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ADVANCED TRACKING AND COMMUNICATION SATELLITES

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INTRODUCTION AND SUMMARY

This paper describes a synchronous-orbit tracking and communication satellite system. The spacecraft is essentially a communication satellite that uses a large electronically steered antenna in conjunction with tracking interferometers and low-powered solid state transmitter-receiver components. The system will track and communicate with target vehicles that are equipped with a dipole type antenna, UHF receiver and a 10-w transmitter.

The satellite uses the spherical reflector and the associated packaging and deployment techniques that were analyzed and ground tested in connection with passive communication satellite programs.[1,2,3] A spherical reflecting structure similar to Figure 1, View A, will serve as the VHF/UHF communication link antenna reflector and as a support for the UHF tracking interferometer antennas. Electronic steering is accomplished by a multiple-feed system similar to Figure 1, View B, that is located in the focal area of the spherical antenna reflector. Target location, trajectory and orbit parameter data processing, system control, and housekeeping functions will essentially be accomplished at a master ground terminal from the data exchanged with the satellite over a low-powered wideband duplex data link operating at X band.

Tracking satellite attitude and yaw angle are also determined at the master ground terminal from signals radiated from the UHF satellite interferometer antennas and polarization vector of the X-band antenna signal respectivity.

Finally, this paper presents data concerning the electronic system, satellite configuration, payload weight and volume, tracking accuracy, system coverage, antenna beam steering, system trades, data links, ground terminal, and other satellite applications.

SYSTEM CONCEPT

General

The synchronous satellite tracking and communication concept is described in this section.

The satellite will use the gravity-gradient stabilization and solar-sail station-keeping subsystems that have been studied and analyzed for similarly configured passive communication satellites.[1,2,3] Ancillary active thrusters are also provided to ensure that the antenna is pointed towards the earth after deployment and to facilitate the initial positioning of the satellite. The satellite is stabilized to within ±3 deg and all satellite antennas have 24 deg of beam coverage, (see Figure 2). The large VHF antenna achieves the 24-deg coverage by electronically switching its 3-deg beam. The interferometer and microwave antennas realize the 24-deg coverage by limiting their gain to 17 db. The target vehicle antenna has almost hemispheric coverage by virtue of its low gain.

The system is capable of handling a number of target vehicles simultaneously. They may be assigned from the mission control center or may enter by individually initiated interrogation such as in emergency rescue. The target vehicle requires a receiver and a transponder with a radiated power in the 10-w class operating in VHF/UHF bands and a simple antenna such as a dipole.

Satellite

The satellite has a VHF electronically-steered 150-ft diameter unfurlable spherical antenna, four fixed interferometer antennas, solid-state receivers, transmitters, stabilization and station-keeping subsystems, and a 250-w solar-cell power supply. It will weigh less than 780 lb, will package into a 120-cu ft volume, and could be placed into synchronous orbit with an Atlas Agena launching vehicle system.

Communications and Ranging

Duplex VHF and UHF voice or data channels with a 10-kc RF bandwidth and a carrier-to-noise ratio of 32 db can be provided over a 20,000-mi link to vehicles equipped with a dipole type antenna, a 10-w transmitter, and a receiver with an effective 900-K noise temperature, (Figure 3).

Ranging is achieved by acquiring the target via the high ERP signal of the 150-ft VHF electronically-scanned antenna and then relaying a pseudo-random amplitude modulated noise pulse through the tracking satellite and target vehicle transponders back to the master ground terminal. The ranging system is similar to that used with Mariner IV.[4] However, the system bandwidth is increased from base bandwidth of 8 cycles used for Mariner IV to 1600 cycles to accommodate doppler frequency shift and to permit faster ranging measurements. Target vehicle to satellite radial velocity is determined by the processing of the doppler frequency shift data.

Range and range rate measurement accuracies are expected to be better than 500 ft and 15 fps respectively.

Figure 4, View A shows the communication and ranging system data links.

Tracking

Tracking is accomplished by the ground processing of target vehicle signals relayed from four interferometer antennas that are mounted orthogonally on the rim of the 150-ft VHF satellite antenna. Two-axis angular resolution of the order of 0.02 milliradian appears possible if sensors are used to measure the temperature and stress of the interferometer support ring (0.02-milliradian accuracy would locate a target on the earth's surface to about 1/2 mi). The microwave interferometer principle allows determination in spacecraft coordinates of the direction from which the RF wave is eminating, by phase comparison of the signal received at separated antennas. Ambiguities are resolved by multifrequency operation. The tracking system concept and data links are shown in Figure 4, View B and the tracking geometry is shown in Figure 5. References 5 through 8 describe phase-measuring and tracking techniques.

Data Links

The system employs the following data links (see Figure 6).

Communication and Ranging, Ground - Satellite Duplex - Voice, command, and broadband data, up at 8 Gc, down at 7 Gc

Communication and Ranging, Satellite - Vehicle Duplex - Voice and data transmission up at 300 Mc, down at 250 Mc

Vehicle Tracking Interferometer, Vehicle to Satellite - Interferometer receive at 400 Mc

Satellite Sensing Interferometer, Satellite to Ground - Interferometer transmit at 500 Mc.

The characteristics of the above baseline data links are shown in Table I.

Satellite Position and Attitude Measurement

Precise location of the satellite is accomplished by existing ground-station tracking techniques which continually up-date the satellite's ephemeris.

Two-axis attitude determination is achieved by interferometer measurements similar to those described above for target tracking. However, the interferometers would now be used in a transmit mode to the master ground station. The third angular coordinate of the satellite, yaw or rotation about the Z axis of minimum inertia, is sensed on the ground from the polarization vector of the 7-Gc communication down link. Figure 4, View C shows the satellite attitude sensing concept and data links.

Stabilization and Station Keeping

Attitude control is provided by a passive, gravity-gradient system. The system takes advantage of the torques that act on a satellite having differing principal moments of inertia. These torques are due to the gradient of the earth's gravitational field. The axis of minimum moment of inertia aligns itself with the local vertical. Further, the orbital rate of the satellite causes gyroscopic torques that align the principle axis of maximum moment of inertia with the normal to the orbital plane. Satellite orientation is thus provided by the proper selection of the principal axes moments of inertia.

Disturbances due to the action of natural phenomena would tend to induce and maintain intolerable attitude motion. Therefore, a damping mechanism is incorporated to dissipate energy, thus reducing the oscillation to acceptable levels.

The damper is essentially a modified Ames configuration. The damper rod and satellite are excited at different frequencies thus inducing relative motion. By introducing a viscous dashpot between the damper and main satellite body, rotational energy is dissipated. The fixed boom (in conjunction with the damper) only serves to provide yaw attitude control. This is accomplished by rotating the entire damper mechanism thus rotating the principal axes which in turn will rotate the entire satellite through the gyroscopic torque.

Station keeping is accomplished by control of the direction (and magnitude) of the solar pressure incident on the satellite's body (or sail). Proper programmed orientation of the satellite (or sail) relative to the sun provides adequate thrust to maintain a given orbit or position relative to other satellites or the earth. Orientation control is provided by programmed rotation of the damper mechanism thus inducing satellite rotation as explained earlier.

The entire operation is passive with the exception of the yaw attitude control mechanism which must be actuated actively.

Satellite Configuration

As shown in Figure 7, the COMSAT consists of:

TABLE I - BASELINE DATA LINK CHARACTERISTICS

				Antenna									
				Ground			Satellite			Target vehicle			
Link	Frequency (Mc)	Bandwidth (kc)	Power (w)	Size (ft)	Beamwidth (deg)	Gain (db)	Size (ft)	Beamwidth (deg)	Gain (db)	Beamwidth (deg)	Gain (db)	Receiver noise temperature (K)	Carrier to noise ratio
Communication and ranging													
Ground to satellite	8000	1000. 0	20. 0	85	0. 1	64	0. 5	24	17	. . .	. . .	900	30
Satellite to ground	7000	1000. 0	1. 0	85	0. 1	64	0. 5	24	17	. . .	. . .	58	30
Satellite to vehicle	250	10. 0	10. 0	. . .	. . .	. . .	100. 0	3	35	152	1	900	32
Vehicle to satellite	300	10. 0	10. 0	. . .	. . .	. . .	100. 0	3	35	152	1	900	32
Vehicle tracking interferometer Vehicle to satellite	400	3. 2	10. 0	. . .	. . .	. . .	8. 0	24	17	152	1	900	15
Satellite sensing interferometer Satellite to ground	500	10. 0	0. 2	85	1. 6	40	6. 5	24	17	. . .	. . .	900	30

1. A 150-ft diameter, 200-ft radius-of-curvature central lenticular shape (two gas-erected spherical end caps) for the main antenna reflector, with an unfurlable tape rim, an inflatable film torus and four flat spiral interferometer antennas.

2. Wire-grid film tubes to connect the central structure to the top and bottom structures.

3. A top structure composed of a satellite stabilization system, solar cells for power, and a solar sail and jets for station keeping.

4. A bottom structure containing an X-band parabola, flat spiral feeds for the large reflector, receivers, transmitters, power supplies, command and control equipment, and associated electronics.

The satellite is compactly packaged into a simple canister. (Figure 8). Its deployment sequence consists of canister deployment, deployment of torus and rim through a controlled inflation procedure, inflation and deployment of booms for positioning of top and bottom structures, inflation and deployment of lenticular shape and deployment of Ames type damper. The lenticular shape is pressurized until the wire grid in the upper cap is near the yield point of the wires, creating a spherical reflector with excellent contour.

Photolyzable film is used for the entire torus and for the pressure barrier film on the lenticular caps. After deployment and wire-grid rigidization, this polymeric film is photodegraded through the action of solar ultraviolet energy to a molecular weight form that evaporates. The remaining central structure consists of the wire-grid antenna reflector, the tape rim and the relatively small interferometer antennas. This configuration presents a small area for solar pressure, minimizing perturbations and station keeping problems.

The flat spiral feeds on the bottom structure are at the upper spherical cap focal point, or at one-half radius of curvature of the cap.

Weight and power requirements are summarized in Table II.

TABLE II -
WEIGHT AND POWER REQUIREMENTS

Item	Weight (lb)	Power required (w)
Basic structure and reflector		
Lens	156	
Torus	37	
Tape rim	25	
Support booms (8)	41	
Inflation system	33	
Canister	39	
Stabilization	67	
Flat-spiral feed array for spherical reflector 64 elements, 250 Mc, 24-ft diameter	40	
Four interferometer antennas 7 elements, 400-500 Mc, spiral arrays	16	
Solar-cell power supply 250-w output	125	
X-band transmitter, receiver, antenna and transmission line	12	20
Four 250-Mc transmitter and receivers at 8 lb and 40 w	32	160

TABLE II -

WEIGHT AND POWER REQUIREMENTS

(Continued)

Item	Weight (lb)	Power required (w)
Eight 500-Mc interferometer transmitters at 2 lb and 4 w	16	32
Eight 400-Mc receivers, 8 required at 2 lb and 3 w	16	24
Command, control, telemetry, housekeeping, programming, etc.	10	25
Thrustors	10	—
Totals	675	261

OTHER MISSIONS

The subject communication satellite is one of a family of satellites being studied for the missions indicated on Figure 9. Satellites with diameters greater than 1000 ft have been analyzed in connection with the work associated with Reference 1.

This tracking and communication satellite, because it is essentially an oriented spherical cap, might also be used as a passive communication satellite. It could also be used to implement the specific missions shown on Table III.

SYSTEM TRADES

Trades are discussed below for two general types of links, (1) those with a constant-gain target vehicle antenna, and (2) those with a constant-area target vehicle antenna. The information capacity of the link is assumed constant.

The link frequency is a dominant parameter of the satellite design. The relationship of link frequency to other parameters is shown in Table IV.

TABLE IV -

PARAMETRIC RELATIONSHIPS

Item	Relationship between item and frequency for antenna type	
	Constant gain antenna	Constant area antenna
Antenna tolerance	Proportional to	Proportional to
Beam angle	Independent of	Inversely proportional to
Steering requirement	Independent of	Proportional to
Transmitter power	Independent of	Proportional to inverse squared

In general, if antenna steering, and beam area coverage are not a problem on either end of the link, higher frequency operation is usually warranted. Lower frequencies are quite

TABLE III - DATA LINKS, SYNCHRONOUS ORBIT*

Type of link	RF band-width	Fre-quency (Mc)	Antenna diameter (ft)	Spacecraft antenna beam angle (deg)	Ground circle coverage (naut mi)	Radiated power (w)	Mobile antenna gain (db)	Mobile antenna beam angle (deg)	Comment
Voice data	10.0 kc	250.0	100	3.0	1040	7.0	1	152	4-kc channel
Command	0.1 Mc	250.0	100	3.0	1040	7.0	1	152	40-kc channel, C/N = 20
Data relay	1.0 Mc	250.0	100	3.0	1040	70.0	1	152	400-kc channel, C/N = 20
Marine	10.0 kc	250.0	100	3.0	1040	0.5	13	38	Yagi on mast
Rescue or combat	10.0 kc	125.0	200	3.0	1040	0.5	1	152	C/N = 24 db
Ocean or weather buoys	0.4 kc	125.0	25	24.0	8360	0.5	1	152	0.160-kc channel, C/N = 20
Lunar communications	10.0 kc	2000.0	100	0.36	NA	0.5	33	38	10-ft dish on moon
FM broadcast	200.0 kc	100.0	100	7.5	2600	64.0	1	152	15-kc channel, C/N = 27, FM modulation index = 5, S/N = 53 db
TV broadcast	6.0 Mc	62.5	200	6.0	2090	160.0	13	38	TV channel No. 2, cable loss = 4 db

*Carrier to noise (C/N) = 30 db, Noise figure (NF) = 6 db, same parameters for duplex operation attractive because of ease of RF power generation, equipment cost, and reduced antenna tolerance and steering requirements. It should be noted that the data link bandwidth is independent of frequency for the constant-gain antenna case. This fact makes the lower VHF frequencies attractive for broadcast type services where large antenna apertures and large beamwidth are desirable. Large antennas for low-frequency use are lighter and much easier to implement because of relaxed dimensional tolerance requirements.

CONCLUSIONS

The type of tracking and communication satellite described herein, because of its simple stabilization system, expected long life, early availability, and capability to operate with simple target vehicle equipment illustrates an attractive solution to the problem of implementing a wide-area coverage tracking and communication system with today's inexpensive low-powered target vehicle equipment.

A satellite of this general type could provide communication such as command and rescue links for aircraft, missiles, spacecraft, ships, and persons.

Further study and a flight-test program is recommended to define the most utilitarian missions, electronics systems, and satellite configurations.

The vehicle and astronaut capabilities of the Apollo program could accelerate the development of a tracking and communication satellite by accomplishing things such as providing a flight-test laboratory, reducing test-booster cost, controlling and observing the deployment of the satellite, boresighting the interferometer antenna, measuring satellite surface temperature, checking and adjusting antenna contour, and gathering design improvement data.

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BASELINE DATA LINK CHARACTERISTICS

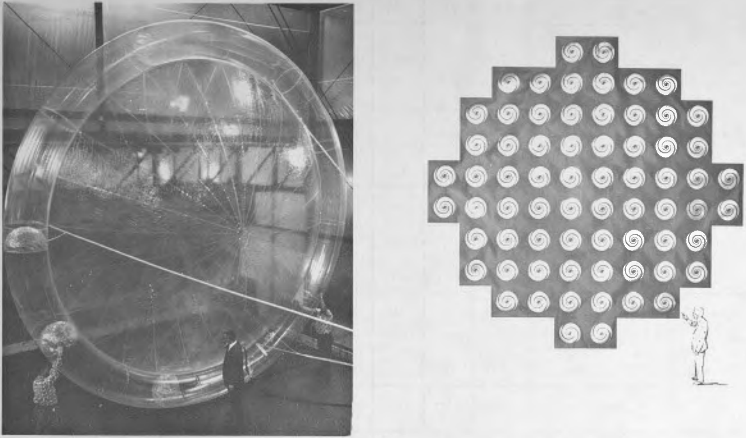
LINK	FREQUENCY	BANDWIDTH	POWER	GROUND ANTENNA			SATELLITE ANTENNA			TARGET VEHICLE ANTENNA		RECEIVER NOISE TEMPERATURE	CARRIER TO NOISE
	MC	KC	WATT	SIZE FT.	BEAM DEG.	GAIN DB	SIZE FT.	BEAM DEG.	GAIN DB	BEAM DEG.	GAIN DB	°K	
COMMUNICATION AND RANGING													
GROUND TO SATELLITE	8000	1000	20	85	.1	64	.5	24	17	—		900	30
SATELLITE TO GROUND	7000	1000	1	85	.1	64	.5	24	17	—		58	30
SATELLITE TO VEHICLE	250	10	10	—			100	3	35	152	1	900	32
VEHICLE TO SATELLITE	300	10	10	—			100	3	35	152	1	900	32
VEHICLE TRACKING INTERFEROMETER													
VEHICLE TO SATELLITE	400	3.2	10	—			8.0	24	17	152	1	900	15
SATELLITE SENSING INTERFEROMETER													
SATELLITE TO GROUND	500	10	.2	85	1.6	40	6.5	24	17	—		900	30

TABLE I. BASELINE DATA LINK CHARACTERISTICS

	DATA LINKS - SYNCHRONOUS ORBIT								C/N = 30 db NF = 6 db Same Parameters for Duplex Operation
	RF BANDWIDTH	FREQUENCY (MC)	ANTENNA DIAM. (FT.)	SPACECRAFT ANTENNA BEAM ANGLE (DEG.)	GROUND CIRCLE COVERAGE (NA-MI)	RADIATED POWER (WATTS)	MOBILE ANTENNA GAIN (db)	MOBILE ANTENNA BEAM ANGLE (DEG)	
VOICE DATA LINK	10 KC	250	100	3.0	1040	7	1	152	4-KC CHANNEL
COMMAND LINK	0.1 MC	250	100	3.0	1040	7	1	152	40-KC CHANNEL, C/N = 20
DATA RELAY LINK	1.0 MC	250	100	3.0	1040	70	1	152	400-KC CHANNEL, C/N = 20
MARINE LINK	10 KC	250	100	3.0	1040	0.5	13	38	YAGI ON MAST
RESCUE OR COMBAT LINK	10 KC	125	200	3.0	1040	0.5	1	152	C/N = 24db
OCEAN OR WEATHER BUOYS	0.4 KC	125	25	24	8360	0.5	1	152	0.160-KC CHANNEL, C/N = 20
LUNAR COMMUNICATIONS	10 KC	2000	100	0.36	NA	0.5	33	38	10-FT DISH ON MOON
FM BROADCAST	200 KC	100	100	7.5	2600	64	1	152	15KC CHANNEL, C/N=27, FM MOD INDEX = 5, S/N = 53 db
TV BROADCAST	6 MC	62.5	200	6	2090	160	13	38	TV CHANNEL #2, CABLE LOSS = 4 db

TABLE III. DATA LINKS - SYNCHRONOUS ORBIT

SATELLITE LENS AND FEED



20-FOOT PAS COMSAT MODEL

VIEW A

FLAT SPIRAL ANTENNA ELEMENTS FOR SPHERICAL ANTENNA AND INTERFEROMETERS

VIEW B

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FIGURE 1. SATELLITE LENS AND FEED

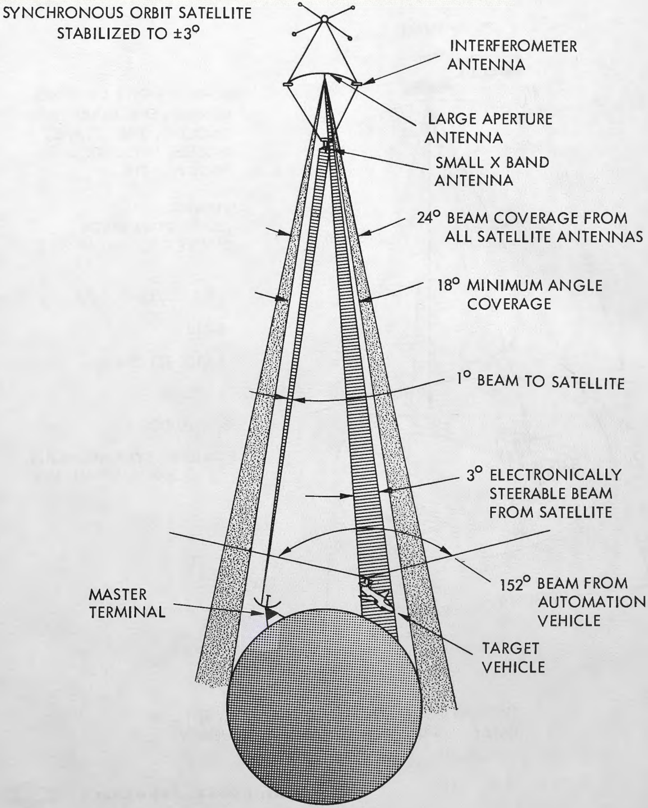
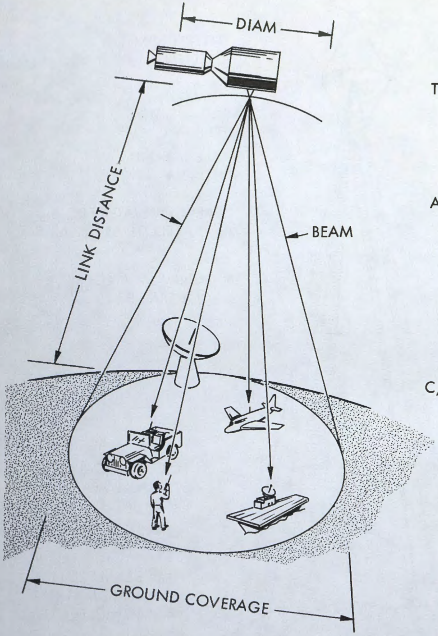


FIGURE 2. SYSTEM GEOMETRY

TYPICAL COMMUNICATION LINK



TWO-WAY VOICE CHANNEL BETWEEN SPACECRAFT AND GROUND, SHIP, PLANE, MISSILE, SATELLITE, PERSONS, ETC

ANTENNAS
100-FT-DIAM SPACE
DIPOLE GROUND MOBILE

$$P_T = B + C/N + \infty - G_T - G_R - KT_R$$

$B = 10$ KC

$f = 100$ TO 2500 MC

$C/N = 32$ DB

$T_R = 900$ DEG K

$P_T = 10$ W; SYNCHRONOUS, 20,000-NAUT-MI LINK

GROUND COVERAGE VARIES DIRECTLY WITH LINK DISTANCE AND INVERSELY WITH FREQUENCY.

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FIGURE 3. TYPICAL COMMUNICATION LINK

MASTER TERMINAL TO TARGET VEHICLE COMMUNICATIONS AND RANGING

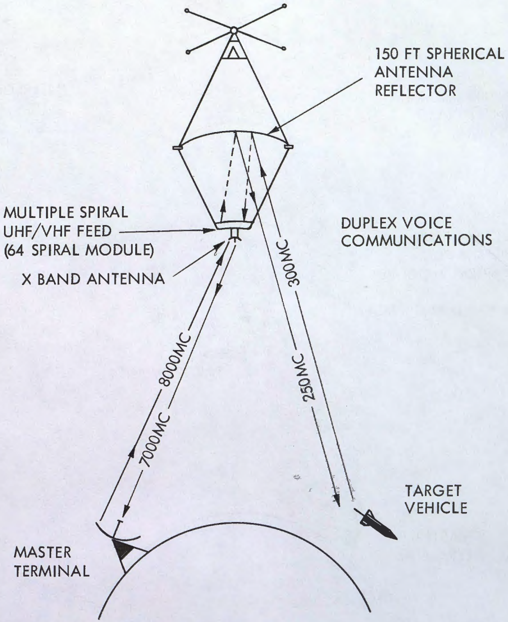

FIGURE 4A. SYSTEM DATA LINKS

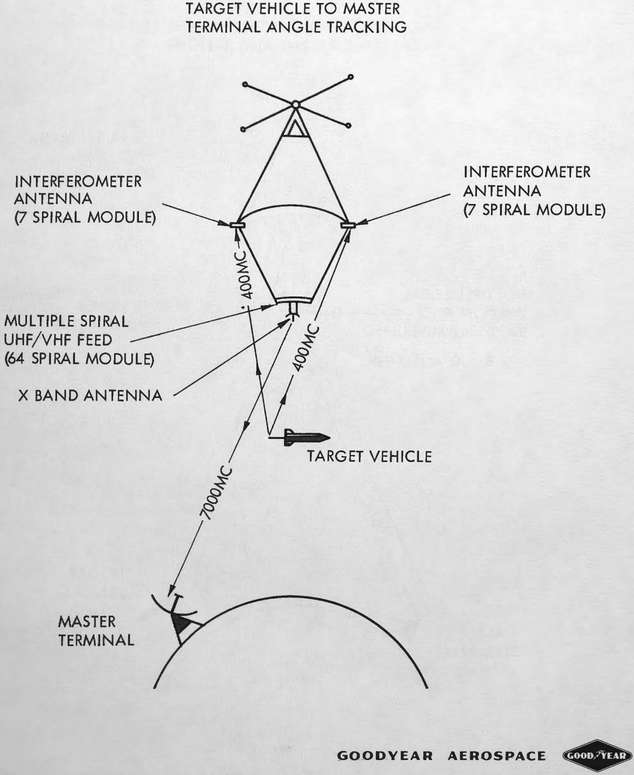

FIGURE 4B. SYSTEM DATA LINKS

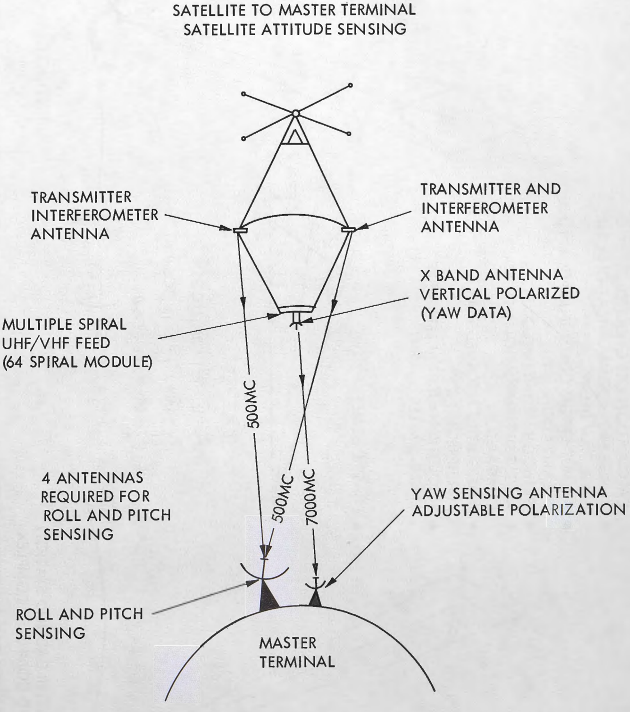

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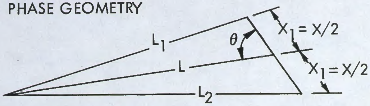
FIGURE 4C. SYSTEM DATA LINKS

TRACKING GEOMETRY

- ALL DATA PROCESSING AND COORDINATE CALCULATION ON GROUND
- RANGE FROM COMMUNICATION LINK PULSE TIME DELAY
- AZIMUTH FROM COMMUNICATION LINK POLARIZATION
- ORTHOGINAL INTERFEROMETERS
- ANGLE DETERMINATION VIA PHASE COMPARISON
- AMBIGUITIES RESOLVED VIA MULTIFREQUENCY
- RESOLUTION ≈ 0.02 MILLIRADIUS AND 0.5 MILES
- PHASE GEOMETRY



$$\phi = \frac{L_2 - L_1}{\lambda}$$

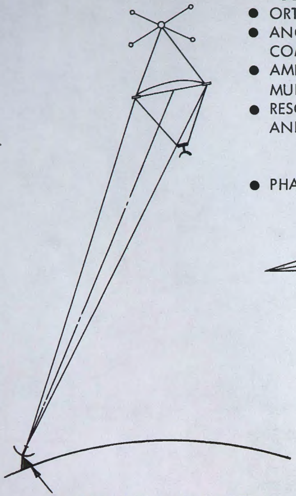
$$L_2^2 = L^2 + X_1^2 + 2X_1L \cos\theta$$

$$L_1^2 = L^2 + X_1^2 + 2X_1L \cos\theta$$

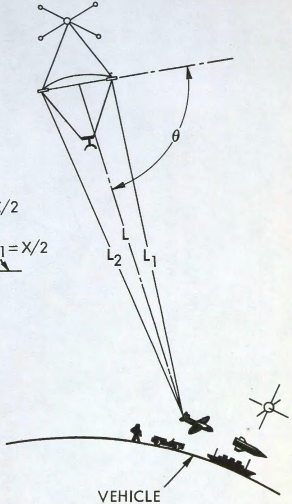
$$L_2^2 - L_1^2 = 2XL \cos\theta$$

$$L_2 - L_1 = X \cos\theta \; \left(\frac{2L}{L_2 + L_1} \approx 1\right)$$

$$\phi = \frac{X}{\lambda} \cos\theta$$



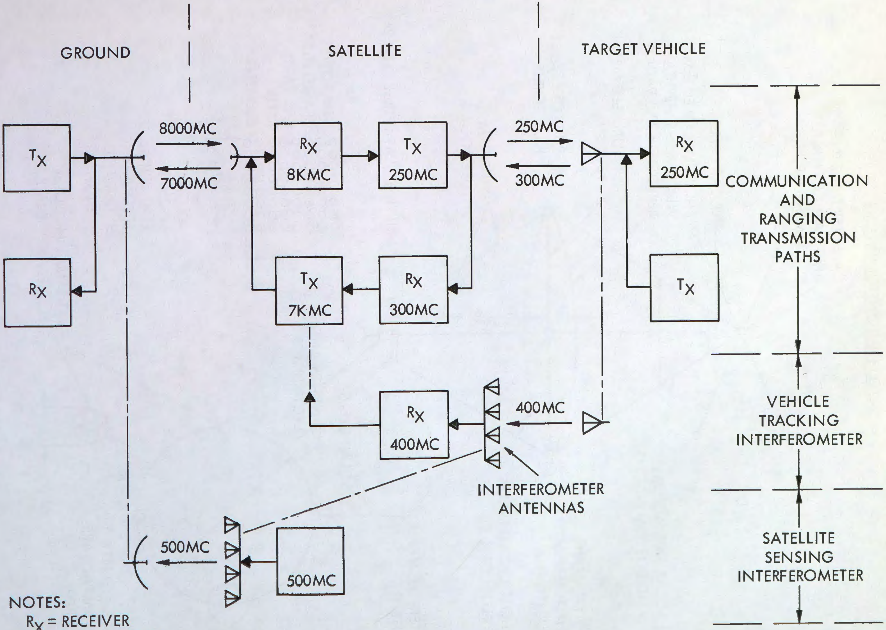
SATELLITE ORIENTATION DETERMINATION



VEHICLE LOCATION DETERMINATION

FIGURE 5. TRACKING GEOMETRY

DATA LINK BLOCK DIAGRAM



NOTES:
R_X = RECEIVER
T_X = TRANSMITTER

FIGURE 6. DATA LINK BLOCK DIAGRAM

SATELLITE CONFIGURATION

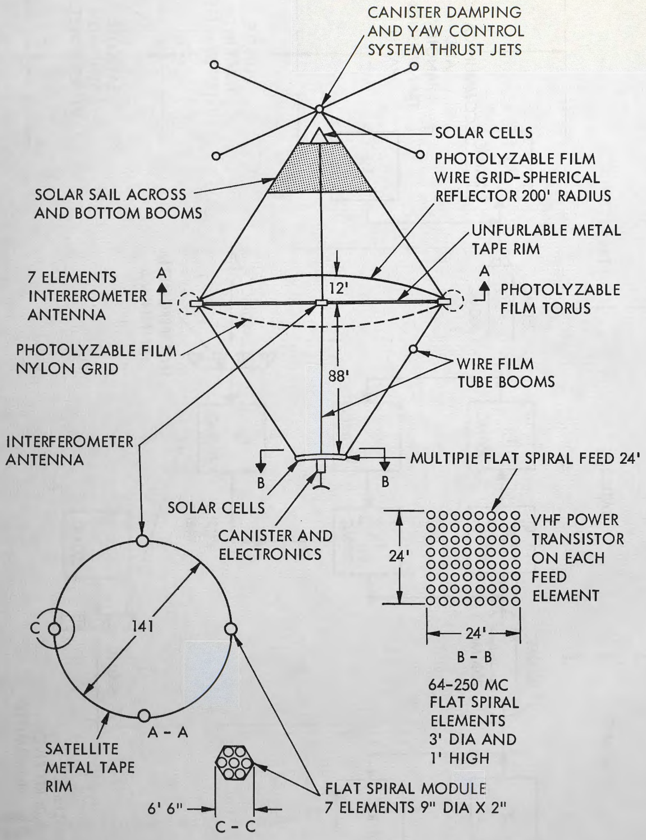


FIGURE 7. SATELLITE CONFIGURATION

PAYLOAD CONFIGURATION

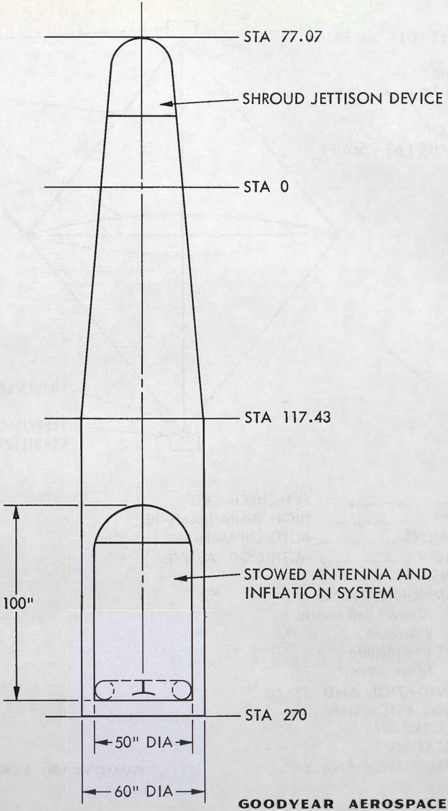


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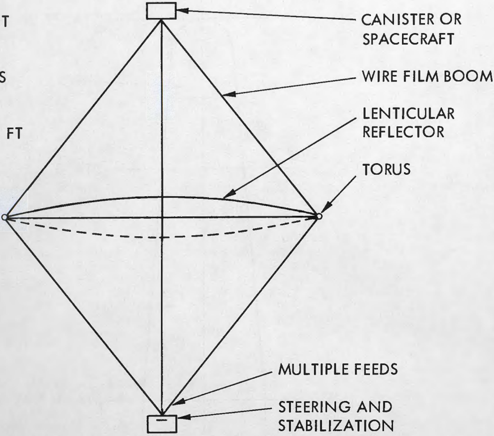
FIGURE 8. PAYLOAD CONFIGURATION

HIGH GAIN LENTICULAR SYNC SATELLITE

DIAMETER (D) - 200 FT

REFLECTOR
WEIGHT (W) - 400 LBS

RADIUS OF
CURVATURE (ρ) - 560 FT



ORBIT ___________ SYNCHRONOUS
CONCEPT ________ HIGH GAIN TRANS-REC
DEPLOYMENT ______ AUTO OR MANUAL
OPERATION _______ ACTIVE OR PASSIVE

MISSIONS:
- COMMUNICATIONS
  - Aircraft and mobile
  - Broadcast
  - Interplanetary
  - Range support
- NAVIGATION AND RESCUE
- RADIO ASTONOMY
- RADIOMETRY
- TRACKING
- INTERFERENCE ANALYSIS

GOODYEAR AEROSPACE GOODYEAR

FIGURE 9. HIGH GAIN LENTICULAR SYNC SATELLITE