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APOLLO C-BAND RADAR TRACKING CAPABILITY

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Mission and Systems Analysis Branch
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ABSTRACT

The purpose of this report is to document the current (1967) tracking capability of the Apollo land and ship based C-band radar equipment. This documentation is in support of the Apollo Navigation Working Group task of periodically updating the information contained in Technical Report AN-1 "Apollo Mission and Navigation System Characteristics", a joint Goddard Space Flight Center–Manned Spacecraft Center publication.

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APOLLO C-BAND RADAR

TRACKING CAPABILITY

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ABBREVIATIONS USED IN THIS REPORT

C-band	frequency range of 4 to 8 GHz (all equipment in this report operates from 5.4 to 5.9 GHz)
CM	Command Module
dB	decibel
dBm	power level expressed as decibels relative to 1 milliwatt
deg	degree
ft	feet
GHz	10^9 Hz
GSFC	Goddard Space Flight Center (NASA)
Hz	unit of frequency — cycles per second
IU	Instrumentation Unit
LM	Lunar Module
m	meter
mrad	milliradian (10^{-3} radians)
MHz	10^6 Hz
microsec.	10^{-6} seconds
MSC	Manned Spacecraft Center (NASA)
MSFN	Manned Space Flight Network
n. mi.	nautical mile
NASA	National Aeronautics and Space Administration
RF	radiofrequency
S/N	ratio of mean power during the received pulse to mean noise power.
sec	second

APOLLO C-BAND
RADAR TRACKING CAPABILITY

1.0 INTRODUCTION

The purpose of this report is to document the current (1967) tracking capability of the Apollo land and ship based C-band radar equipment. All currently planned Apollo missions require C-band radar beacon (or "transponder") tracking of the Instrumentation Unit (IU). There will also be C-band beacons aboard the Lunar Module (LM) and Command Module (CM) up through and including mission 503 (ref. 1).

During the Lunar mission (Mission 504 – first lunar landing capability) the five Apollo ships will employ C-band tracking as follows:

1. The Vanguard (T-AGM-19) during launch and insertion into earth orbit.

2. The Redstone (T-AGM-20) and Mercury (T-AGM-21) during injection into the translunar trajectory.

3. The Watertown (T-AGM-6) and Huntsville (T-AGM-7) during spacecraft reentry into the earth's atmosphere. (ref. 2).

The parameters used in this report reflect current individual site and ship characteristics associated with the various C-band radar types. Also included in the calculations are beacon power levels, antenna gains and radio frequency (RF) losses associated with the LM, CM, and IU.

The Manned Space Flight Network (MSFN) is taken to include all stations configured to support the Apollo program. Thus, along with the NASA sites such as Bermuda (BDA) and Carnarvon, Australia (CRO), are included Apollo support elements of the Eastern Test Range, Western Test Range, White Sands Missile Range, Eglin Gulf Test Range, and the Weapons Research Laboratories at Woomera, Australia. This definition of the MSFN is consistent with such definitive Apollo documentation as NASA MG-401 (ref. 3).

2.0 MSFN LAND BASED C-BAND RADAR CHARACTERISTICS

The MSFN land based C-band pulse radar types consist of the AN/FPS-16, AN/MPS-25, AN/FPQ-6, AN/TPQ-18 and AN/MPS-26. The MPS-25 is a transportable version of the FPS-16, the TPQ-18, a transportable version of the FPQ-6. The indicator AN (originally "Army – Navy") does not necessarily mean that the Army, Navy or Air Force use the equipment, but simply that the type nomenclature was assigned according to the military nomenclature system (ref. 4). The meaning of the three letter prefixes; FPS, MPS, FPQ and TPQ are:

FPS	—	fixed; radar; detecting and/or range and bearing
MPS	—	ground, mobile; radar; detecting and/or range and bearing
FPQ	—	fixed; radar; special, or combination of purposes
TPQ	—	ground, transportable; radar; special, or combination of purposes

(for full listing of military nomenclature see ref. 4).

The individual site characteristics pertinent to maximum range calculations are given in Table 1 which is based upon current information from RCA, Moorestown, New Jersey (ref. 5).

3.0 APOLLO SHIPS C-BAND RADAR CHARACTERISTICS

As indicated in Table 2, the Apollo ship C-band radar types consist of the RCA AN/FPS-16(V), CAPRI and modified CAPRI. Table 2 presents those characteristics pertinent to maximum range calculation.

The FPS-16(V), used aboard the Apollo insertion and injection ships, is a shipboard version of the FPS-16. The CAPRI ("Compact All-Purpose Range Instrument") used aboard the reentry ship, the Watertown, is a radar which has evolved from the FPS-16, employing solid state and integrated circuit design. The "modified CAPRI" aboard the reentry ship Huntsville incorporates the following deviations from the standard CAPRI system: (ref. 5 and 6)

1. Peak transmitter power 3.2 megawatts.

2. Cooled parametric amplifier to achieve a 1.1 dB noise figure in the reference (or sum) receiver channel.

3. Limited electronic antenna elevation scan by means of transmitter frequency stepping during acquisition. The electronic elevation sector scan covers 6° while a 23° azimuth sector is scanned mechanically. The 6° by 23° window is scanned in 5 seconds (ref. 6 and 7).

Table 1

Apollo Land Based C-Band Radar Characteristics

Station	Station Location	[1]Radar Type	Peak Power (Mega-watts)	[3]Antenna Dia. (ft)	Gain (dB)	Receiver Noise Figure (dB)	[2]Receiver Band-width (MHz)	Unam-biguous Range Capability (n. mi)
CNV	Cape Kennedy	FPS-16	1	12	44.5	4	2	1000
MLA	Merritt Island	TPQ-18	3	29	51	4	1.6	32000
PAFB	Patrick Air Force Base	FPQ-6	3	29	51	4	1.6	32000
GBI	Grand Bahama Island	FPS-16	1	12	44.5	11	2	1000
		TPQ-18	3	29	51	4	1.6	32000
SSI	San Salvador Island	FPS-16	1	12	44.5	11	2	1000
GTI	Grand Turk Island	TPQ-18	3	29	51	4	1.6	32000
ANT	Antiqua	FPQ-6	3	29	51	4	1.6	32000
BDA	Bermuda	FPS-16	1	12	44.5	8	2	500
		FPQ-6	3	29	51	8	1.6	32000
CYI	Grand Canary Island	MPS-26	0.25	10	41	10	2	2500
ASC	Ascension Island	TPQ-18	3	29	51	4	1.6	32000
		FPS-16	1	12	44.5	11	2	1000
PRE	Pretoria, South Africa	MPS-25	0.25	16	47	11	2	1000
CRO	Carnarvon, Australia	FPQ-6	3	29	51	4	1.6	32000
WOM	Woomera, Australia	FPS-16	1	12	44.5	11	2	500
HAW	Kauai, Hawaii	FPS-16	1	12	44.5	4	2	500
CAL	Point Arguello, California	FPS-16	1	12	44.5	4	2	500
WHS	White Sands	FPS-16	1	12	44.5	4	2	200
EGL	Eglin Air Force Base	FPS-16	1	12	44.5	11	2	200

[1]Nominal frequency range is 5.4 to 5.9 GHz for all types

[2]For 1 microsecond pulsewidth

[3]All FPS-16 radars except HAW and CAL are linearily polarized, all others have circular polarization capability

Table 2

Apollo Land Based C-Band Radar Characteristics

Ship	Designation	Prime Support Function	Radar Type	Peak Power (Megawatts)	Antenna[3] Dia. (ft)	Antenna[3] Gain (dB)	Receiver Noise Figure (dB)	Receiver Bandwidth (MHz)	Unambiguous Range Capability (n.mi.)
Vanguard	T-AGM-19	launch and earth orbit insertion	FPS-16 (V)	1	16	46	11	2.2	32,000
Redstone	T-AGM-20	injection into translunar trajectory	FPS-16 (V)	1	16	46	11	2.2	32,000
Mercury	T-AGM-21	injection into translunar trajectory	FPS-16 (V)	1	16	46	11	2.2	32,000
Watertown	T-AGM-6	reentry	CAPRI	1	12	44.5	5	2.0	4,000
Huntsville	T-AGM-7	reentry	modified CAPRI[1]	3.2	16	47	1.1[2]	2.0	4,000

(references 5, 6, and 8)

1 Modified to include electronic antenna scan

2 Cooled parametric amplifier

3 Circular polarization capability

4.0 APOLLO SPACECRAFT C-BAND CHARACTERISTICS

The C-band beacons (or "transponders") aboard the IU, CM, and LM all operate in the same manner, that is, an interrogating pulse (or pulse group) is received and detected by the beacon receiver to provide a trigger to the beacon transmitter pulse modulator. The beacon characteristics affecting maximum range calculations are given in Table 3. No C-band beacons are planned aboard the CM and LM beyond Mission 503. During Lunar Missions the IU will be jettisoned at an altitude above the earths surface of 6200 n.mi.

Table 3

Apollo C-Band Beacon Cnaracteristics

Vehicle	Beacon Type	Peak Power (watts)	RF Loss (dB)	[2]Maximum Antenna Gain (dB)	Transmit Pulse Width (microsec.)	Receiver Sensitivity (dBm)
[3]Instrumentation Unit (IU)	Motorola SST-135C	400	-1	6	1	-65
[1]Command Module (CM)	ACF 621 G-1	2500	-7	0	0.75	-70
[1]Lunar Module (LM)	Motorola AN/DPN66	500	-6.5	-6	0.75	-70

Note:
1. No C-band beacons aboard CM and LM beyond Mission 503
2. Antennas are circularly polarized
3. For Lunar Mission I.U. jettisoned at 6200 n.mi. altitude during the translunar phase.

5.0 MAXIMUM RANGE CALCULATIONS

5.1 BEACON TRACK

The maximum range calculation from each C-band radar location is straightforward using the information presented in Tables 1, 2 and 3. The "unambiguous range" has to do only with the particular data processing technique employed and is not a function of radio frequency propagation. The range limiting link is easily shown to be spacecraft to earth transmission. This is a result of the relatively high peak power radiated by the C-band radar transmitter, for example, 3 megawatts for FPQ-6 or 1 megawatt for FPS-16.

The maximum range for beacon track in the absence of pulse integration is given by:

$$R = \frac{1}{4\pi}\left[\frac{P_T\, G_T\, G_R\, \lambda^2\, L_T\, L_R\, L_P}{\frac{S}{N}\,(k\,T_e\,B)}\right]^{1/2} \qquad (1)$$

where: P_T = peak radiated beacon power (watts)

G_T = beacon transmit antenna gain

G_R = radar receive antenna gain

λ = wavelength corresponding to beacon frequency (meters)

L_T = beacon total RF losses

L_R = radar receiver total RF losses

L_P = polarization loss

(L_T, L_R, L_P): $0 < L \leq 1$

$\frac{S}{N}$ = the ratio of mean power during the received pulse to mean noise power required for a high probability of acquisition

k = Boltzmann's constant = 1.38×10^{-23} (Joules / °K)

B = equivalent noise bandwidth of radar receiver (Hz)

T_e = effective radar receiver noise temperature (°K)

R = maximum range corresponding to the specified signal to noise ratio.

The "effective noise temperature" includes the effects of noise intercepted by the antenna, (earth radiation into sidelobes, tropospheric noise, Galactic noise and so on), the noise generated by the RF coupling between antenna and receiver (waveguide, diplexers, duplexers) and the receiver noise. This effective temperature is generally expressed as: (see for example ref. 10)

$$T_e = \frac{T_a}{L_R} + \left(1 - \frac{1}{L_R}\right) T_L + (F - 1)\ T_R \tag{2}$$

where: T_L = waveguide and/or transmission line temperature

T_R = receiver temperature

T_a = effective antenna noise temperature

L_R = radar receiver RF losses $1 < L_R < \infty$

F = receiver noise figure = ratio of actual receiver preamplifier and mixer noise spectral density to the theoretical minimum spectral density given by kT_R (where k is Boltzmann's constant)

In order to obtain a maximum range value which would be realizible even under adverse conditions, the following parameters were used in equation (2).

T_a = antenna effective noise temperature = 100°K corresponding to near horizon antenna pointing at 5GHz (see for example ref. 11)

L_R = radar receiver overall RF losses = -4dB (a somewhat pessimistic value to cover all sites; can be as low as 1db in which case maximum range is increased by a factor of approximately $\sqrt{2}$)

L_P = -3dB for linearily polarized FPS-16 radars (see Table 1)

T_L = T_R = 290°K

F = radar receiver noise figure as tabulated in Tables 1 and 2.

The noise spectral density for each site is given by:

$$\Phi_n = kT_e \text{ (watts/Hz)} \tag{3}$$

where: k = Boltzmann's constant = 1.38×10^{-23} Joules /°K

T_e = effective noise temperature (°K) as determined by equation (2).

The mean noise power is then obtained by multiplying equation 3 by the receiver equivalent noise bandwidth, B, as given in tables 2 and 3. That is, the mean noise power, N, is given by:

$$N = \Phi_n B \text{(watts)} \tag{4}$$

The range, R, in equation (1) is then calculated for two values of single pulse signal-to-noise ratio (S/N), namely, that minimum value assuring high probability of acquisition (10dB) and a value which assures high accuracy tracking (20dB). The FPQ-6 (and its transportable counterpart the TPQ-18) employ video integration of up to 100 pulses. However, the 10dB minimum S/N considered here is the single pulse value required to assure reliable automatic acquisition (99.5% probability of acquisition in 0.2 seconds) by the auxiliary range tracking subsystem of the FPQ-6 (and TPQ-18) or the minimum reliable tracking signal for the FPS-16 (and MPS-25) (ref. 5). In all cases a 20dB single pulse S/N will assure high accuracy tracking. If non-coherent (i.e. video) pulse integration is utilized the range for high accuracy track will be increased by the factor $N^{1/4}$, where N represents the number of pulses integrated. FPQ-6 video integration is operator selectable in nine steps from $N = 3$ to $N = 100$, hence the single pulse 20dB S/N is conservative for this radar.

Table 4 summarizes the C-band beacon tracking capability of the land as well as insertion and injection ship radar systems.

5.2 SKIN TRACK

During spacecraft reentry the Apollo ships Watertown (T-AGM-6) and Huntsville (T-AGM-7) will be capable of skin tracking the CM at C-band frequencies. As indicated in section 3.0, these ships are equipped with the "CAPRI"

Table 4

C-Band Tracking Accuracies and Limitations

Station	C-Band Radar Type	Angular Tracking Limits				Tracking Accuracies						Maximum Range						Unambiguous Range (n. mi.)
		Azimuth		Elevation		Azimuth		Elevation		Range		High Accuracy[3,4]			Degraded Accuracy			
		Angle Limit (deg)	Max. Angular Rate (deg/sec)	Angle Limit (deg)	Max. Angular Rate (deg/sec)	Noise (m rad)	Bias (m rad)	Noise (m rad)	Bias (m rad)	Noise (ft)	Bias (ft)	IU (n.mi.)	CM (n.mi.)	LM (n.mi.)	IU (n.mi.)	CM (n.mi.)	LM (n.mi.)	
CNV	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	4,800	3,000	700	15,000	9,500	2,300	1,000
MLA	TPQ-18	360	28	-2 to 85	28	0.15	0.3	0.15	0.3	20	40	16,500	10,300	2,500	52,100	32,500	7,800	32,000
PAFB	FPQ-6	360	28	-2 to 85	28	0.15	0.3	0.15	0.3	20	40	16,500	10,300	2,500	52,100	32,500	7,800	32,000
GBI	FPS-16 TPQ-18	360 360	42 28	-10 to 190 -2 to 85	22 28	0.2 0.15	0.4 0.3	0.2 0.15	0.4 0.3	30 20	60 40	1,900 16,500	1,200 10,300	300 2,500	6,000 52,100	3,700 32,500	900 7,800	1,000 32,000
SSI	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	1,900	1,200	300	6,000	3,700	900	1,000
GTI	TPQ-18	360	28	-2 to 85	28	0.15	0.3	0.15	0.3	20	40	16,500	10,300	2,500	52,100	32,500	7,800	32,000
ANT	FPQ-6	360	28	-2 to 85	28	0.15	0.3	0.15	0.3	20	40	16,500	10,300	2,500	52,100	32,500	7,800	32,000
BDA	FPS-16 FPQ-6	360 360	42 28	-10 to 190 -2 to 85	22 28	0.2 0.15	0.4 0.3	0.2 0.15	0.4 0.3	30 20	60 40	2,800 9,500	1,800 6,000	400 1,400	8,800 30,000	5,500 19,000	1,300 4,500	32,000 32,000
CYI	MPS-26	360	56	0 to 89.5	28	1.0	2.0	1.0	2.0	60	120	2,150	1,350	340	6,600	4,100	1,000	2,500
ASC	TPQ-18 FPS-16	360 360	28 42	-2 to 85 -10 to 190	28 22	0.15 0.2	0.3 0.4	0.15 0.2	0.3 0.4	20 30	40 60	16,500 1,900	10,300 1,200	2,500 300	52,100 6,000	32,500 3,700	7,800 900	32,000 1,000
PRE	MPS-25	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	3,500	2,200	520	11,500	7,200	1,700	1,000
CRO	FPQ-6	360	28	-2 to 85	28	0.15	0.3	0.15	0.3	20	40	16,500	10,300	2,500	52,100	32,500	7,800	32,000
WOM	FPS-16	360	42	-10 to 90	22	0.2	0.4	0.2	0.4	30	60	1,900	1,200	300	6,000	3,700	900	500
HAW	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	6,800	4,250	1,000	21,500	13,500	3,200	32,000
CAL	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	6,800	4,250	1,000	21,500	13,500	3,200	32,000
WHS	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	4,800	3,000	700	15,000	9,500	2,300	32,000
EGL	FPS-16	360	42	-10 to 190	22	0.2	0.4	0.2	0.4	30	60	1,900	1,200	300	6,000	3,700	900	200
Insertion and Injection Ships[1]	FPS-16 (V)	360	45	-10 to 70	25	0.4	0.8	0.4	0.8	30	60	3,500	2,200	520	11,500	7,200	1,700	32,000
Reentry Ship T-AGM-6[1,2] Watertown	CAPRI	360	48	-10 to 85	28	0.4	0.8	0.4	0.8	30	60	–	80	–	–	140	–	4,000
Reentry Ship[1,2] T-AGM-7 Huntsville	Modified CAPRI	360	48	-10 to 85	28	0.4	0.8	0.4	0.8	30	60	–	200	–	–	350	–	4,000

NOTES:
1. Includes ship attitude errors.
2. Skin track of CM during reentry; target cross-section = 1 m^2.
3. No C-band beacon aboard CM or LM beyond Mission 503, IU jettisoned at 6200 n. mi. altitude.
4. High Accuracy S/N = 20 db, Degraded Accuracy S/N = 10 db.

and "modified CAPRI" C-band radar systems respectively. As indicated in Figure 1 (ref. 12), the calculated CM cross section, in the absence of an ion plasma sheath, would generally equal or exceed 1 square-meter. Thus the reentry ships skin tracking calculation is based on a 1 square-meter Apollo CM cross section. The maximum range varies as the fourth root of cross section, hence a factor of 10 increase in cross section, represents a range increase factor of approximately 2. The effect of plasma formation upon Apollo spacecraft reentry is a subject of continuing study (see for example ref. 13).

The maximum single pulse range for skin tracking can be estimated from the well known "radar range equation" which can be written as:

$$R = \left[\frac{P_T G_T G_R \lambda^2 A_o L_R L_T L_P}{64\pi^3 \left(\frac{S}{N}\right) K T_e B} \right]^{1/4} \tag{5}$$

where: P_T = peak radiated radar transmitter power

G_T = G_R = radar antenna gain

L_R = radar receive RF losses

L_T = radar transmit RF losses

L_P = polarization loss

A_o = equivalent radar cross section (m^2) and all other parameters are as defined in equations 1 through 4.

For the purpose of skin track calculations for the two Apollo reentry ships it is assumed that one-way RF losses (L_R or L_T) can be held to 1dB.

Because of uncertainties associated with CM cross section during reentry the maximum ranges presented in Table 4 must necessarily be considered as coarse estimates of C-band skin track capability by the Apollo reentry ships. The maximum 1 square-meter range of the CAPRI for a 10 dB S/N is calculated as 140 n.mi. which is comparable to the 150 n.mi., 1 square-meter, maximum skin tracking range RCA presents for the land based FPS-16 with the latter using a 16 foot antenna (ref. 5). The shipboard CAPRI, while using a smaller antenna (12 foot diameter) has a lower receiver noise figure (5dB

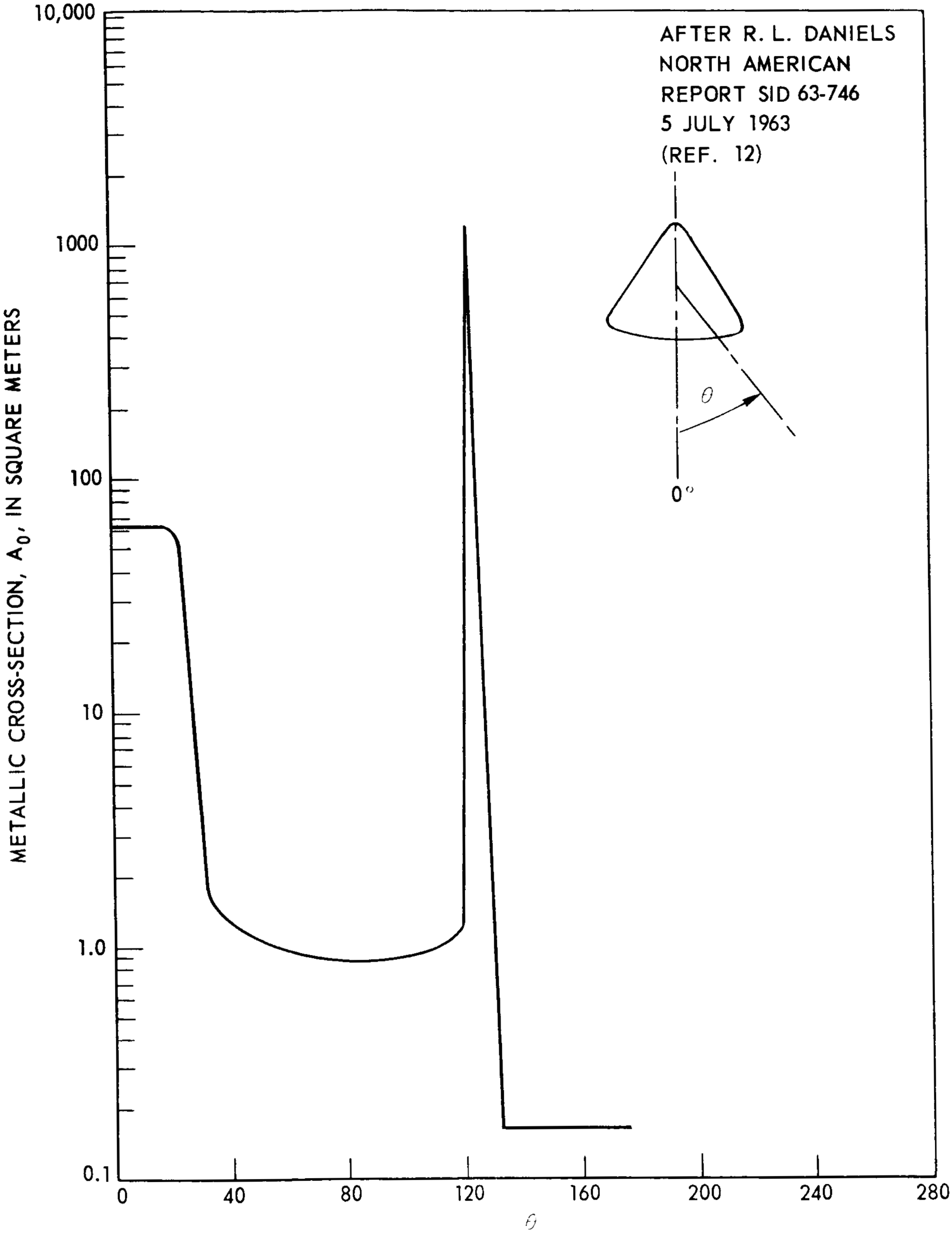

Figure 1. Apollo Radar Cross Section, A_o, versus Aspect Angle, θ, at 5.5 GHz

compared to 11 dB for the standard FPS-16). Both radars employ 1 megawatt peak power transmitters.

6.0 SUMMARY

It is seen (Table 4) that during the Apollo lunar mission, 15 of the 25 land and ship C-band tracking radars considered can track the IU unambiguously up to and during IU jettison at a nominal altitude of 6,200 n.mi. The reentry ship Watertown employing the CAPRI radar can skin track a 1 square-meter target to 140 n.mi. whereas the Huntsville, utilizing the modified CAPRI, can track 1 square-meter to approximately 350 n.mi. It is expected that the lunar mission CM upon reentry will, except for possible anomalous effects due to the ion sheath (ref. 13), present a cross section in excess of 1 square-meter.

The angular tracking limits listed in Table 4 are based upon published RCA radar system characteristics. However the tracking accuracies listed in Table 4 are conservative error estimates currently used by the Apollo Navigation Working Group (GSFC-MSC) and are not to be construed as equipment specifications.

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