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TITLE- Tether Management Considerations for AAP-4

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DATE- April 13, 1967

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ABSTRACT

If tethered operation of the LM-ATM is included in the AAP-3/AAP-4 mission, a solution to the tether wrap-up problem must be found. Tether wrap-up occurs when the tethered system is gravity-gradient stabilized because, to maintain its sun orientated attitude, the LM-ATM must revolve once per orbit with respect to the tether.

A possible method of tether management is to attach the tether to a boom that is extended from the LM-ATM. The boom is held normal to the orbital plane by the ATM-CMG control system, and is of sufficient length that the LM-ATM will clear the tether as it rotates. In this stable attitude, the tether tension is constant and causes a torque on the LM-ATM because it acts at a moment arm approximately equal to the boom length. Since the LM rotates with respect to the tether once each orbit, the torque about any LM axis is perfectly periodic and integrates to zero with time. Although the net requisite change in CMG angular momentum is zero after an orbit, the tether torque must always be countered by the CMG's. Therefore CMG capacity sets limits on the boom length.

If the sum of the momentum vectors, 6000 ft lb sec, can be used the boom can be extended 27.91 feet from the LM centerline (assuming a 100 foot tether). This is not possible for all orientations of the boom because of gryo gimbal limits. The absolute minimum available is the momentum of a single CMG, 2000 ft lb sec, and here the boom extension is limited to 9.44 feet. If this scheme is adopted, the configuration of the LM-ATM solar panels must be changed from the present MSFC design. The cruciform of 1350 sq. feet area will not clear the tether with the boom allowed by using the maximum CMG capacity. But several other panel configurations will provide clearance, even with the boom allowed by the momentum capacity of a single CMG.

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1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Tether Management Considerations for AAP-4
Case 600-3

DATE: April 13, 1967

FROM: W. W. Hough

TM-67-1022-1

TECHNICAL MEMORANDUM

INTRODUCTION

This memorandum discusses the tether wrap-up problem associated with the operation of the LM-ATM in a tethered mode during the AAP-3/AAP-4 missions, and an analysis of a possible tether management scheme. For brevity, the assembly at the other end of the tether which consists of the S-IVB Workshop, Airlock, Multiple Docking Adapter, CSM, and possibly the Lunar Mapping and Survey System will be called the Cluster.

The mode for tethered operation assumed for purposes of this discussion has the following characteristics:

1. The whole tethered vehicle system is gravity-gradient stabilized. This implies that the tether is of sufficient length that the axis of minimum moment of inertia of the system will be approximately parallel to it, regardless of the orientation of the Cluster with respect to the tether.

2. The LM-ATM is further away from the earth than the Cluster in the stabilized attitude so that the ATM's view of the sun will not be obstructed by the Cluster on the sunlit side of the orbit.

3. The tether is always taut. The system is initialized such that the gravity-gradient forces insure this condition.

4. The LM-ATM is inertially orientated with respect to the sun by its CMG control system. Under this constraint, the LM-ATM must make one revolution with respect to the Cluster each orbit.

TETHER WRAP-UP

Figure 1 is a view of a particular orbital plane that contains the sun line with the tethered LM-ATM and Cluster shown at several positions. It illustrates the above characteristics as well as the tether wrap-up problem. If the tether is connected to the LM-ATM at a single point such as the center of the LM docking port as illustrated, the system may be initialized such that the centers of mass of both vehicles and the tether will lie in the orbital plane. This condition will be maintained as a consequence of the gravity-gradient stable attitude. As the tethered vehicles progress around the orbit from the light to dark side, the tether and the LM-ATM begin to intersect. The tether cannot pass through the LM on the dark side as shown in the inner diagrams, so will wrap around it. The actual wrap-up process is illustrated by the three outer sketches as the vehicles move from to the center of the dark side into the sunlight.

EXTENDED BOOM TETHER AVOIDANCE SCHEME WHEN ORBITAL PLANE CONTAINS SUN LINE

A possible tether avoidance scheme for this condition is shown in Figure 2. A rigid boom is attached to the LM and extended laterally from the LM-ATM center of mass. (The fact that the centerline of the boom passes through the LM-ATM center of mass is a convenience for analysis purposes, it is not a prerequisite for a working scheme.) The outboard end of the boom is equipped with a swival for attatchment to the tether. The boom is held normal to the orbital plane by the LM-ATM CMG system, and is of a length that allows the end of an extended LM-ATM solar panel to pass underneath the tether. This position is the one shown in Figure 2; it occurs when the vehicles are at the center of the dark side pass. The fact that the tether axis no longer passes through the LM-ATM center of mass forces both the LM and the Cluster out of the orbital plane. For a stable attitude the out-of-plane component of the tether tension must be equal and opposite to the out-of-plane component of the gravity force on both vehicles. The tether tension acts on the LM with a moment arm approximately equal to the boom length, and although the resulting torque on the LM is periodic (in the stable orientation) with a circular frequency equal to the orbital rate the LM-ATM CMG's must store the requisite angular momentum. CMG momentum storage capacity places limits on boom and tether lengths. A two dimensional analytical treatment of this problem is given later in this memorandum.

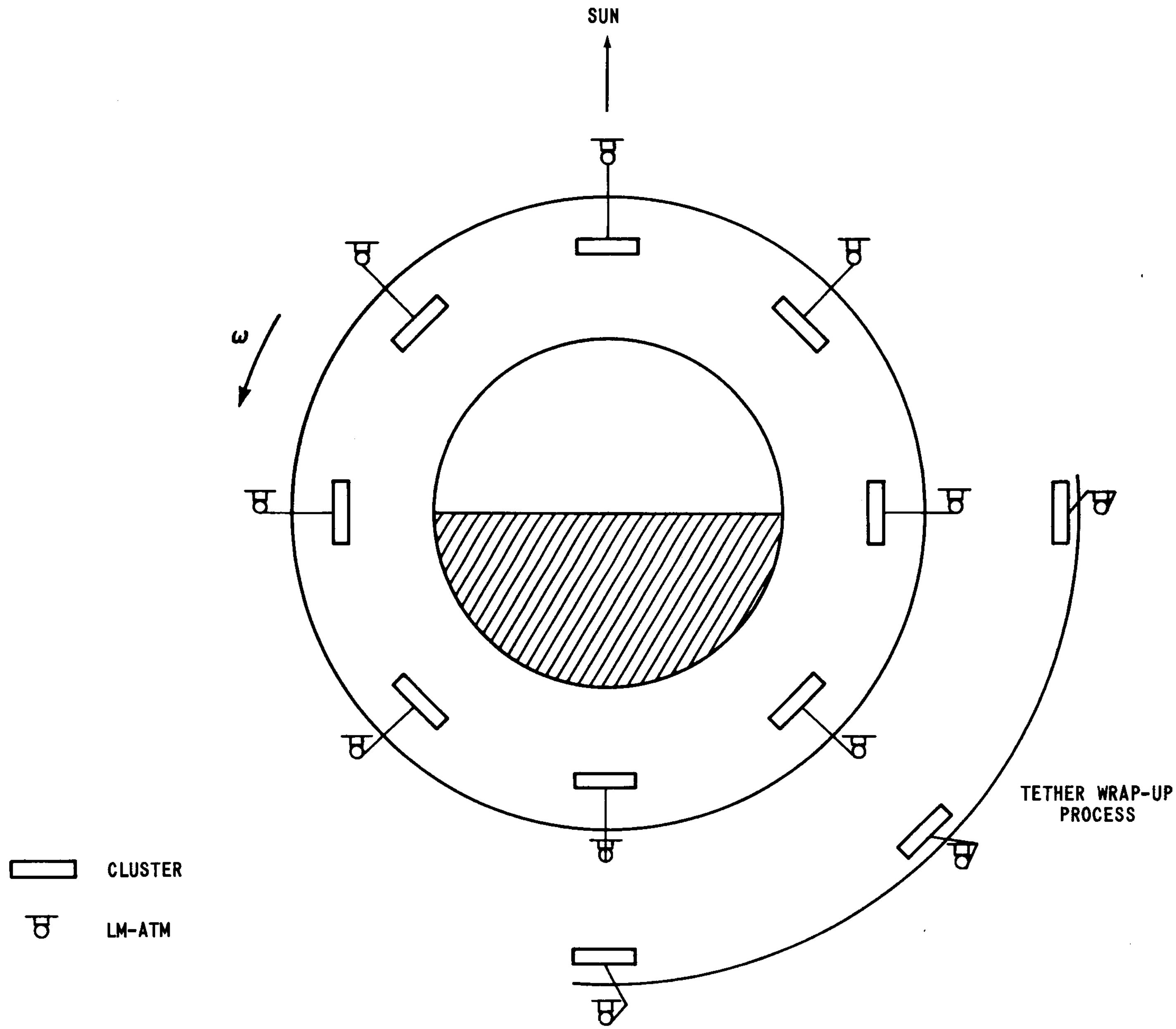


FIGURE 1 - IN-PLANE POSITIONS OF CLUSTER AND TETHERED LM-ATM
IN GRAVITY GRADIENT STABILIZED MODE

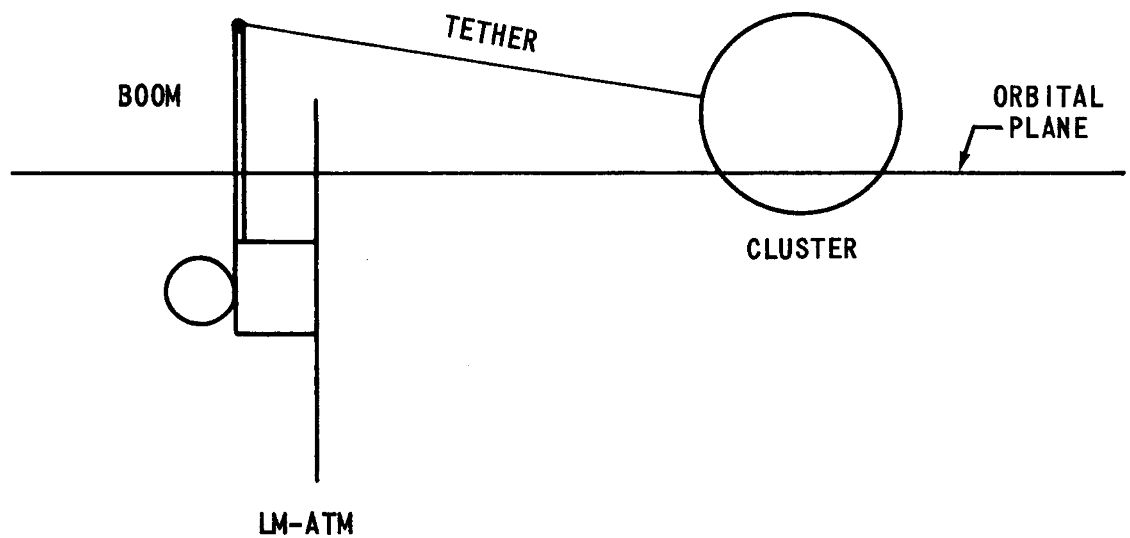


FIGURE 2 - EXTENDED BOOM TETHER AVOIDANCE SCHEME

DISCUSSION OF THE ANGLE BETWEEN SUN LINE AND ORBITAL PLANE

All discussion to this point has been based on tethered operation of the LM-ATM when the orbital plane contains the sun line. This is a special condition that, for a 28 1/2° orbital inclination, occurs periodically with an average interval over a year of approximately 23 days. At all other times, there is an angular deviation between the orbital plane and the sun line. Figure 3 illustrates how this angle varies with time. In the earth-sun system shown, the earth's polar axis will lie somewhere on a cone of 23.5° half-angle whose centerline is normal to the ecliptic plane. The polar axis makes one revolution around the cone per year. The normal to the orbital plane, defined as the vector Z, will always make an angle to the earth's polar axis that is equal to the orbital inclination. In the AAP-3/AAP-4 mission, the inclination is to be 28 1/2°. The vector Z regresses around the polar axis at a nodal regression rate which is determined by the orbital altitude and inclination, forming a cone of half-angle equal to the orbital inclination. The projection of the orbit on a plane containing the earth-sun line and the Z vector is a line. The angle between the sun line and the orbital plane is defined as β. If β is taken positive as shown in Figure 3, the limits on β can be specified for any time of the year. At the beginning of winter, $-5^\circ \leq \beta \leq +52^\circ$; at the beginning of summer, $-52^\circ \leq \beta \leq +5^\circ$; and at the beginning of spring and fall, $-28\ 1/2^\circ \leq \beta \leq 28\ 1/2^\circ$. The out-of-plane angle, β, is zero when the Z vector coincides with the plane normal to the sun line. For any orbital inclination greater than 23 1/2°, the cone on which Z lies will always intersect this plane at two places. The average interval between occurrences of $\beta = 0$ can be determined by dividing the average angle transversed by the Z vector between crossings of this plane by the angular rate of the Z vector, which is the sum of the angular rate of the earth about the sun, Ω_E, and the orbital regression rate, Ω_R. Ω_E is approximately 1°/day and Ω_R for a 28 1/2° inclination and 250 NM altitude is approximately 6.9°/day. The average interval is then:

$$I = \frac{180^\circ}{7.9^\circ/\text{day}} = 23 \text{ days}$$

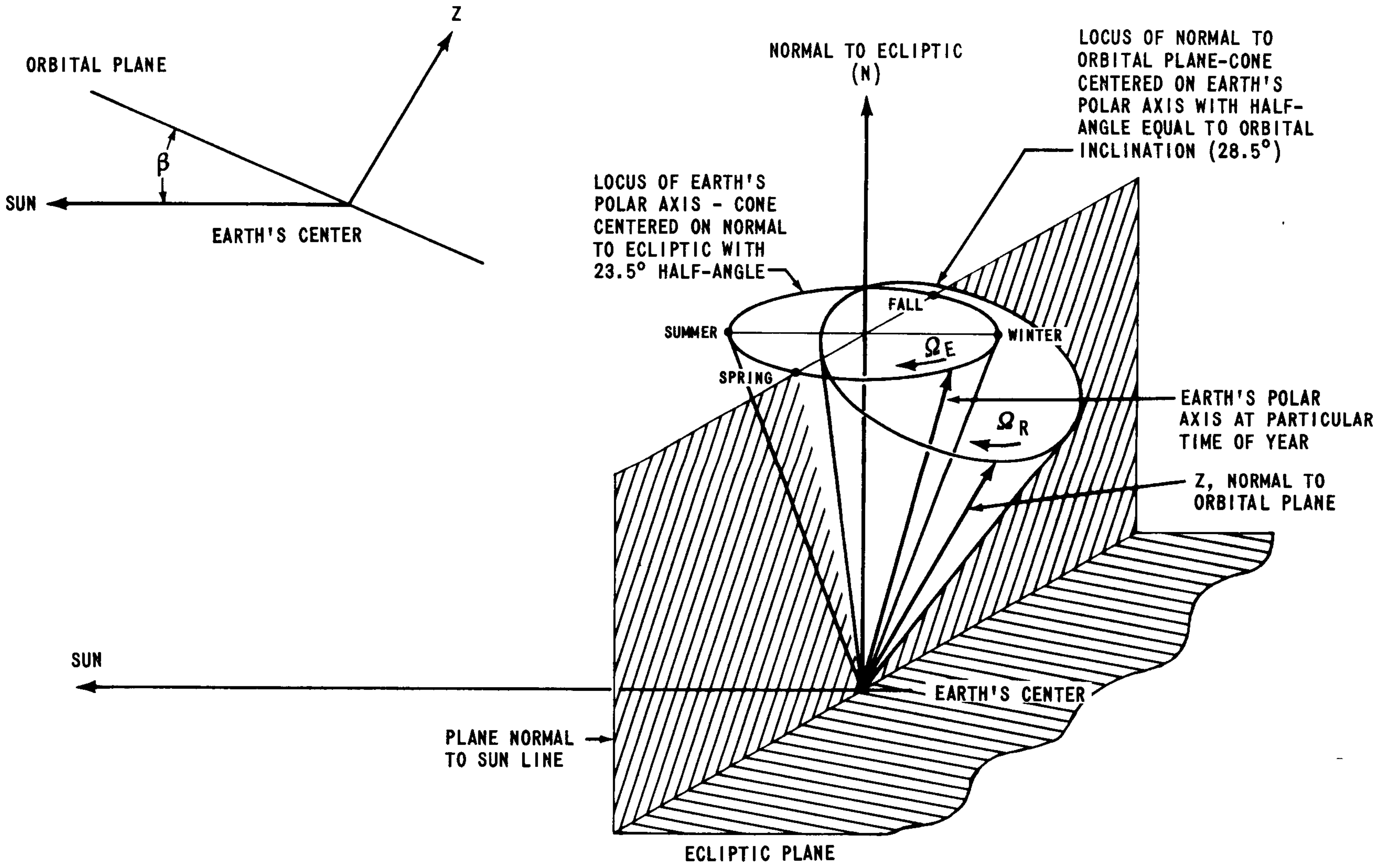


FIGURE 3 - DETERMINATION OF ANGLE BETWEEN SUN LINE AND ORBITAL PLANE

There will therefore be either two or three opportunities in the 56-day AAP-3/AAP-4 mission to operate the LM-ATM in a tethered mode with $\beta = 0$.

DISADVANTAGES OF FIXED BOOM WHEN SUN LINE-ORBITAL PLANE ANGLE IS NOT ZERO

Tethered operation with the fixed boom (fixed in the sense that it is always in a single position normal to the LM-ATM X axis) at a time when β is not zero has two disadvantages. First, stability conditions vary with orbital position. A three dimensional dynamic analysis is required and it results in three simultaneous, second-order, non-linear differential equations which require computer solution by numerical integration for any given case. Such solutions have not been obtained because of a second disadvantage, which is discussed with the help of Figure 4. The center of mass of the tethered system travels around the orbit which is inclined to the sun line at an angle β. A local vertical coordinate system with origin at the combined center of mass also travels around the orbit. This right-handed coordinate system has axes:

x = in the orbital plane opposite the velocity vector

y = along the local vertical, positive up

z = normal to the orbital plane positive toward the north.

The coordinate system rotates about z with rate ω which is equal to the orbital rate. The LM-ATM with a fixed tether management boom is inertially held by its CMG's with the ATM axis pointed at the sun. The boom, of fixed length b, is held normal to the sun line and to provide maximum tether clearance, it is held in the sun line-z plane. Therefore the angle between the boom and the z axis is always β. The two positions of the tethered assembly shown in Figure 4 are the position closest to the sun and the position furthest away for the sun. They are the only positions where, in an orientation of dynamic equilibrium, the centers of mass of the LM-ATM and the Cluster, the boom, and the tether are in a single plane, the y-z plane. With a tether of fixed length S, the distance L between the center of mass of the LM-ATM and the Cluster changes as a function of orbital position, being minimum at the point closest to the sun and maximum at the point furthest from the sun. The tension in the tether increases as this separation increases, and is therefore maximum at the point furthest from the sun. The moment arm between the tether's line of action and the center of mass of the LM-ATM, labled a in Figure 4, is also greater at the point furthest from the sun.

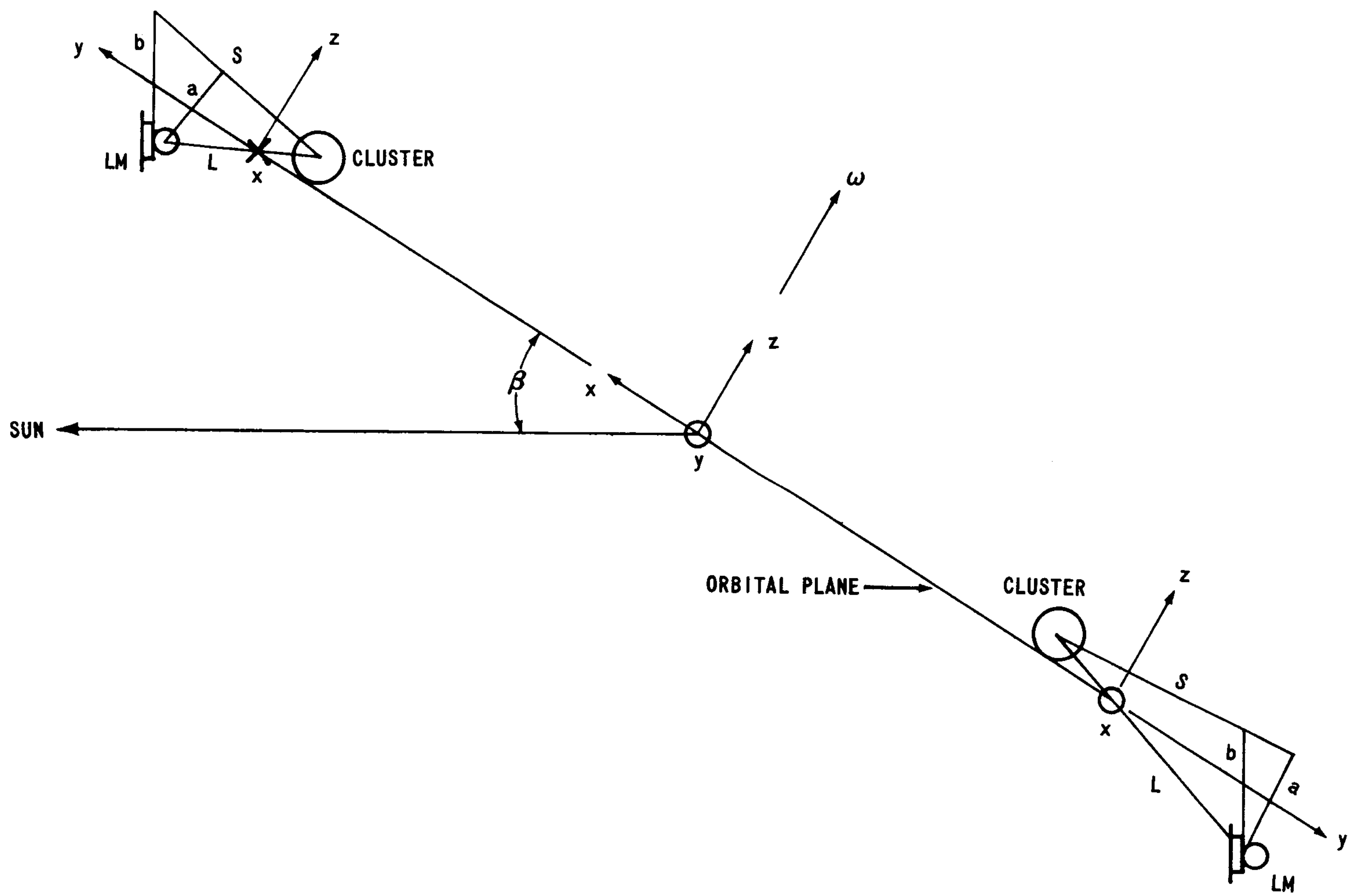


FIGURE 4 - VARIATION IN RELATIVE POSITIONS FOR TETHERED CLUSTER AND LM-ATM WITH BOOM NORMAL TO SUN LINE

The absolute torque in the LM caused by the tether tension is therefore maximum at the point furthest from the sun and minimum at the point closest to the sun. The torques at these two points are opposite each other with respect to the inertially held LM-ATM. We can conclude that about the LM-ATM axis that is held normal to the plane of the paper in Figure 4, the torque caused by the tether tension, although periodic, does not integrate to zero with time over an orbit and that there must be a net change in the angular momentum of the three CMG's. The accumulation of this momentum change over several orbits will, at some time, exceed the momentum exchange capacity of the CMG's and their momentum will have to be unloaded by firing the LM RCS system.

ANALYSIS OF STABILITY CONDITIONS WITH BOOM NORMAL TO ORBITAL PLANE

The one-orbit average of tether-induced torque about any LM axis will be zero (for a stable orientation) only when the boom is held normal to the orbital plane. For a boom fixed normal to the LM-ATM X axis, this occurs only when β is zero. However, if the boom is given one degree of freedom with respect to the LM in the sun line-z plane, and a rotating mechanism that sets the boom at an angle of $90^{\circ} + \beta$ to the sun line, then the conditions for stability are identical for any β. The boom and therefore the LM-ATM center of mass will lie in the y-z plane of the rotating x-y-z coordinate system shown in Figure 4. A non-oscillating stable orientation implies that the Cluster center of mass will also lie in the y-z plane. Since the tether connects the Cluster center of mass to the end of the boom, the tether must also lie in the y-z plane, and the stable orientation can be found by considering only the positions in this plane. Figure 5 shows this plane and parameters needed in the stability analysis.

The LM-ATM has coordinates y_L and z_L, the Cluster coordinates y_C and z_C, and the outboard end of the boom, y_P and z_P. Since the boom is perpendicular to the orbital plane, x-y, it is parallel to the z axis. Therefore:

$$y_P = y_L \qquad (1)$$

$$z_P = z_L + b \qquad (2)$$

where b is the fixed boom length.

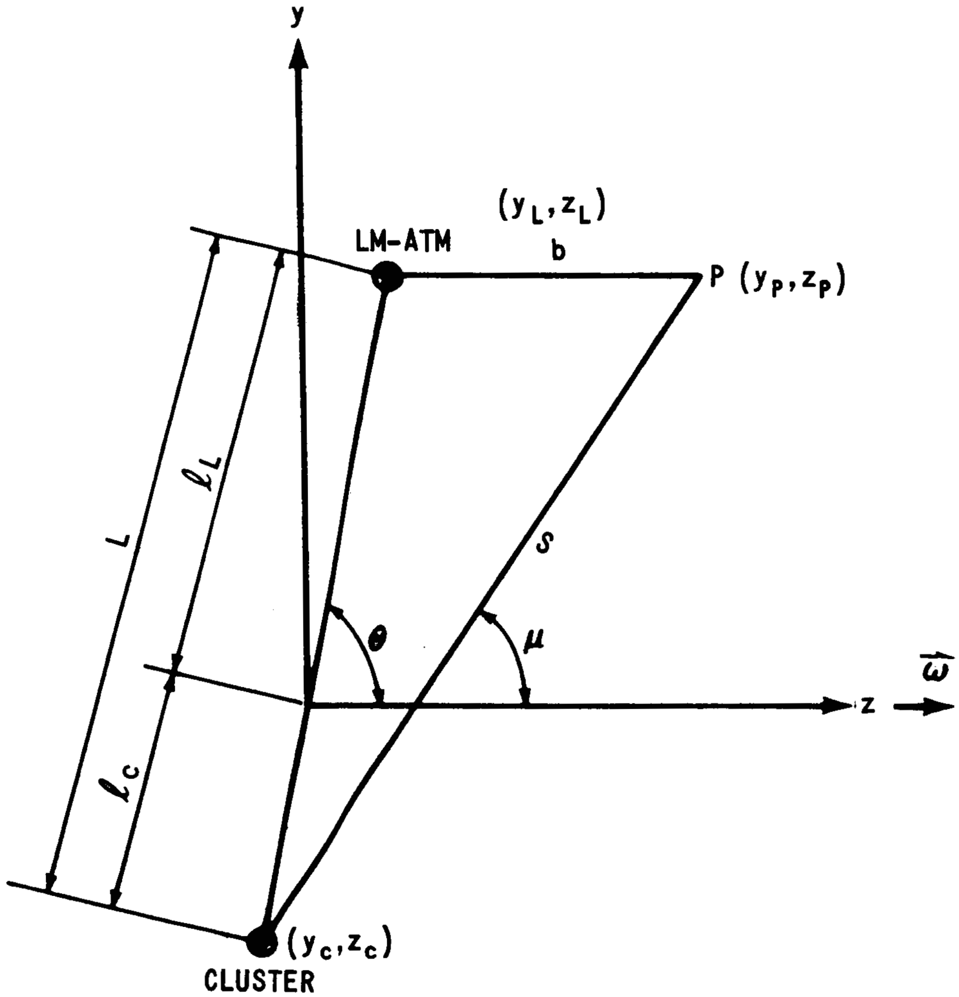


FIGURE 5 - DIAGRAM FOR STABILITY ANALYSIS

The distance from the center of mass of the tethered system, which is the origin of the coordinate system, is l_L to the center of mass of the LM-ATM, and l_C to the center of mass of the Cluster. The distance between the centers of mass of both vehicles is L, and therefore:

$$l_L + l_C = L \tag{3}$$

If θ is the angle between the z axis and the line connecting the centers of mass:

$$y_L = l_L \sin\theta \tag{4}$$

$$z_L = l_L \cos\theta \tag{5}$$

$$y_C = -l_C \sin\theta \tag{6}$$

$$z_C = -l_C \cos\theta \tag{7}$$

If μ is the angle between the z axis and the tether of fixed length S, then:

$$y_P = y_C + S \sin\mu \tag{8}$$

$$z_P = z_C + S \cos\mu \tag{9}$$

Substituting in (8) for y_P by (1) and (4), and for y_C by (6) we obtain:

$$l_L \sin\theta = -l_C \sin\theta + S \sin\mu$$

and utilizing (3):

$$L \sin\theta = S \sin\mu \tag{10}$$

Substituting in (9) for z_P by (2) and (5), and for z_C by (7) we obtain:

$$l_C \cos\theta + b = -l_C \cos\theta + S\cos\mu$$

or, utilizing (3):

$$L\cos\theta + b = S\cos\mu \tag{11}$$

If we write the general accelerations for a point described by coordinates y and z and apply Newton's law, we obtain for the y direction

$$-R\omega^2 + \ddot{y} + 2\omega\dot{x} - \omega^2 y = \frac{F_y}{M} \tag{12}$$

and for the z direction:

$$\ddot{z} = \frac{F_z}{M} \tag{13}$$

In (12) the $-R\omega^2$ term is due to the rotation of the origin of the coordinate system about the earth's center at rate ω and distance R, and $-\omega^2 y$ is due to the rotation of the coordinate system at the same rate about its origin. $2\omega\dot{x}$ is the Coriolis acceleration in the y direction, but is zero in this case because the point is constrained to lie in the y-z plane and $\dot{x} = 0$. F_y and F_z are the y and z components of the sum of gravitational forces and forces transmitted through the tether. The gravitational force on a body of mass M is directed to the center of the earth and is approximately:

$$\frac{GM_e M}{(R + y)^2}$$

The y and z components can be written:

$$F_{gy} = - \frac{G\, M_e\, M}{(R + y)^2} = - \frac{R\omega^2\, M}{(1 + \frac{y}{R})^2} \tag{14}$$

$$F_{gz} = - \frac{GM_e\, M}{(R + y)^2} \; \frac{z}{(R + y)} = - \frac{\omega^2\, M\, z}{(1 + \frac{y}{R})^3} \tag{15}$$

where $\omega^2 = \frac{GM_e}{R^3}$ from the dynamics of the center of mass of the total system.

The tension in the tether, F_t, has components acting on either body of:

$$F_{ty} = - F_t \left(\sin \mu\right) \frac{y}{|y|} \tag{16}$$

$$F_{tz} = - F_t \left(\cos \mu\right) \frac{z}{|z|} \tag{17}$$

Putting (14) and (16) into (12),

$$-R\omega^2 + \ddot{y} - \omega^2 y = - \frac{R\omega^2}{(1 + \frac{y}{R})^2} - \frac{F_t}{M} \left(\sin \mu\right) \frac{y}{|y|}$$

and expanding $(1 + \frac{y}{R})^{-2}$ by the binomial theorem,retaining first order terms only, we obtain:

$$\ddot{y} = - \frac{F_t}{M} \left(\sin \mu\right) \frac{y}{|y|} + 3\, \omega^2 y \tag{18}$$

Similarly putting (15) and (17) into (13),

$$\ddot{z} = - \frac{\omega^2 z}{(1 + \frac{y}{R})^3} - \frac{F_t}{M}\left(\cos \mu\right)\frac{z}{|z|}$$

Expansion of $(1 + \frac{y}{R})^{-3}$ gives a $3\omega^2 \frac{yz}{R}$ term which will be neglected as $\frac{y}{R}$ is very small compared to 1. Therefore:

$$\ddot{z} = -\omega^2 z - \frac{F_t}{M}\left(\cos \mu\right)\frac{z}{|z|} \tag{19}$$

The conditions for stability with no oscillations are that the accelerations $\ddot{y}$ and $\ddot{z}$ must be zero. Similarly the angles θ and μ and the coordinates of the masses must be constant. It is apparent that such solutions to (18) and (19) exist, and it remains only to find them. Using these conditions for both bodies, (18) can be written for the LM as:

$$\frac{F_t}{M_L} \sin \mu \; (+ 1) = 3\omega^2 \; l_L \sin \theta \tag{20}$$

and for the Cluster as:

$$\frac{F_t}{M_C} \sin \mu \; (- 1) = -3\omega^2 \; l_C \sin \theta \tag{21}$$

Substracting (21) from (20) and using (3):

$$F_t \sin \mu \left(\frac{1}{M_C} + \frac{1}{M_L}\right) = 3\omega^2 \; L \sin \theta \tag{22}$$

(19) for the LM becomes:

$$\frac{F_t}{M_L} \cos \mu \; (+ 1) = -\omega^2 \; l_L \cos \theta \tag{23}$$

and for the Cluster:

$$\frac{F_t}{M_C} \cos \mu \; (- 1) = \omega^2 \; l_C \cos \theta \tag{24}$$

Subtracting (24) from (23) and using (3):

$$F_t \cos \mu \left(\frac{1}{M_C} + \frac{1}{M_L} \right) = -\omega^2 \; L \cos \theta \tag{25}$$

Substituting (10) in (22):

$$F_t \sin \mu \left(\frac{1}{M_C} + \frac{1}{M_L} \right) = 3\omega^2 \; S \sin \mu \tag{26}$$

Substituting (11) into (25):

$$F_t \cos \mu \left(\frac{1}{M_C} + \frac{1}{M_L} \right) = -\omega^2 \; S \cos \mu + b\omega^2 \tag{27}$$

dividing (26) by sin μ and (27) by cos μ and subtracting gives:

$$4\omega^2 \; S - \frac{b\omega^2}{\cos \mu} = 0$$

or:

$$\cos \mu = \frac{b}{4S} \tag{28}$$

If we divide (22) by (25), we obtain:

$$\tan \mu = -3 \tan \theta \tag{29}$$

After some manupulation through relations of inverse trigonometric functions; we can write:

$$\cos \theta = - \frac{3}{4} \frac{b}{S} \frac{1}{\left(1 + \frac{b^2}{2S^2}\right)^{1/2}} \tag{30}$$

The tension is the tether can be found directly from (26):

$$F_t = \frac{M_C \; M_L}{M_C + M_L} \; 3\omega^2 \; S \tag{31}$$

The torque on the LM about the x axis of the rotating local vertical coordinate system is:

$$T_L = F_t \; b \sin \mu$$

Substitution of F_t by (31) and of $\sin \mu = (1 - \cos^2 \mu)^{1/2}$ with $\cos \mu$ obtained from (28) yields:

$$T_L = \frac{M_C\ M_L}{M_C + M_L} \frac{3\omega^2 b}{4} \left(16S^2 - b^2\right)^{1/2} \tag{32}$$

This torque is constant and positive about the x axis if μ is between 0 and 90°. The LM-ATM is in an inertial orientation with respect to the sun, however, and therefore the x axis and torque vector revolve once per orbit with respect to the LM about a LM axis coincident with the boom. To maintain the LM-ATM in the inertial orientation, the momentum vector of the control-moment gyros must rotate about the same axis lagging the torque vector by 90°. This follows from the relation that the torque vector is equal to the time derivative of the angular momentum vector, H. Integration of that equation gives the magnitude of the momentum vector:

$$H = \frac{T}{\omega}$$

If H_{max} is the maximum CMG momentum vector, then:

$$T_{max} = H_{max}\ \omega \tag{33}$$

From (32) and (33) we can solve for the maximum boom length, b_{max}, that will allow the CMG's to inertially stabilize the LM-ATM.

$$b_{max} \left(16S^2 - b_{max}^{\ 2}\right)^{1/2} = \frac{4}{3} \frac{H_{max}}{\omega} \left(\frac{M_C + M_L}{M_C\ M_L}\right) \tag{34}$$

We are interested in comparing the maximum boom length given by this equation with the boom length needed to allow the LM-ATM solar panels to pass under the tether. The quantities in equation (34) are:

$$M_L = 760 \frac{lb\ sec^2}{ft} \text{ (24,500 lb LM-ATM)}$$

$$M_C = 2785 \frac{lb\ sec^2}{ft} \text{ (89,700 lb Cluster)}$$

$$H_{max} = 6000 \text{ ft lb sec}$$

$$\omega = 1.116 \times 10^{-3} \text{ rad/sec at 250 NM altitude}$$

$$S = 106 \text{ ft (100 ft tether + 6 ft MDA radius)}$$

$$\frac{4}{3} \frac{H_{max}}{\omega} \left(\frac{M_C + M_L}{M_C M_L} \right) = 12008 \text{ ft}^2$$

So equation (34) with all but b_{max} evaluated is:

$$b_{max} \left(179776 - b_{max}^2 \right)^{1/2} = 12008 \text{ ft}^2$$

which yields:

$$b_{max} = 28.38 \text{ ft}$$

The tension in the tether from equation (31) is:

$$F_t = 0.236 \text{ pounds}$$

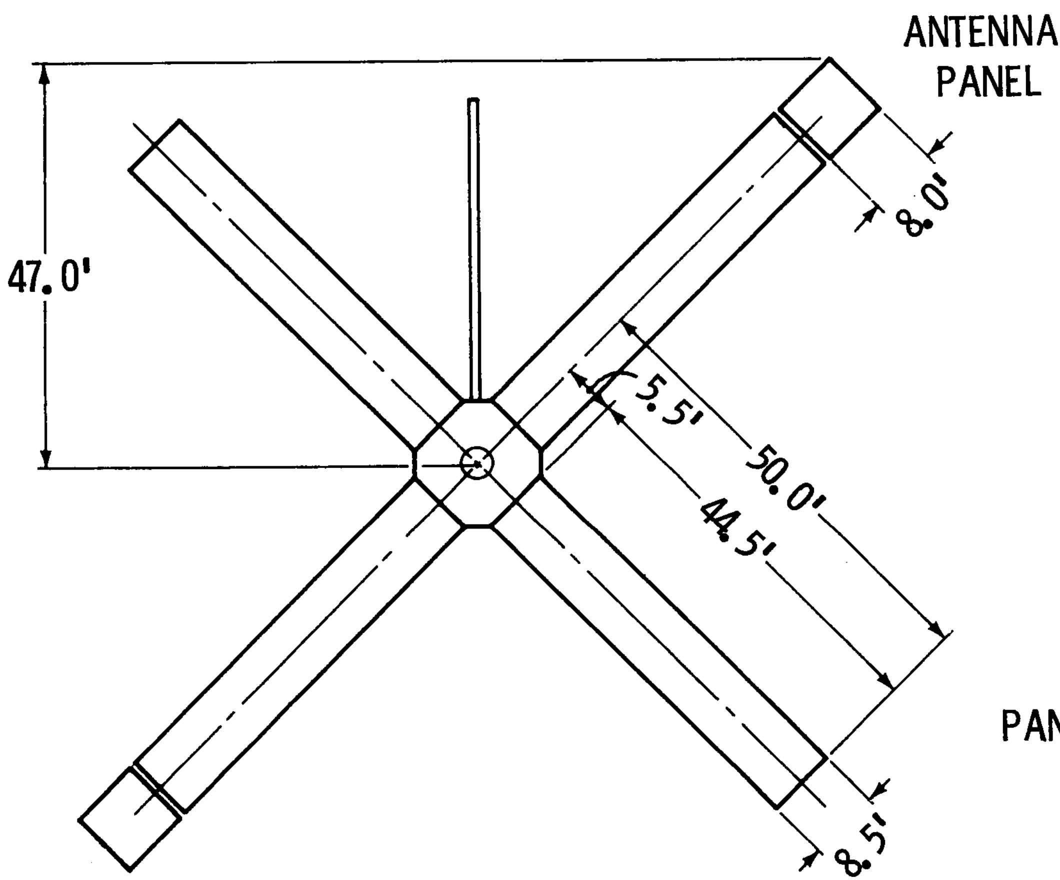
If the LM-ATM solar panel is attached at the base of the ATM rack it may extend a maximum of 27.91 feet from the LM-ATM centerline. If the solar panel is square in shape with a edge 27.5 feet (which gives a 5 inch clearance) from the centerline and an 11 foot square is deleted at the center to allow sun exposure of the ATM and rack subsystems, a total solar panel area of 2900 sq. feet can be obtained. The required solar panel area is 1350 sq. feet, which, if the same pattern is adopted, puts the solar panel edge 19.2 feet from the LM-ATM centerline and gives an 8.7 foot clearance between the edge and the tether. A corner of such a solar panel would just clear the tether if the projection of the boom on the solar panel coincided with the corner rather than the center of an edge. Many other solar panel configurations are suitable, the restriction being that on the side of the LM-ATM to which the boom is attached, the panel cannot extend more than 27.91 feet less the desired tether clearance. The MSFC four-petal arrangement is not suitable, as the extension is 47.0 feet. The MSFC panels and the 38.4 foot square array configurations are shown in Figure 6.

The 6000 ft lb sec angular momentum capability of the three CMG's requires that the vectors of each are aligned and their sum rotates to counter the tether torque. This is not always possible because of gimbal limits on the gryos. The absolute minimum is the momentum of a single gryo, 2000 ft lb sec. If equation (34) is solved for b_{max} with $H_{max} = 2000$ ft lb sec, $b_{max} = 9.44$ feet. In this case, less than 4 feet are available on the boom side of the LM-ATM for solar panels. This would require a non-symmetrical solar panel configuration, or a symmetrical configuration with long panels extending from two opposite sides, neither of which is the side to which the boom is attached.

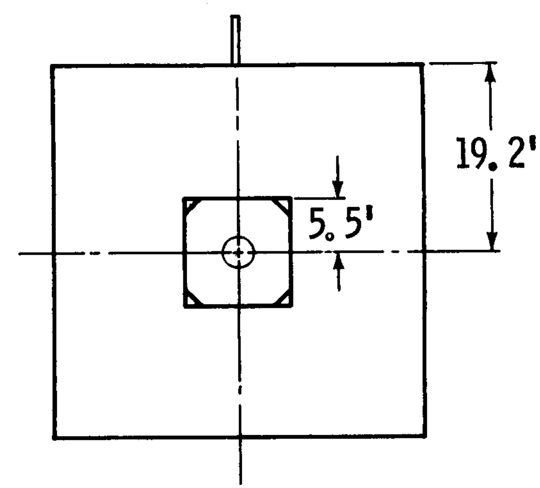
SUMMARY

If tethered operation of the LM-ATM is included in the AAP-3/AAP-4 missions, the tether wrap-up problem can be avoided by the extended boom scheme. Gravity-gradient stabilization of the tethered assembly is feasible, but fixed stability criteria can be obtained only if the boom is held normal to the orbital plane. To satisfy this requirement, for any angle between the sunline and the orbital plane, the boom position with respect to the LM-ATM must be variable about one LM axis.

The magnitude of the angular momentum vector of the Control Moment Gryo system places limits on the length of the boom. Constant tether tension results in a torque on the LM-ATM because it acts on the LM at a moment arm approximately equal to the boom length. Since the LM rotates with respect to the



4 SOLAR PANELS, 8.5 x 44.5 = 1350 SQ. FT.



PANELS 38.4 x 38.4 LESS 11 x 11
IN CENTER = 1350 SQ. FT.

FIGURE 6 SOLAR PANEL CONFIGURATION

tether once each orbit, the torque about any LM axis is perfectly periodic and integrates to zero with time. Although the net requisite change in CMG angular momentum is zero after an orbit, the tether torque must always be countered by the CMG's. If the sum of the momentum vectors (6000 ft lb sec) can be used,the boom can be extended 27.91 feet from the LM centerline (assuming a 100 foot tether). This is not possible for all orientations of the boom because of gryo gimbal limits. The absolute minimum available is the momentum of a single CMG (2000 ft lb sec) and here the boom extension is limited to 9.44 ft. If this scheme is adopted, the configuration of the LM-ATM solar panels must be changed from the present MSFC design. The cruciform of 1350 sq. feet area will not clear the tether even with the boom allowed by using the maximum CMG capacity. But several other panel configurations will provide clearance, even with the boom allowed by the momentum capacity of a single CMG.

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