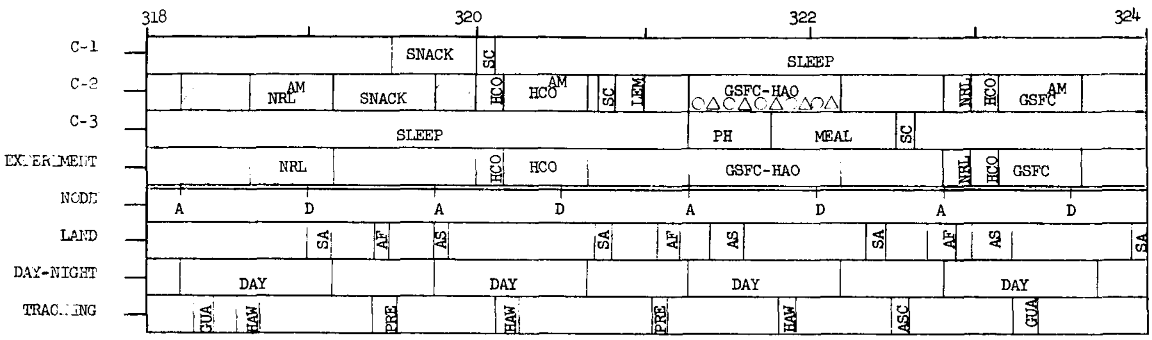
NODE
LAND
DAY-NIGHT
TRACKING
CSM
PH
RENDEZVOUS
TRANSFER
LEM
AIM
GSFC-HAO
HCO
NRL
TRANSFER
MEAL
PH
SLEEP
GSFC, HAO
A D A D A D A D
MX AF AU MX AF MX SA AF SA AF
DAY DAY DAY DAY
HAW GYM GST TEX BDA ANT ASC PRE CRO HAW GST GYM TEX BDA ANT ASC PRE CRO GUA GST GYM TEX ANT ASC PRE GUA HAW GST GYM PRE


318
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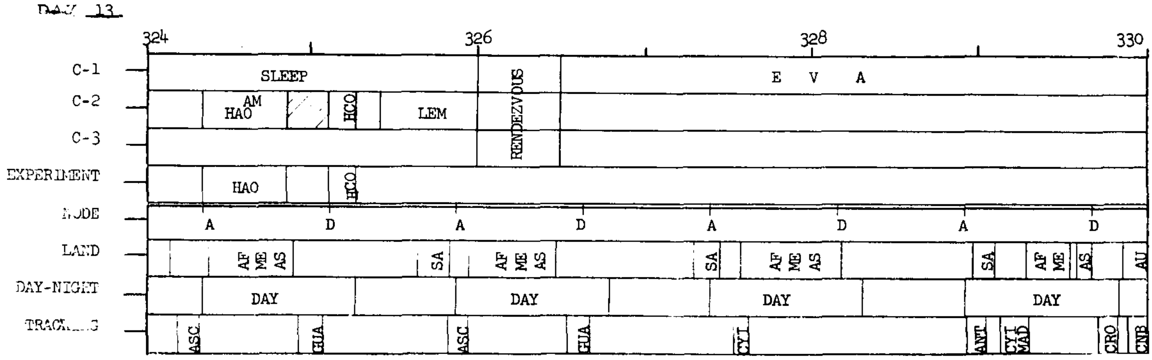
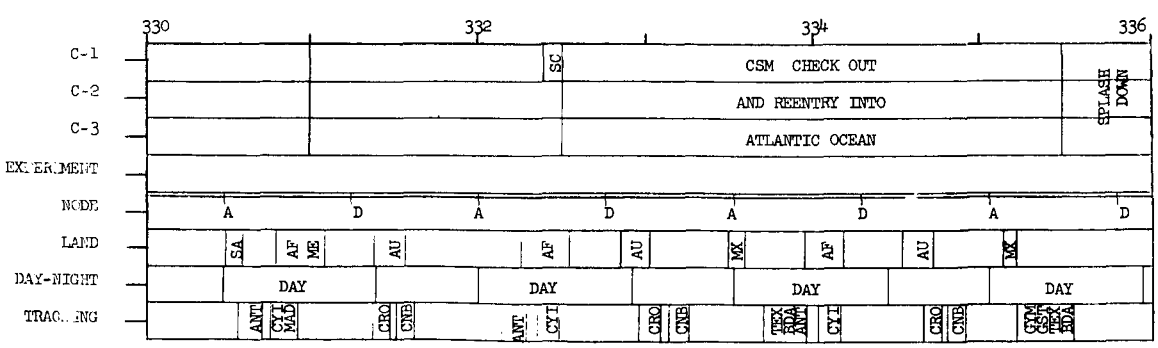
322
324
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SNACK
SC
SLEEP
NRL AM
SNACK
HCO
HCO AM
SC
LEM
GSFC-HAO
NRL
HCO
GSFC AM
SLEEP
PH
MEAL
SC
NRL
HCO
HCO
GSFC-HAO
NRL
HCO
GSFC
A D A D A D A D
SA AF AS SA AF AS SA AF AS SA
DAY DAY DAY DAY
GUA HAW PRE HAW PRE HAW ASC GUA

DAY 13


324
326
328
330
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP
RENDEZVOUS
E V A
HAO AM
HCO
LEM
HAO
HCO
A D A D A D A D
AF ME AS SA AF ME AS SA AF ME AS SA AF ME AS AU
DAY DAY DAY DAY
ASC GUA ASC GUA CYI ANT CYI MAD CRO CNB

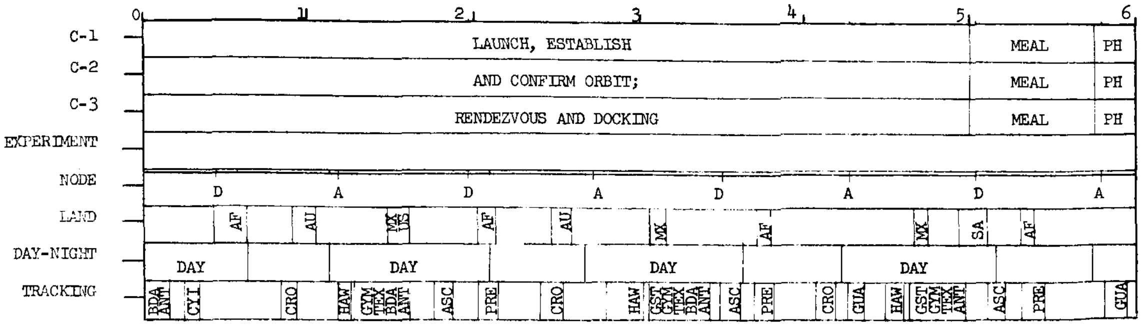

330
332
334
336
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SC
CSM CHECK OUT
AND REENTRY INTO
ATLANTIC OCEAN
SPLASH DOWN
A D A D A D A D
SA AF ME AU AF AU MX AF AU MX
DAY DAY DAY DAY
ANT CYI MAD CRO CNB ANT CYI CRO CNB TEX BDA ANT CYI CRO CNB GYM GST TEX BDA

APPENDIX B

Preliminary Timeline Analysis for Crew Transfer Every Seven Days

The attached timeline is for use with the text of Appendix A. This timeline differs from the other timeline in the assumption that two astronauts may remain in the LM for a period of seven days. This assumption eliminates the need for frequent rendezvous, docking, and crew transfer shown in the other timeline. Other assumptions remain the same, with experiment scheduling according to Table 1A shown in Appendix A.

DAY 0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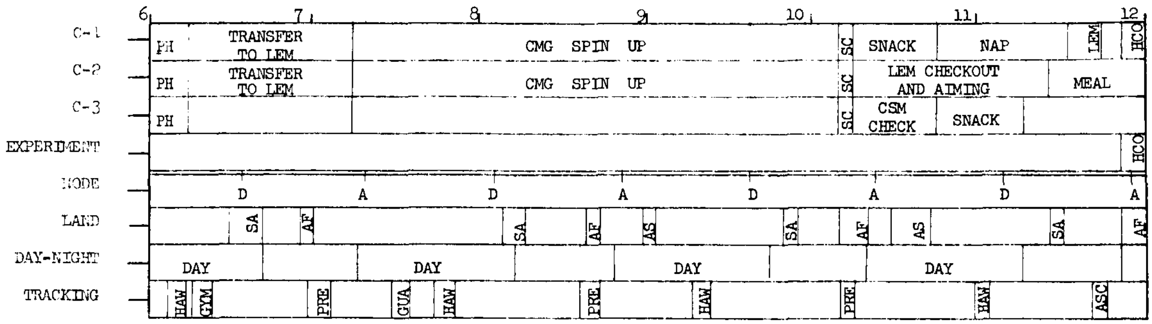
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
LAUNCH, ESTABLISH
AND CONFIRM ORBIT;
RENDEZVOUS AND DOCKING
MEAL
PH
DAY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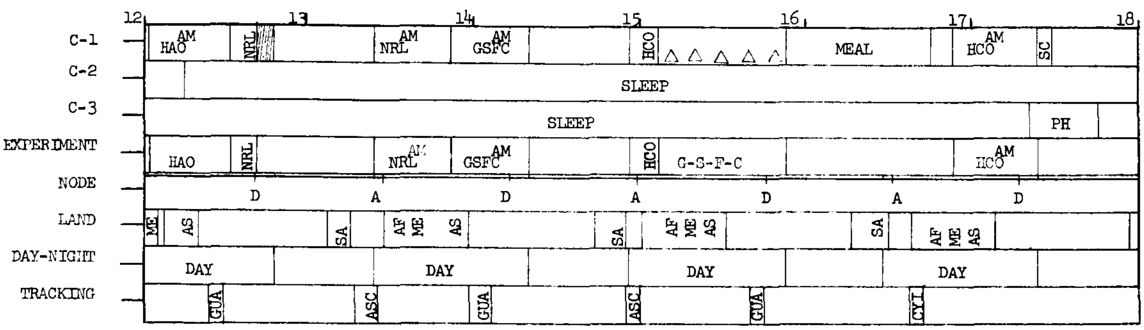
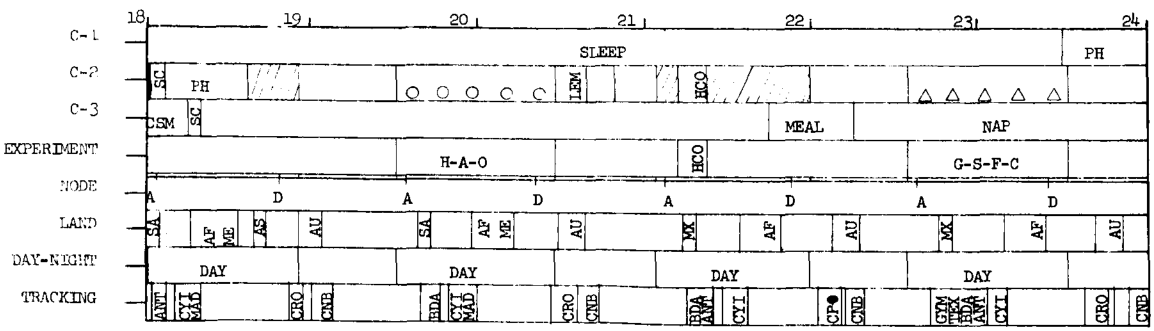
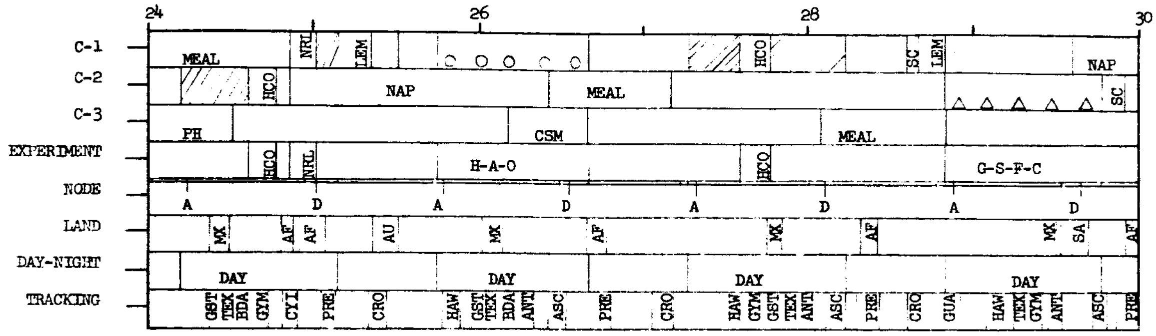
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
PH
TRANSFER TO LEM
CMG SPIN UP
SC
SNACK
NAP
LEM
HCO
LEM CHECKOUT AND AIMING
MEAL
CSM CHECK
DAY

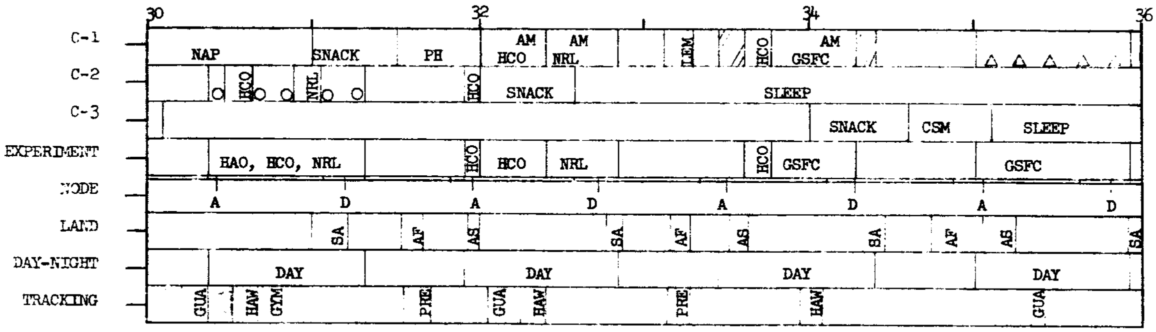
DAY 0


C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
AM
HAO
NRL
GSFC
HCO
MEAL
SC
SLEEP
PH
G-S-F-C
DAY


C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP
PH
SC
LEM
HCO
CSM
MEAL
NAP
H-A-O
G-S-F-C
DAY

DAY 1


24
26
28
30
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
MEAL
NRL
LEM
HCO
SC
NAP
CSM
PH
H-A-O
G-S-F-C
A
D
MX
AF
AU
SA
DAY
GST
TEX
BDA
GYM
CYI
PRE
CRO
HAW
ANT
ASC
GUA


30
32
34
36
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
NAP
SNACK
PH
AM
HCO
NRL
LEM
GSFC
SLEEP
CSM
HAO, HCO, NRL
A
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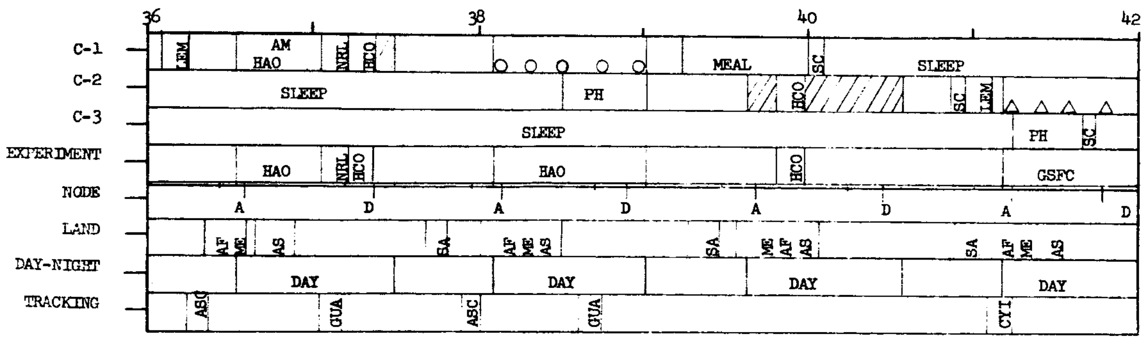
SA
AF
AS
DAY
GUA
HAW
GYM
PRE

DAY 1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C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
LEM
AM
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SLEEP
PH
GSFC
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ME
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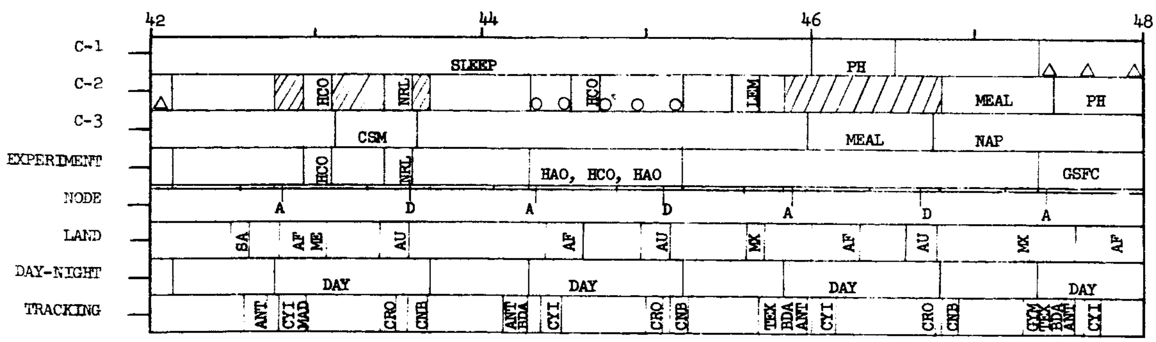
SA
DAY
ASC
GUA
CYI


42
44
46
48
C-1
C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
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HCO
NRL
LEM
MEAL
CSM
NAP
HAO, HCO, HAO
GSFC
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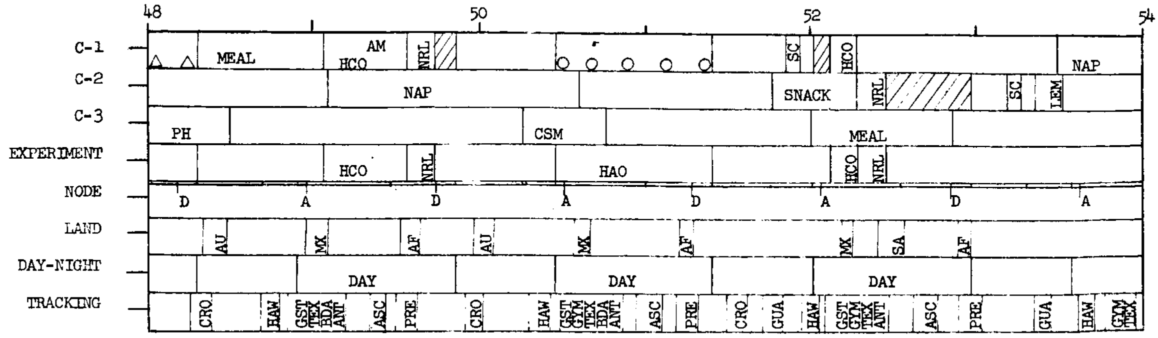
AF
ME
AU
MX
DAY
ANT
CYI
MAD
CRO
CNB
BDA
TEX
GYM

DAY 2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50
52
54
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C-2
C-3
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NODE
LAND
DAY-NIGHT
TRACKING
MEAL
AM HCO
NRL
SC
HCO
NAP
SNACK
LEM
PH
CSM
HAO
D
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MX
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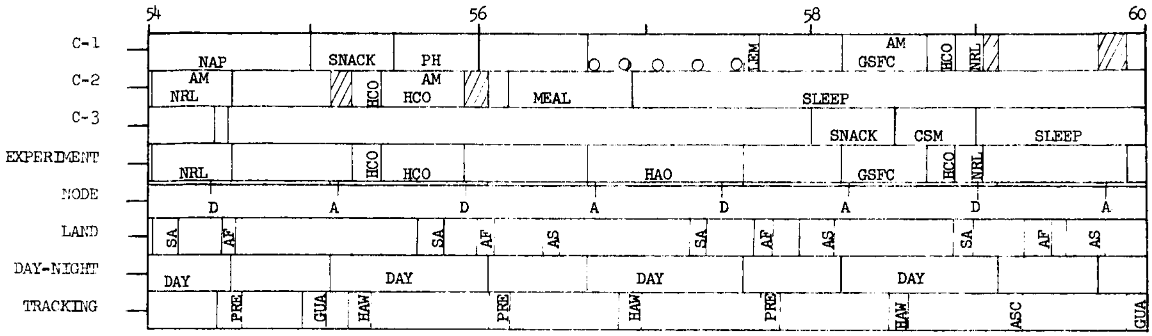
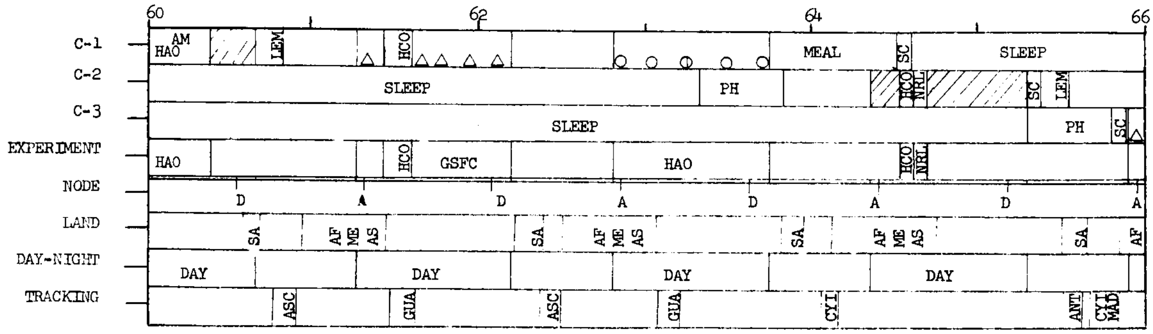
SA
DAY
CRO
HAW
GST TEX BDA ANT
ASC
PRE
GST GYM TEX BDA ANT
GUA
GYM TEX


54
56
58
60
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
NAP
SNACK
PH
LEM
AM GSFC
HCO
NRL
AM NRL
AM HCO
MEAL
SLEEP
SNACK
CSM
HAO
GSFC
D
A
SA
AF
AS
DAY
PRE
GUA
HAW
ASC

DAY 2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62
64
66
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C-3
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DAY-NIGHT
TRACKING
AM HAO
LEM
HCO
MEAL
SC
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PH
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GSFC
HAO
D
A
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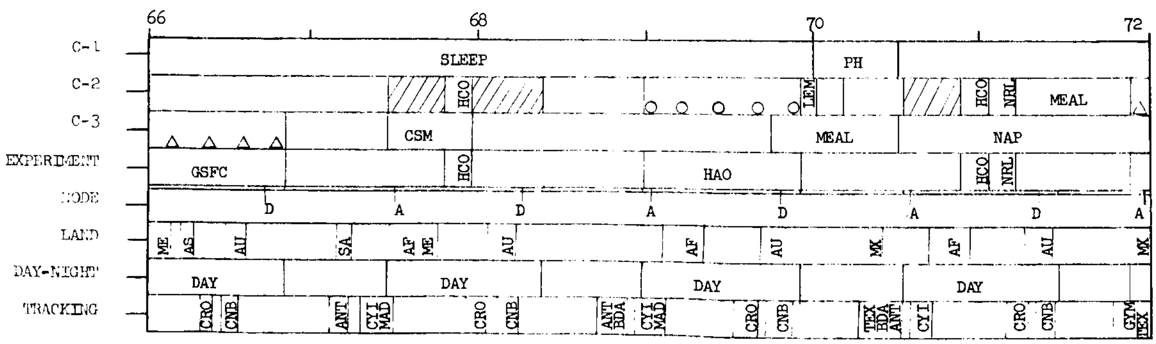
AF
ME
AS
DAY
ASC
GUA
CYI
ANT
CYI MAD


66
68
70
72
C-1
C-2
C-3
EXPERIMENT
NODE
LAND
DAY-NIGHT
TRACKING
SLEEP
PH
HCO
LEM
NRL
MEAL
CSM
NAP
GSFC
HAO
D
A
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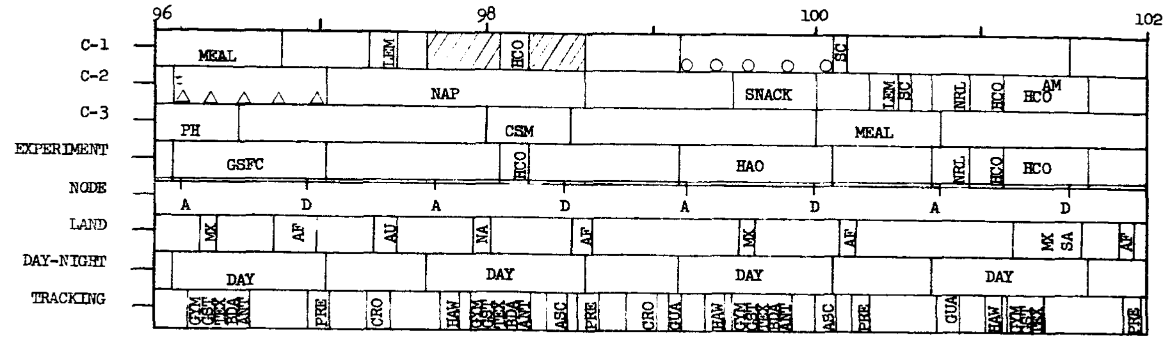
MX
DAY
CRO
CNB
ANT
CYI MAD
ANT BDA
TEX BDA ANT
CYI
GYM TEX

DAY 4


96
98
100
102
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C-3
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DAY-NIGHT
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HCO
SC
NAP
SNACK
LEM SC
NRL
HCO
HCO AM
PH
CSM
MEAL
GSFC
HCO
HAO
NRL
HCO
HCO
A D A D A D A D
MX
AF
AU
NA
AF
MX
AF
MX SA
AF
DAY
DAY
DAY
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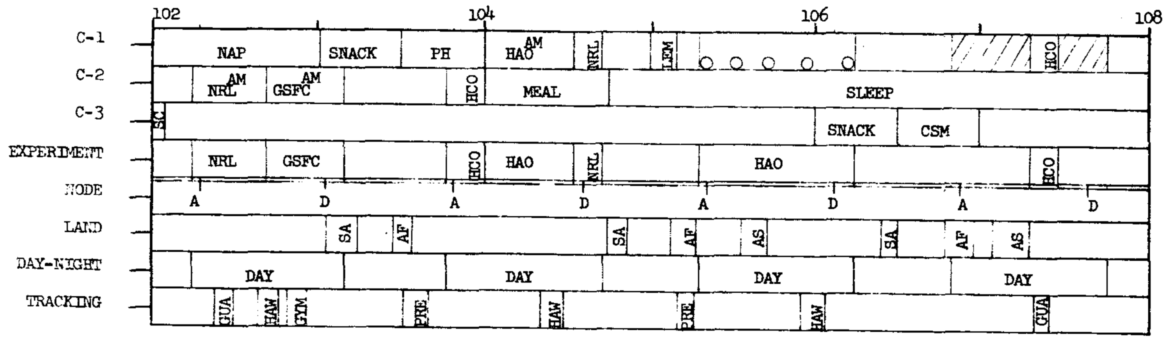
HAW
ASC
PRE
CRO
GUA
HAW
ASC
PRE
GUA
HAW
PRE


102
104
106
108
C-1
C-2
C-3
EXPERIMENT
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LAND
DAY-NIGHT
TRACKING
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SNACK
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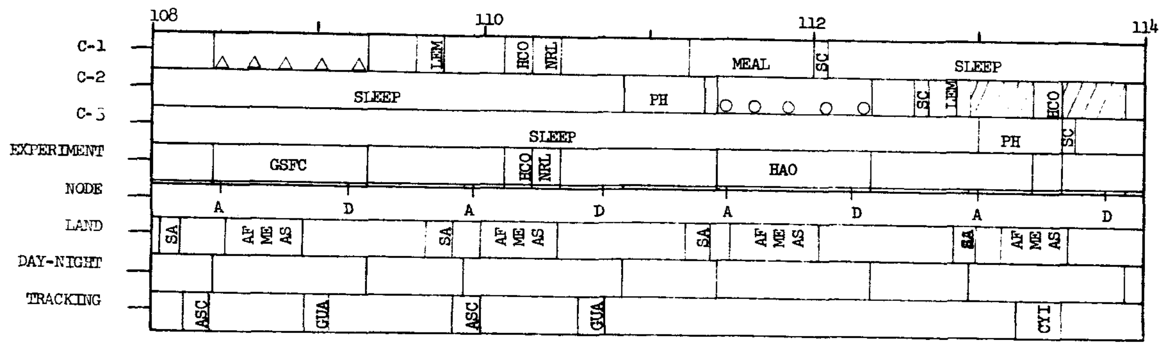
HAO AM
NRL
LEM
HCO
NRL AM
GSFC AM
HCO
MEAL
SLEEP
SC
SNACK
CSM
NRL
GSFC
HCO
HAO
NRL
HAO
HCO
A D A D A D A D
SA
AF
SA
AF
AS
SA
AF
AS
DAY
DAY
DAY
DAY
GUA
HAW
GYM
PRE
HAW
PRE
HAW
GUA

DAY 4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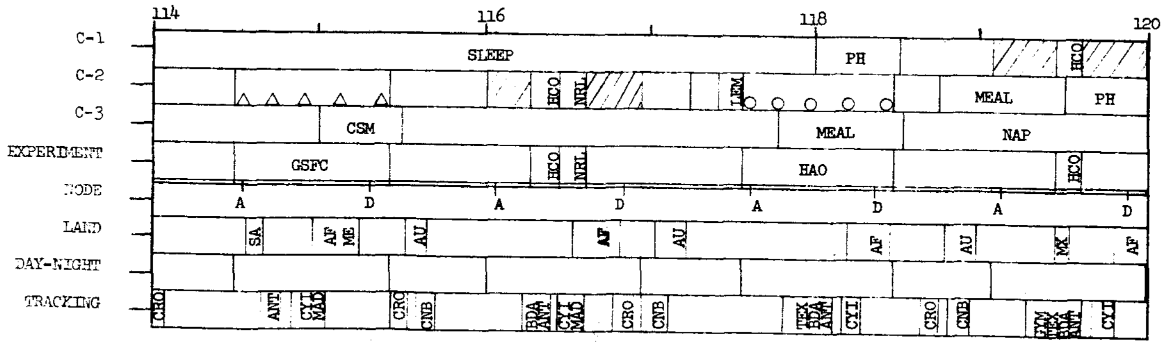
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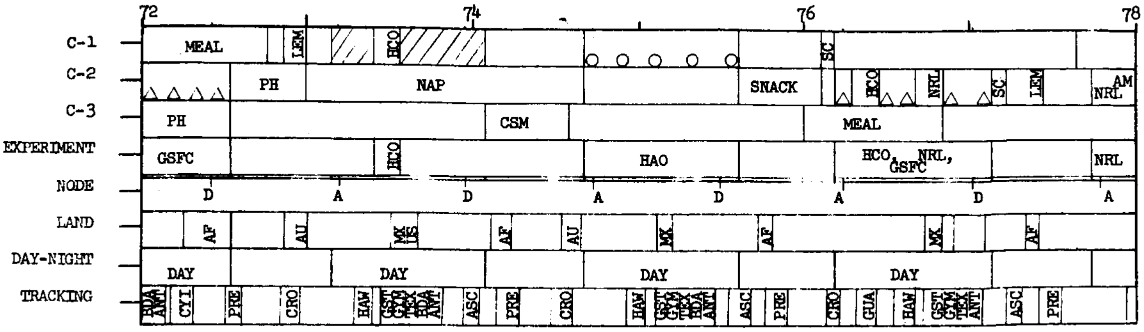
DAY 3



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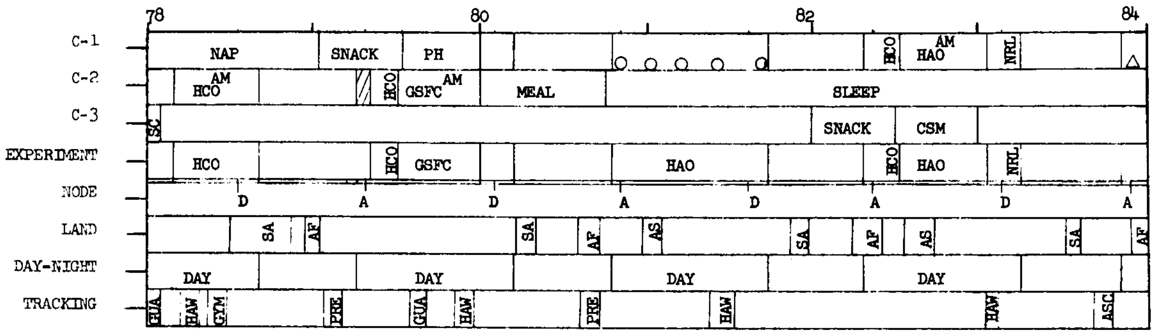

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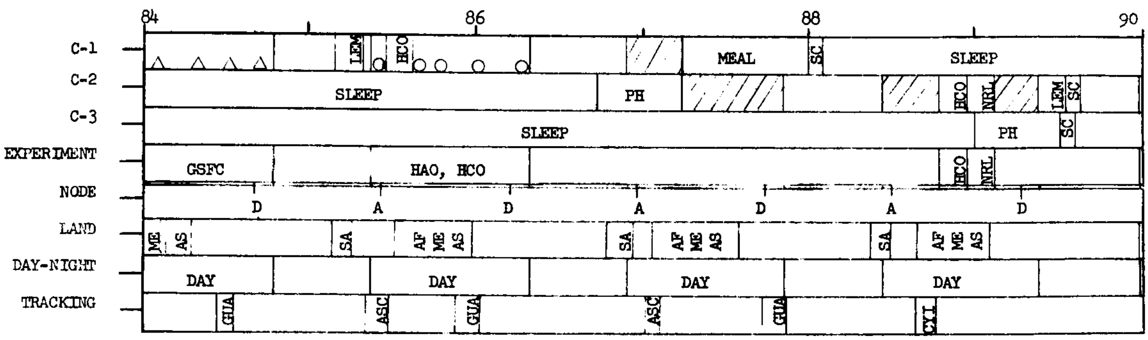
DAY 3



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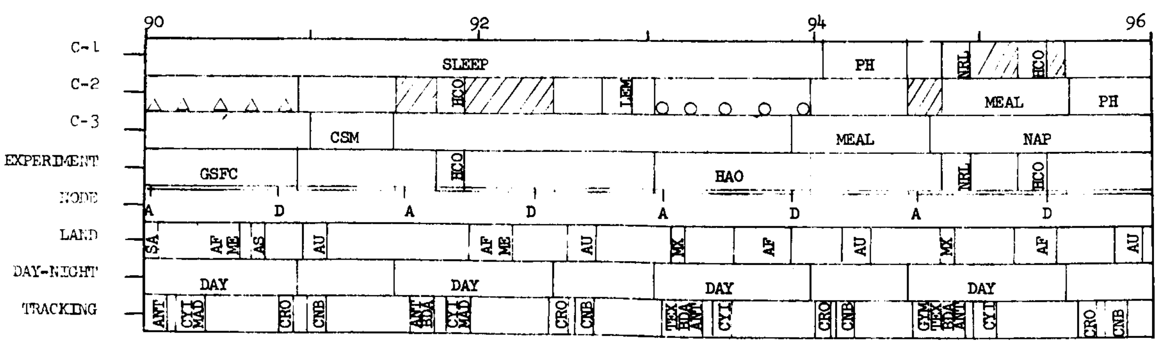

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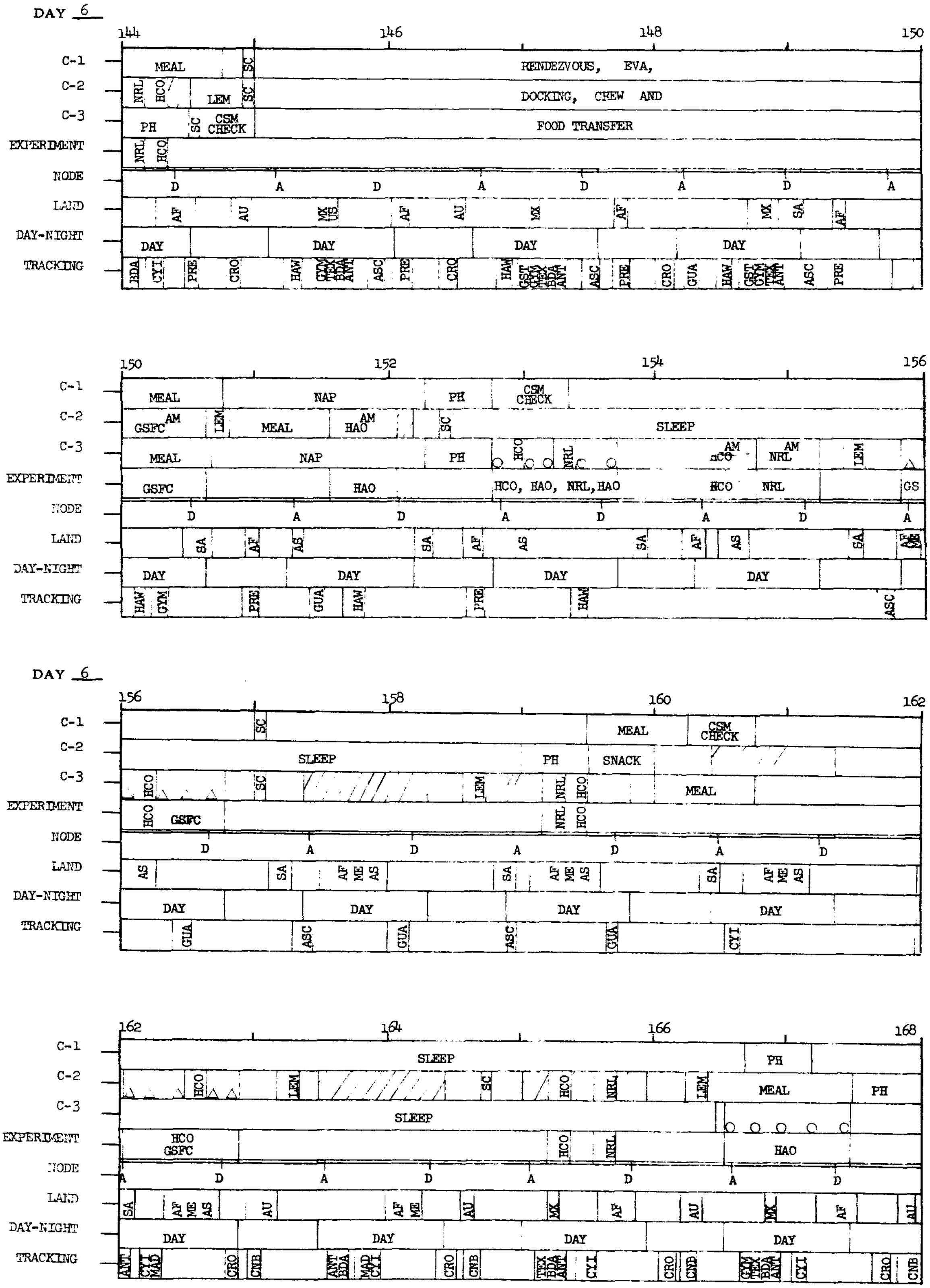
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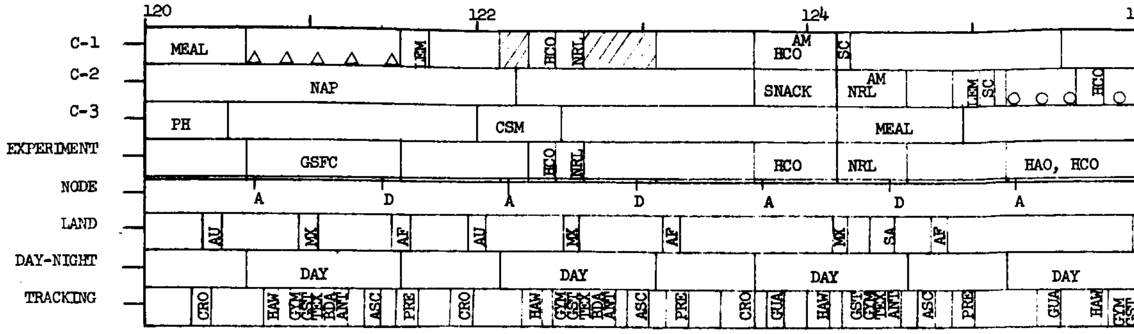
DAY 5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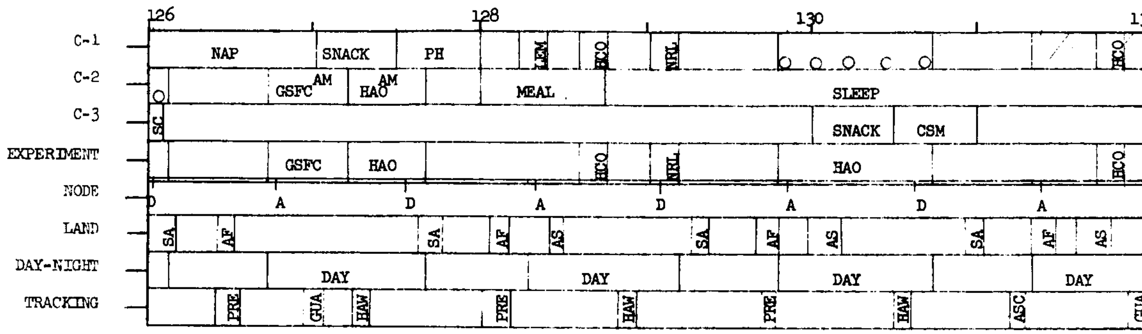
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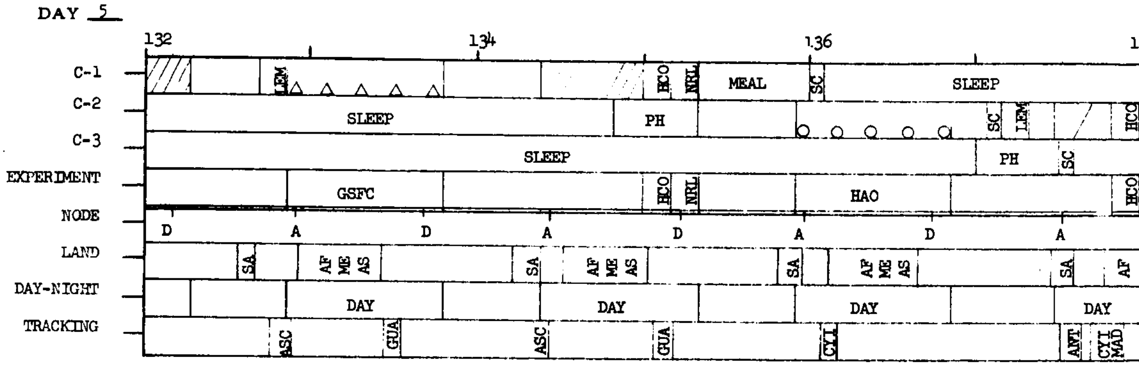
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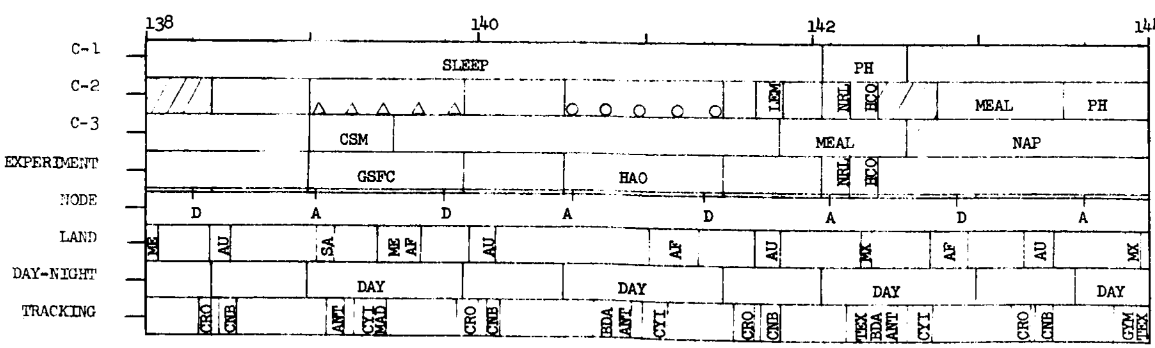
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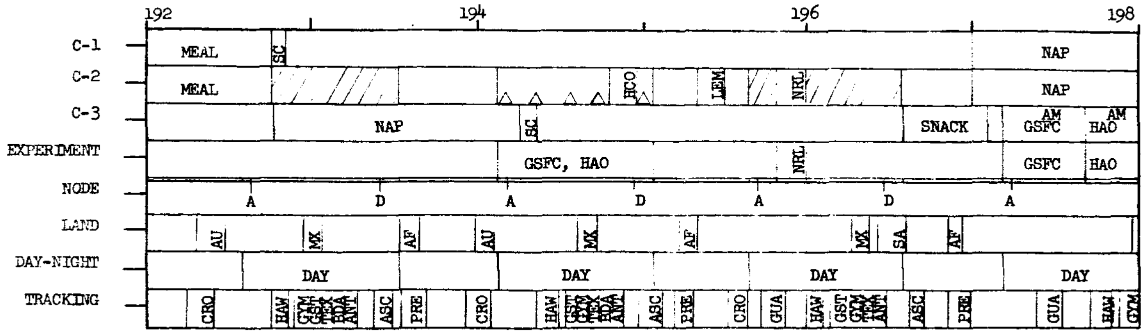

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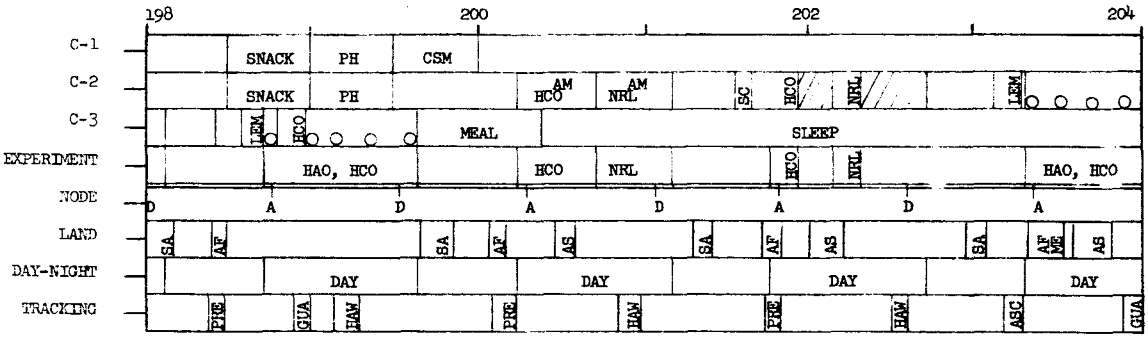

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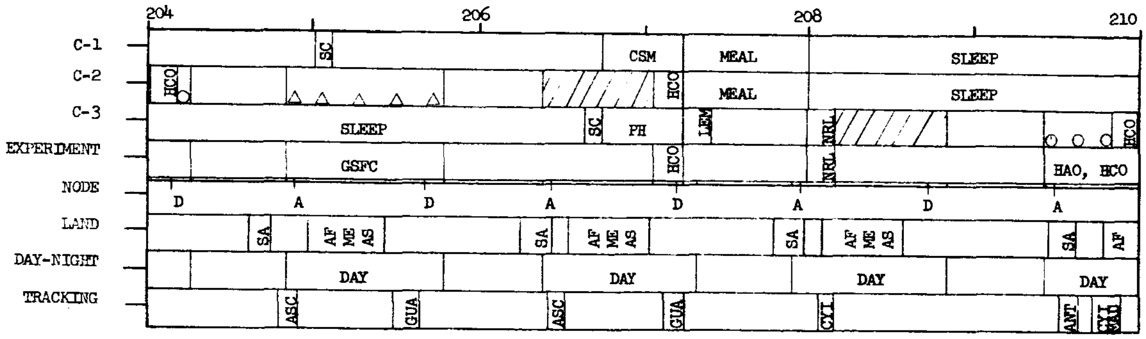
DAY 8



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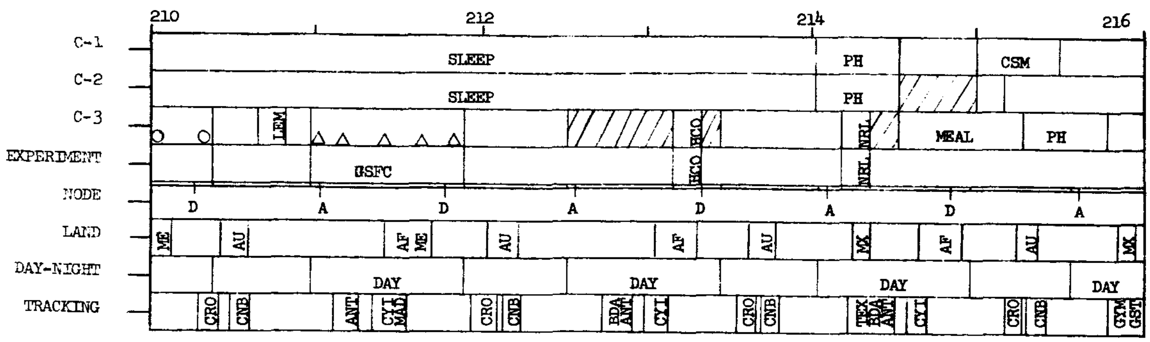

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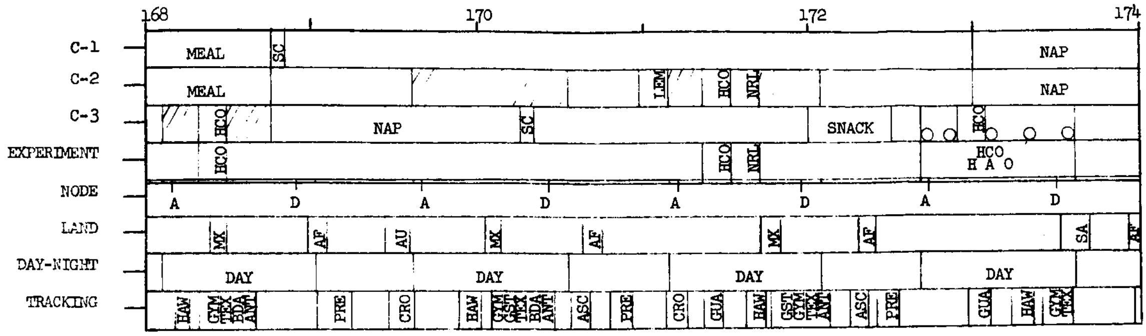
DAY 7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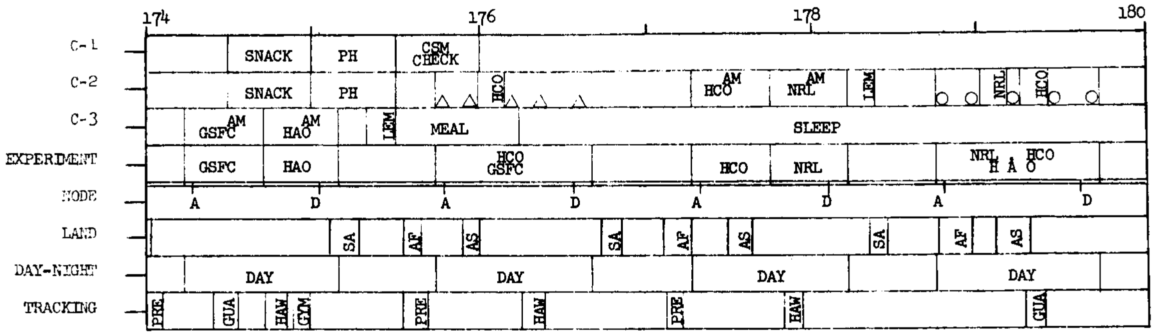
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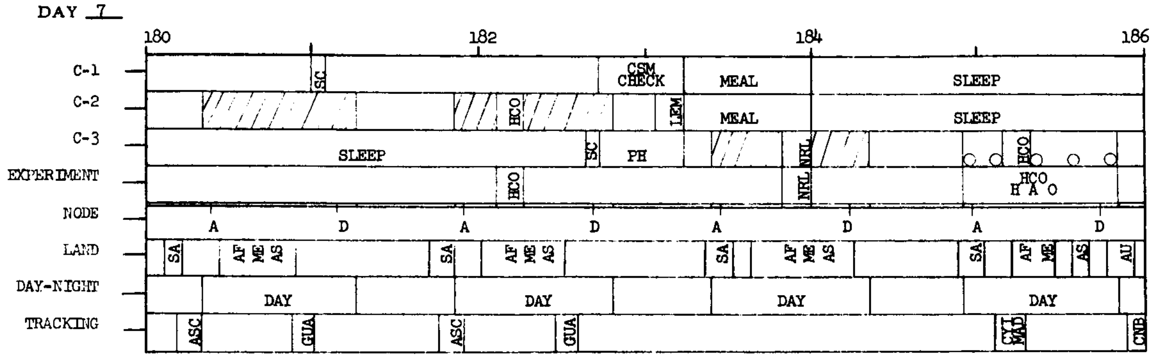
DAY 7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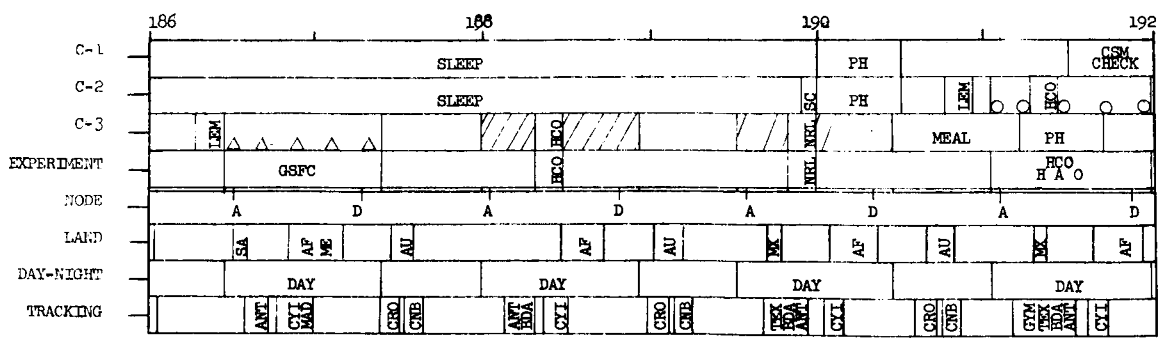
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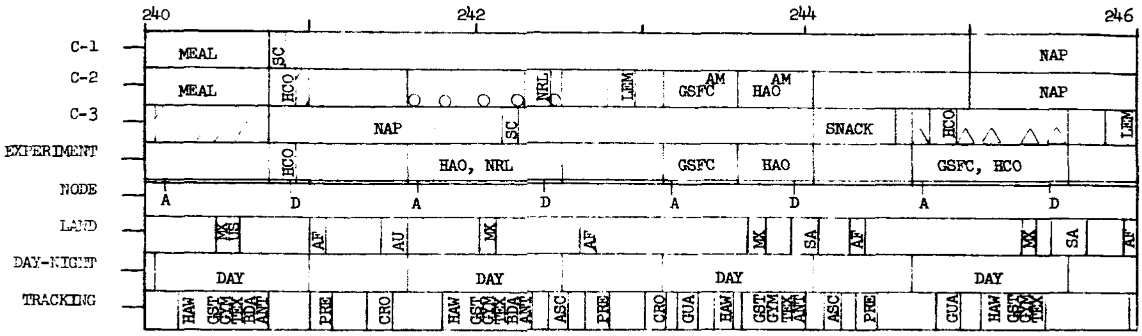
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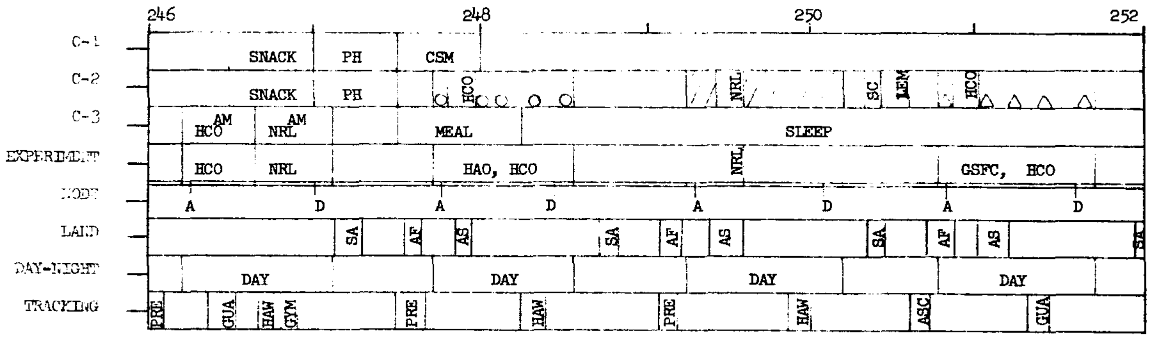
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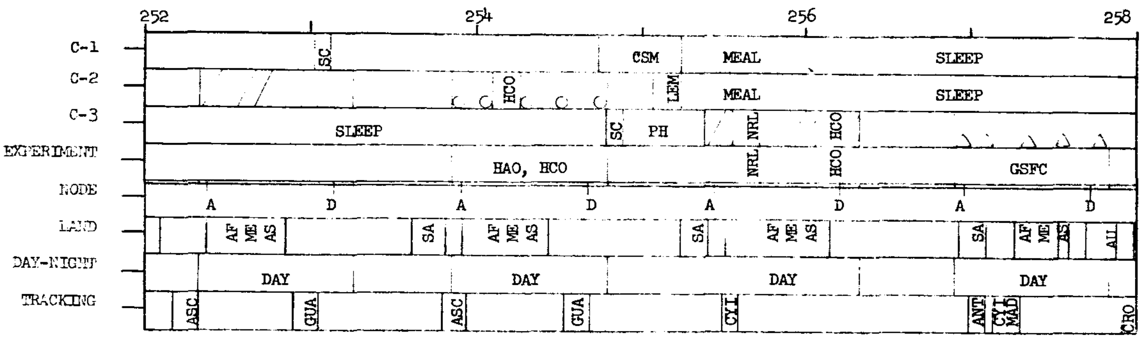
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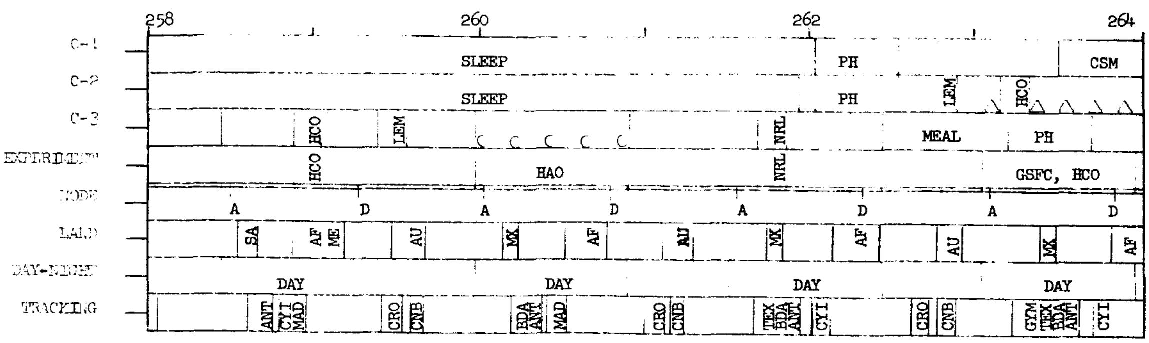
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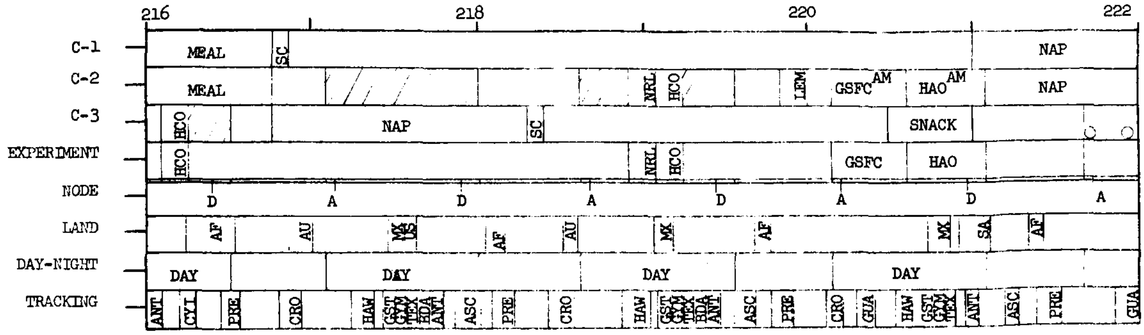
DAY 9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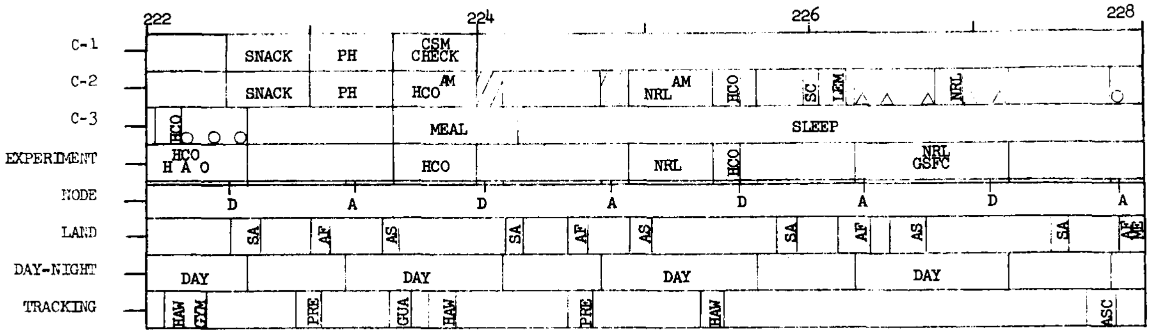
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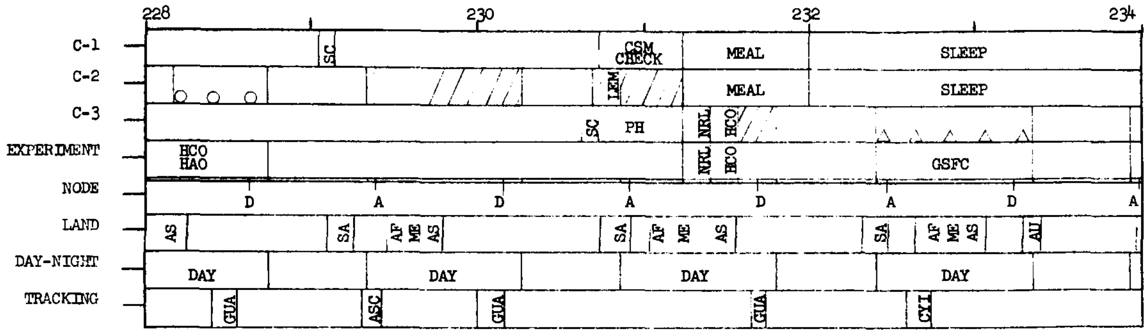
DAY 9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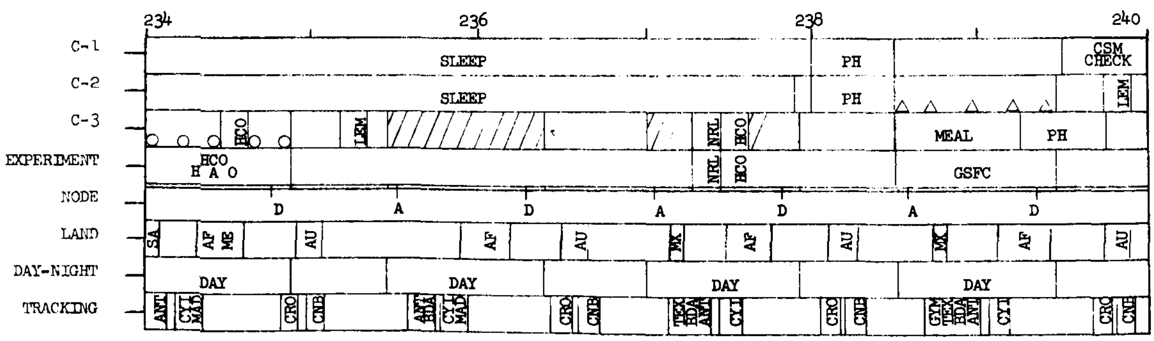
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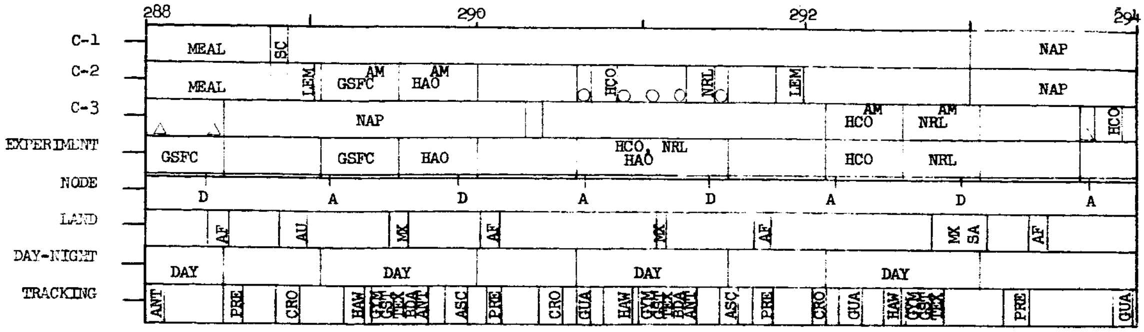
DAY 12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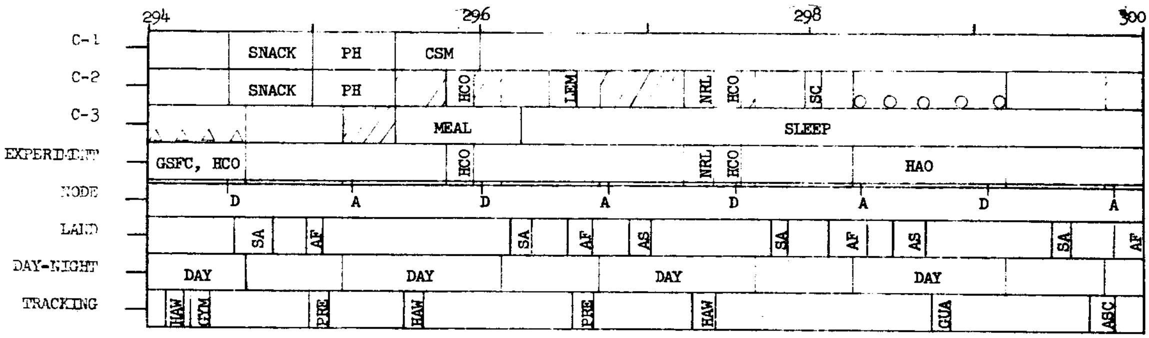
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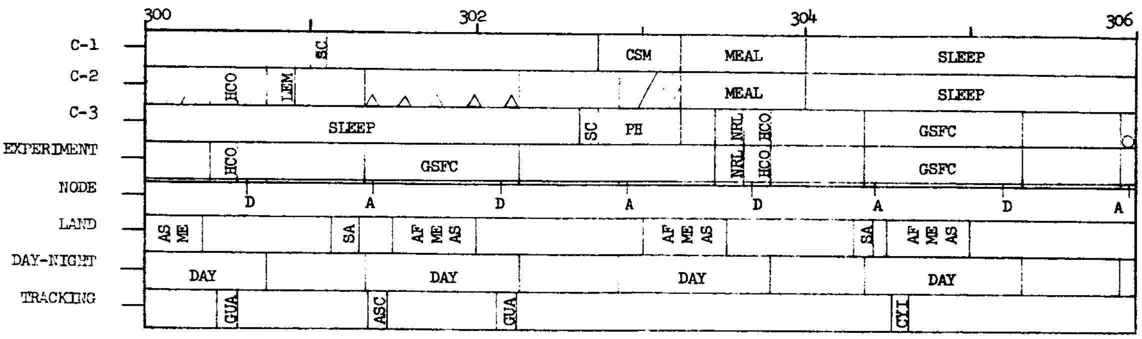
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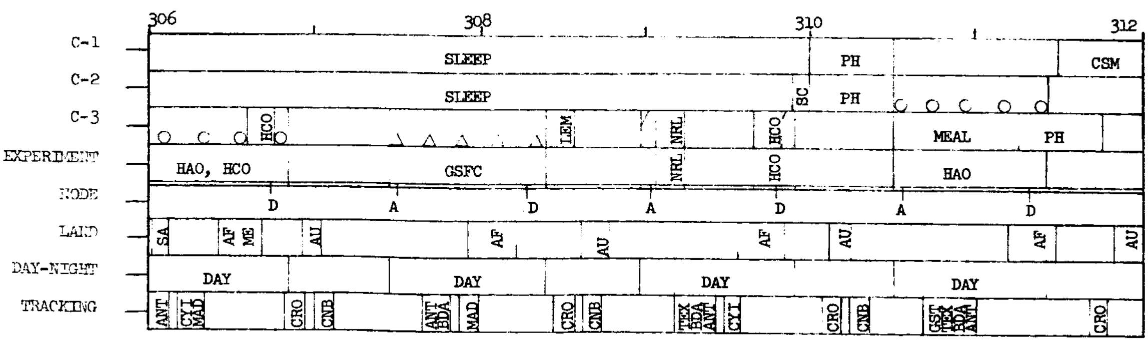
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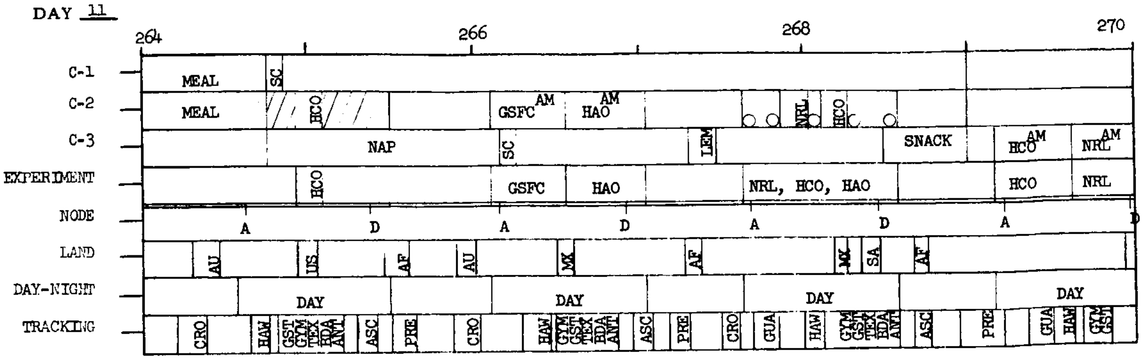
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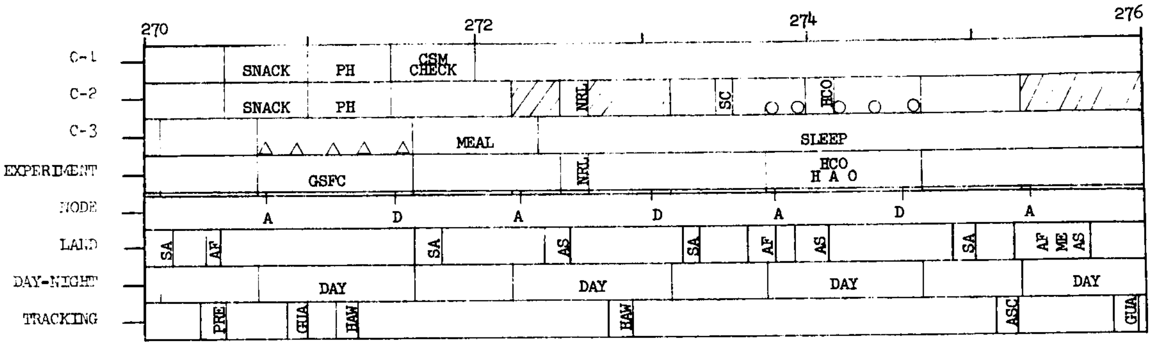
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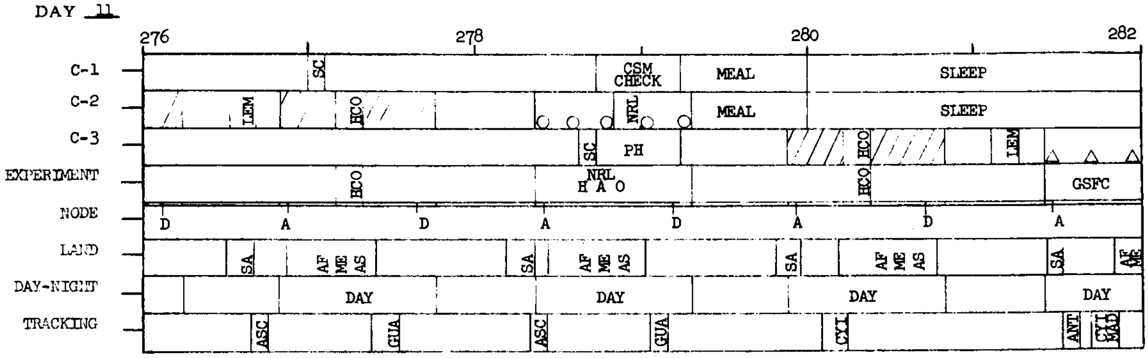
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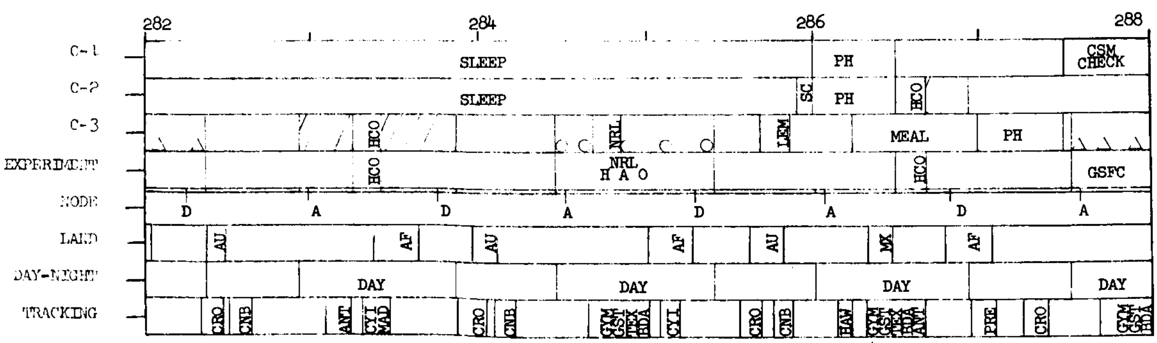
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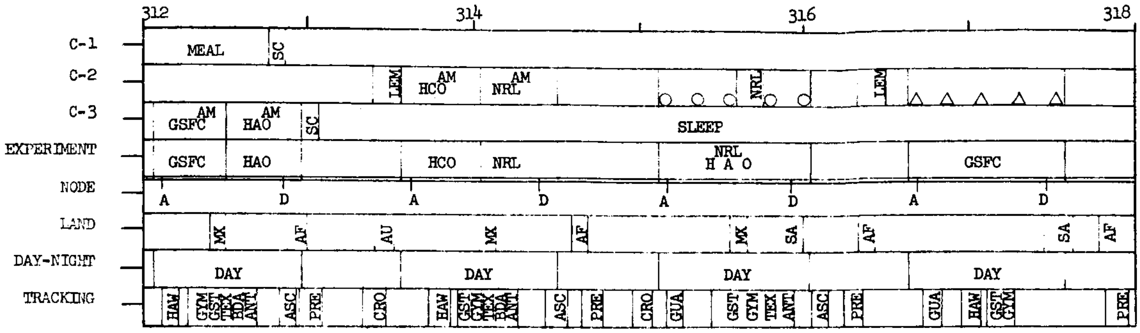

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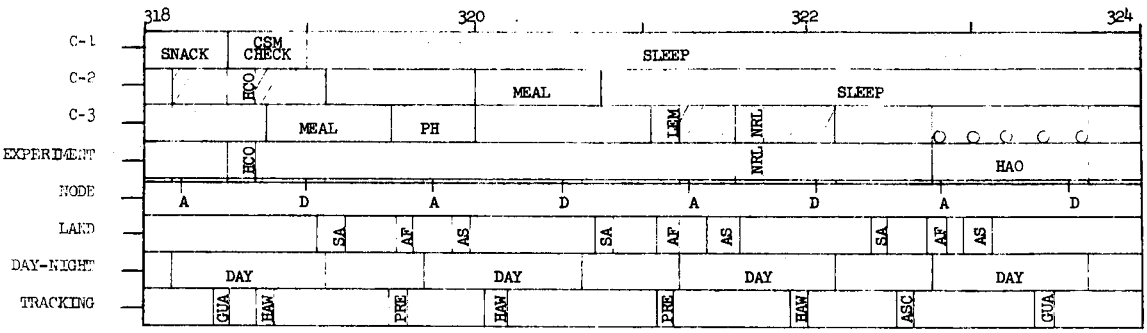

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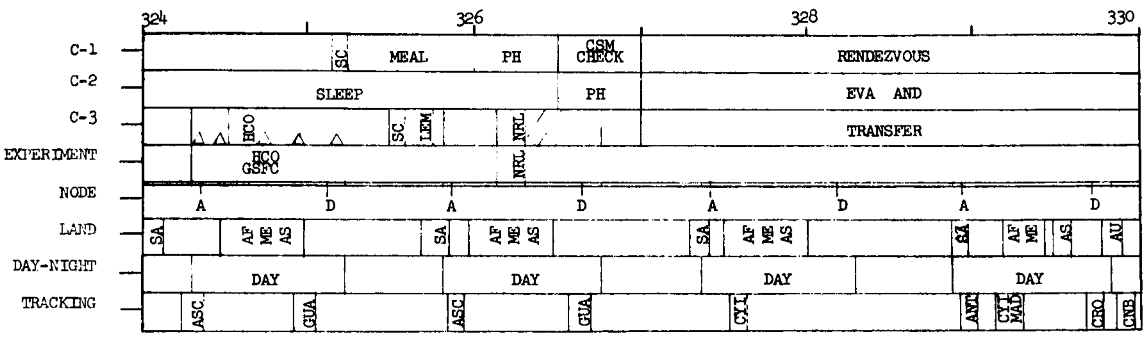

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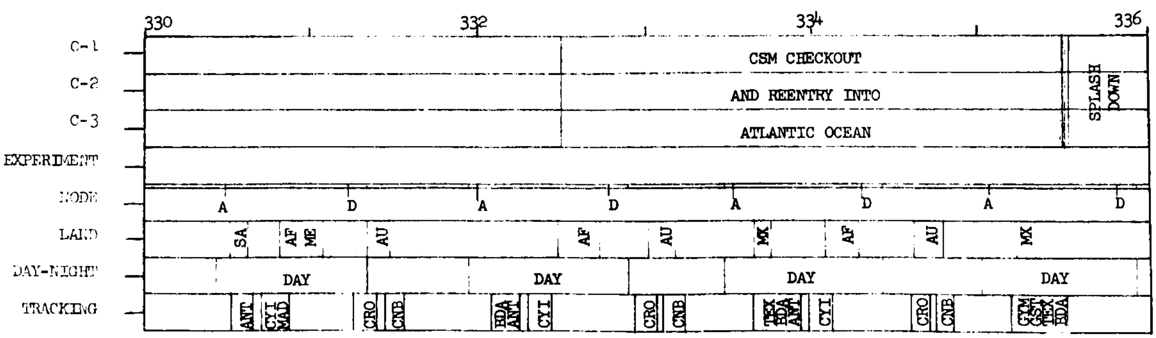

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By Robert E. Lavender

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Director, Aero-Astrodynamics Laboratory

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