INTEGRATION OF RF FUNCTIONS FOR NAVIGATION, VOICE AND DATA COMMUNICATION

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The advent of the Space Shuttle Project has produced requirements for both communication and navigation functions that were non-existent for the Apollo project. These functions are associated with landing at an airport. Although the new functions can readily be accomplished with traditional (FAA type) systems, a much more cost effective approach is proposed. This technique, called USCANS for Unified S-Band Communication and Navigation System, makes maximum use of existing NASA equipment, can be employed on other NASA projects such as Skylab, Space Station, and FFP and increases shuttle system performance during on-orbit phases. The proposed system is also compatible with the Air Force's Satellite Control Network.

SHUTTLE RF FUNCTIONS

The RF functions for NASA missions are comprised of voice transmission, data transmission and navigation. These functions must be intervehicular as well as between space vehicles and ground. On Apollo, the voice and data transmission was done principally with S-band and VHF. Navigation data was obtained at S-band with MSFN. A VHF ranging link between CSM and LM was also employed. Onboard radars were used during both the rendezvous phase and lunar landing phase of the mission.

In the USCANS concept, all functions are performed at S-band. Multilateration to ground transponders is employed for navigation in the terminal region. Ranging between shuttle and target satellite is accomplished with the same shuttle equipment as used with the ground transponders. If the target satellite is compatible with MSFN, no additional onboard equipment is needed for communication or navigation.

With the USCANS concept, all functions shown on the attached chart can be performed by an integrated set of S-band equipments.

SHUTTLE RF FUNCTIONS

FUNCTION / TERMINALS	VOICE	DATA	NAVIGATION
BOOSTER - LAUNCH SITE	P	N	N
BOOSTER - MSFN	N	N	N
BOOSTER - LANDING SITE	P	N	P
BOOSTER - ORBITER	P	N	N
ORBITER - LAUNCH SITE	P	N	D
ORBITER - MSFN	P	P	P
ORBITER - TARGET SATELLITES	P	D	P
ORBITER - LANDING SITES	P	N	P

P - MUST BE PROVIDED

N - NO REQUIREMENT DEFINED

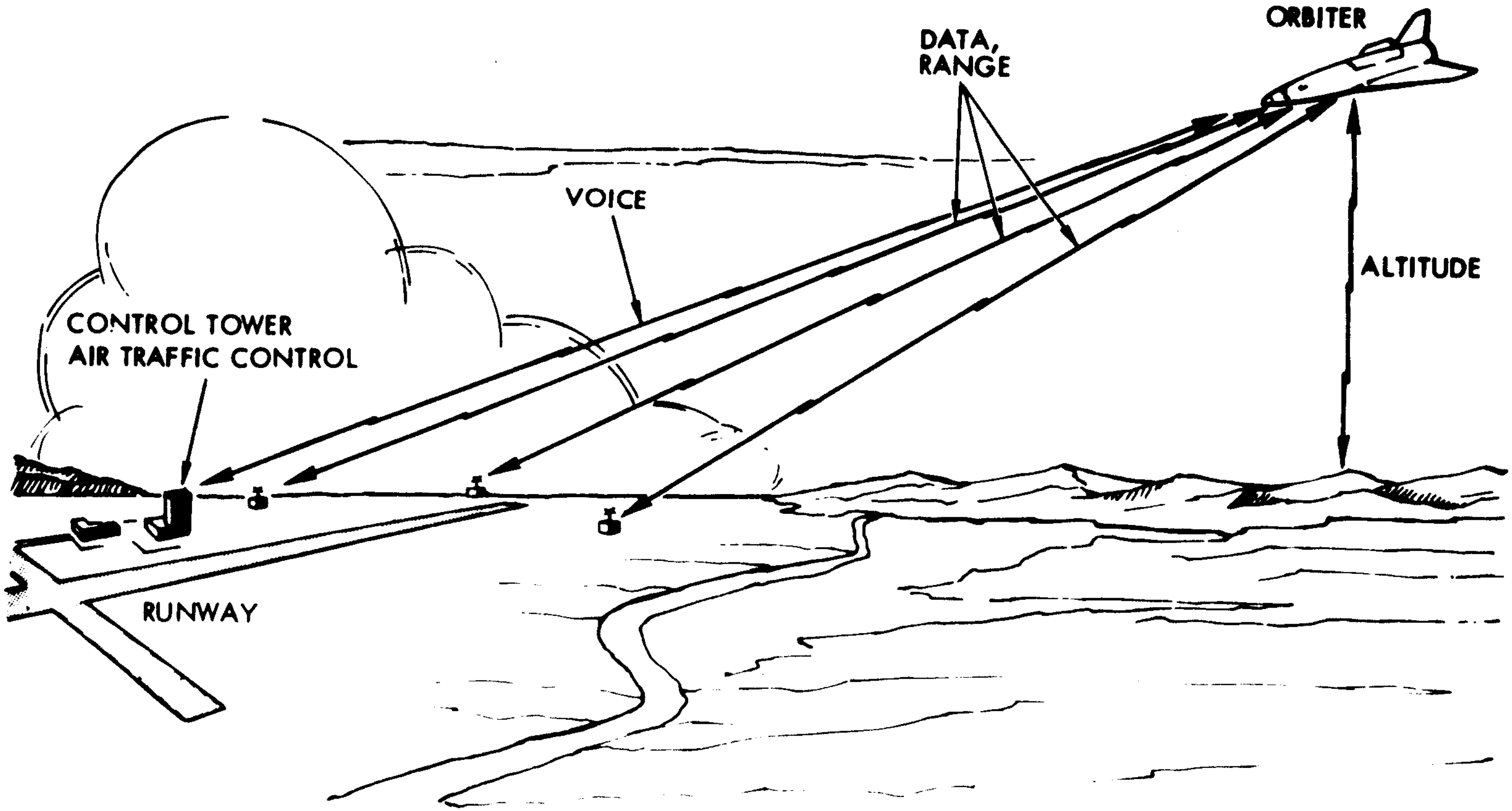
D - DESIRABLE

CRUISE AND LANDING SCENARIO

The USCANS system is conceived as operating with ground transponders located at the designated booster and orbiter landing sites. Location of the transponders in the terminal area will be optimized to provide the best navigation data. Since multiple transponder locations are required for navigation accuracy, redundancy is achieved if more than three locations are used. It is anticipated that the transponders will be dual redundant at each location. All ground transponders are similar except each has its own location code. The receivers are always operating. The ground transponders transmit only when called by means of the location code. To minimize cost, the control tower is tied to only two dual redundant transponders for voice purposes. Meteorological data on ground equipment health status could be sent to the vehicle on the data link.

The booster or orbiter sequentially interrogates the ground transponders, thus obtaining range (and possibly range rate) information. This data is filtered onboard the vehicle for navigation and guidance purposes.

CRUISE AND LANDING SCENARIO



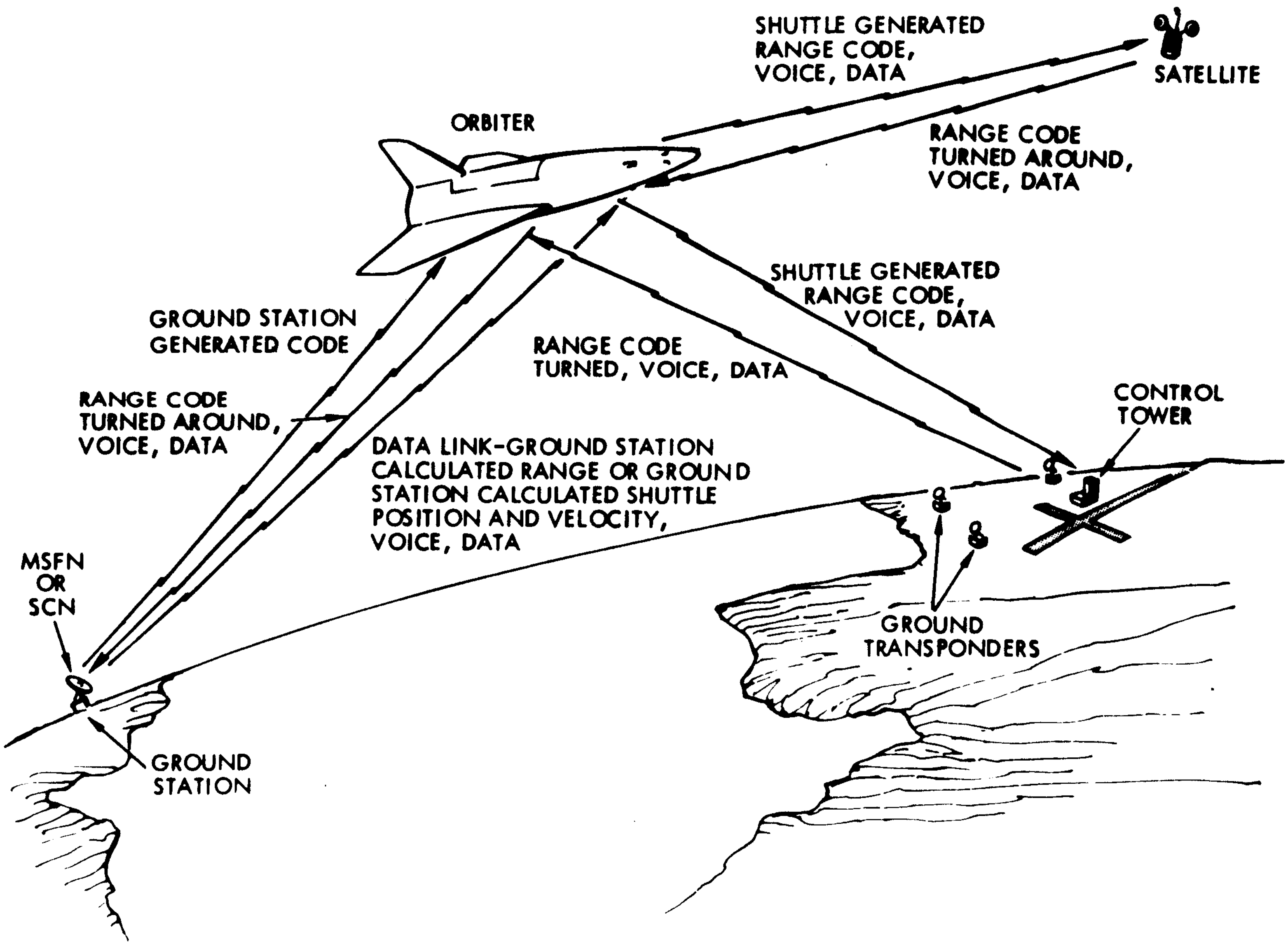
ON ORBIT

On orbit operations with MSFN are the same as on the Apollo project. For navigation, a MSFN generated range code is received by the orbiting vehicle and returned to the MSFN. A ground computed vehicle state vector can be sent to the orbiter on the data link. As an alternate mode, MSFN determined range and range rate can be transmitted via the data link for use in the onboard navigation filter. Voice and data links are the same as presently used.

Additional navigation data (also voice and data if desired) can be obtained from the transponders located at the landing sites. By interrogating one of the transponders, range to the known transponder location can be accurately obtained and on orbit navigation updated.

Communication with a MSFN compatible satellite is the same as to a ground transponder or MSFN. Both voice and data can be transmitted. For navigation, the orbiter generates and transmits a range code which is subsequently turned around by the MSFN compatible satellite. Relative navigation is performed onboard the orbiter.

ON ORBIT

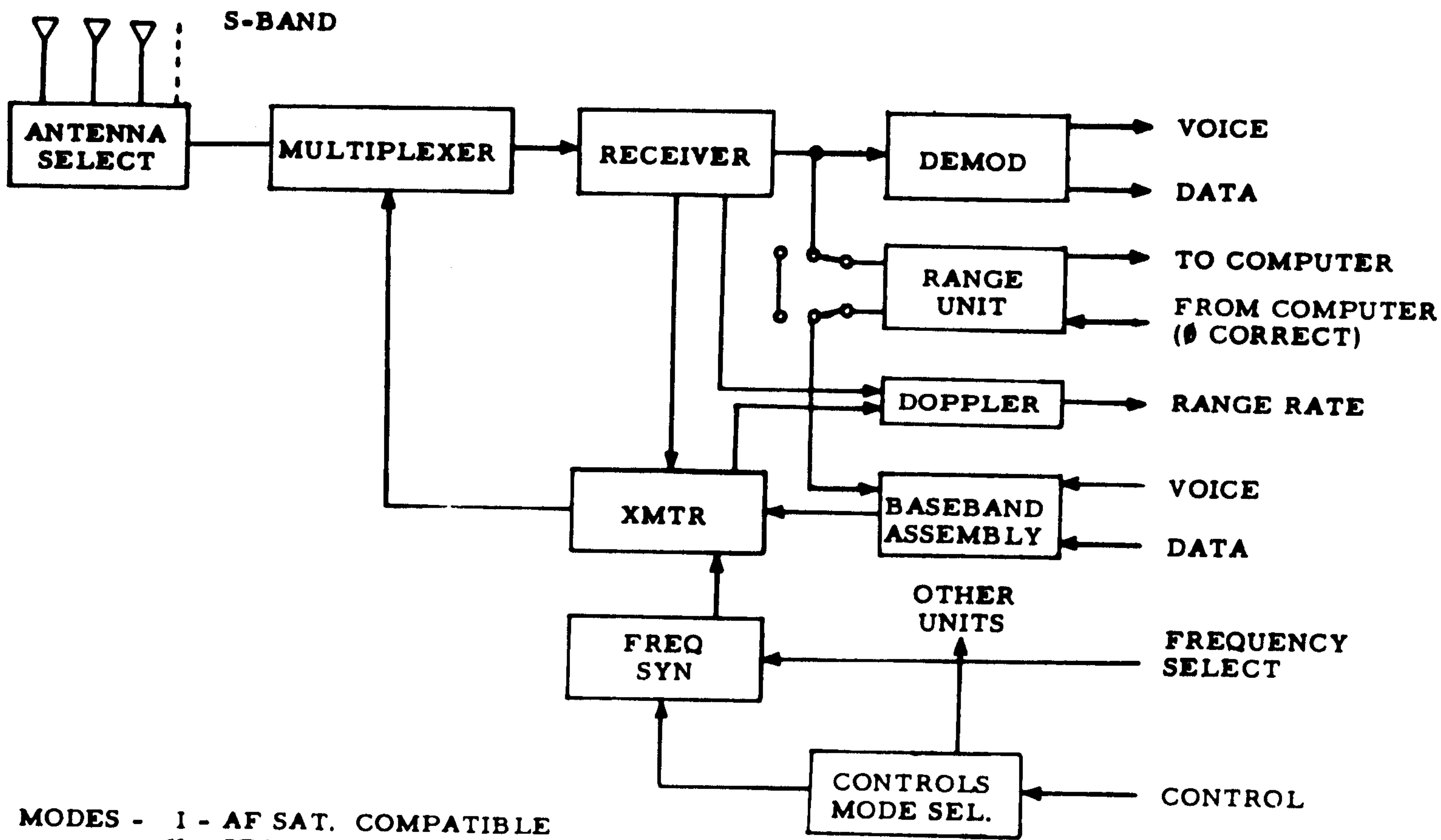

SHUTTLE GENERATED RANGE CODE, VOICE, DATA
SATELLITE
ORBITER
RANGE CODE TURNED AROUND, VOICE, DATA
SHUTTLE GENERATED RANGE CODE, VOICE, DATA
GROUND STATION GENERATED CODE
RANGE CODE TURNED, VOICE, DATA
RANGE CODE TURNED AROUND, VOICE, DATA
CONTROL TOWER
DATA LINK-GROUND STATION CALCULATED RANGE OR GROUND STATION CALCULATED SHUTTLE POSITION AND VELOCITY, VOICE, DATA
MSFN OR SCN
GROUND TRANSPONDERS
GROUND STATION

PROPOSED SYSTEM - VEHICLE EQUIPMENT

The onboard S-band equipment required is very similar to the Unified S-Band Equipment used on Apollo. In effect, only the addition of a range code generator and frequency synthesizer is required. The former is for ranging to target satellites and ground transponders while the latter is to provide compatibility with MSFN, MSFN compatible satellites, SCN, and SCN compatible satellites. A switch is included to eliminate the range unit so that the equipment will be compatible with MSFN by merely turning around the range code.

As presently conceived the ranging is achieved with a sequential binor code. This is in contrast to the tones used on Apollo and the PRN used on MSFN. Sequential binor has been selected because of its rapid acquisition characteristics as well as receiver simplicity.

PROPOSED SYSTEM - VEHICLE EQUIPMENT

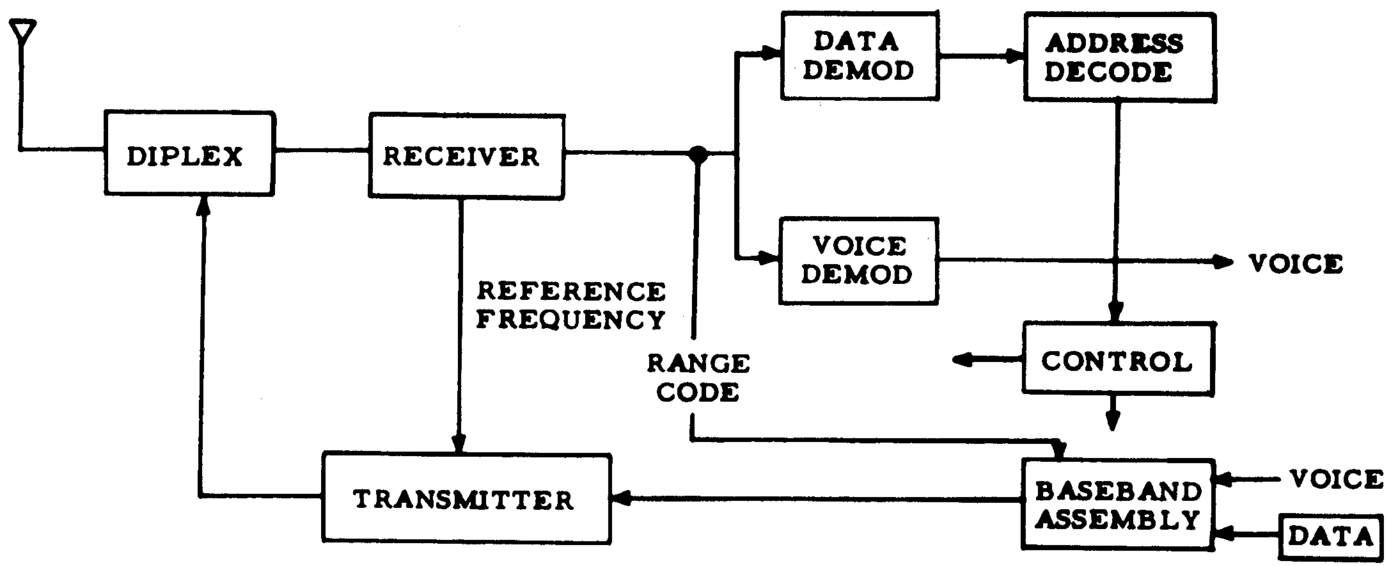


MODES - I - AF SAT. COMPATIBLE
II - SPACE STATION COMPATIBLE
III - MSFN COMPATIBLE
IV - SCF COMPATIBLE

PROPOSED SYSTEM - LANDING SITE TRANSPONDER BLOCK DIAGRAM

The ground transponder (as well as the target satellite transponder) is also very similar to the Unified S-Band Equipment onboard the Apollo. Since each transponder is to contain its own location code and transmit only when that code is received, a technique is provided to recognize the location code and turn on the transmitter.

PROPOSED SYSTEM - LANDING SITE TRANSPONDER BLOCK DIAGRAM



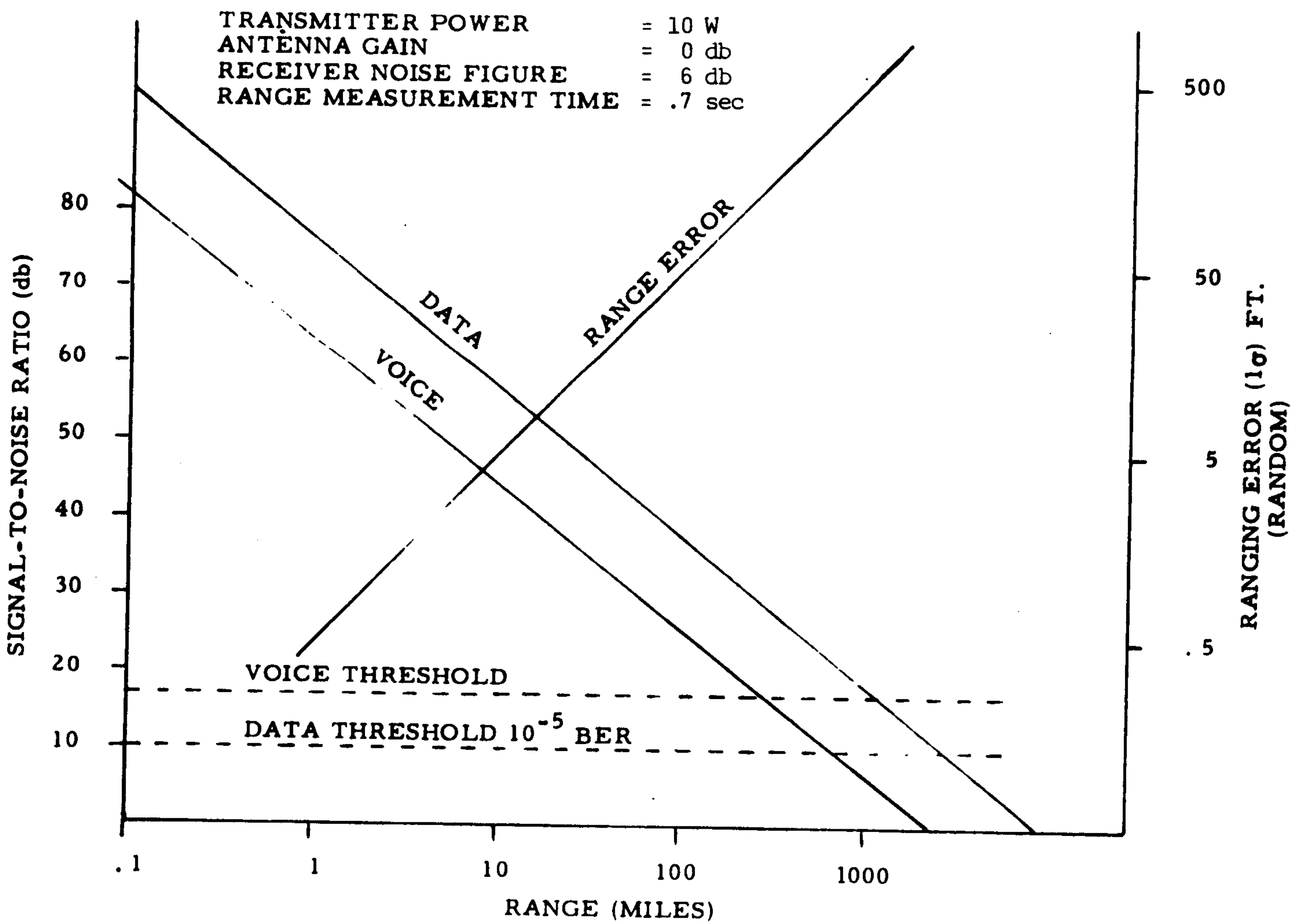
USCANS LINK PERFORMANCE

USCANS link performance is shown on the following chart. As shown, the data link has a signal to noise ratio of greater than 10 db to ranges greater than 1000 miles. The 10 db threshold corresponds to a bit error rate (BER) of 10^{-5}.

The voice threshold shown of 16 db corresponds to an articulation index of approximately 0.4. This provides 82% intelligibility of isolated words and 97% for sentences.

Range error is a function of range measurement time (as well as range). Thus, range error can be decreased by increasing the measurement time if desired.

USCANS LINK PERFORMANCE

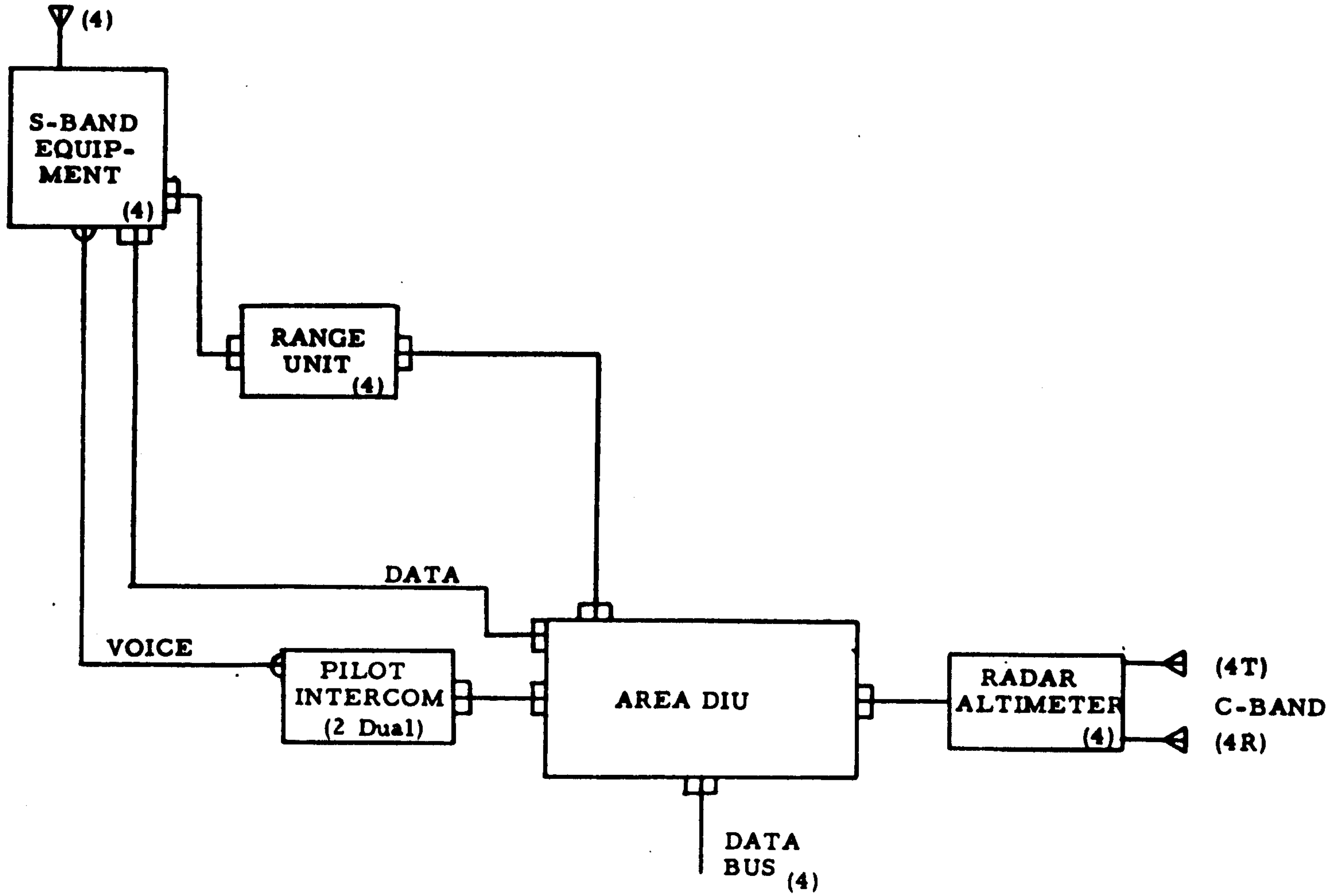


ONBOARD COMMUNICATION AND NAVIGATION EQUIPMENT (USCANS)

Several communication and navigation subsystem configurations are now considered to form the basis of a cost analysis. These configurations all conform to the NASA Level 1 failure operational, fail operational, fail safe redundancy requirement.

The basic configuration is that of USCANS. All communication and navigation functions, as described above, are at S-band. C-band radar altimeters are shown in the figures. However, requirements for their use are in question. The numbers in parentheses indicate the number of units onboard to satisfy the redundancy requirements.

ONBOARD COMMUNICATION AND
NAVIGATION EQUIPMENT
(USCANS)



ONBOARD COMMUNICATION AND NAVIGATION EQUIPMENT (S-BAND AND SEPARATE RANGING)

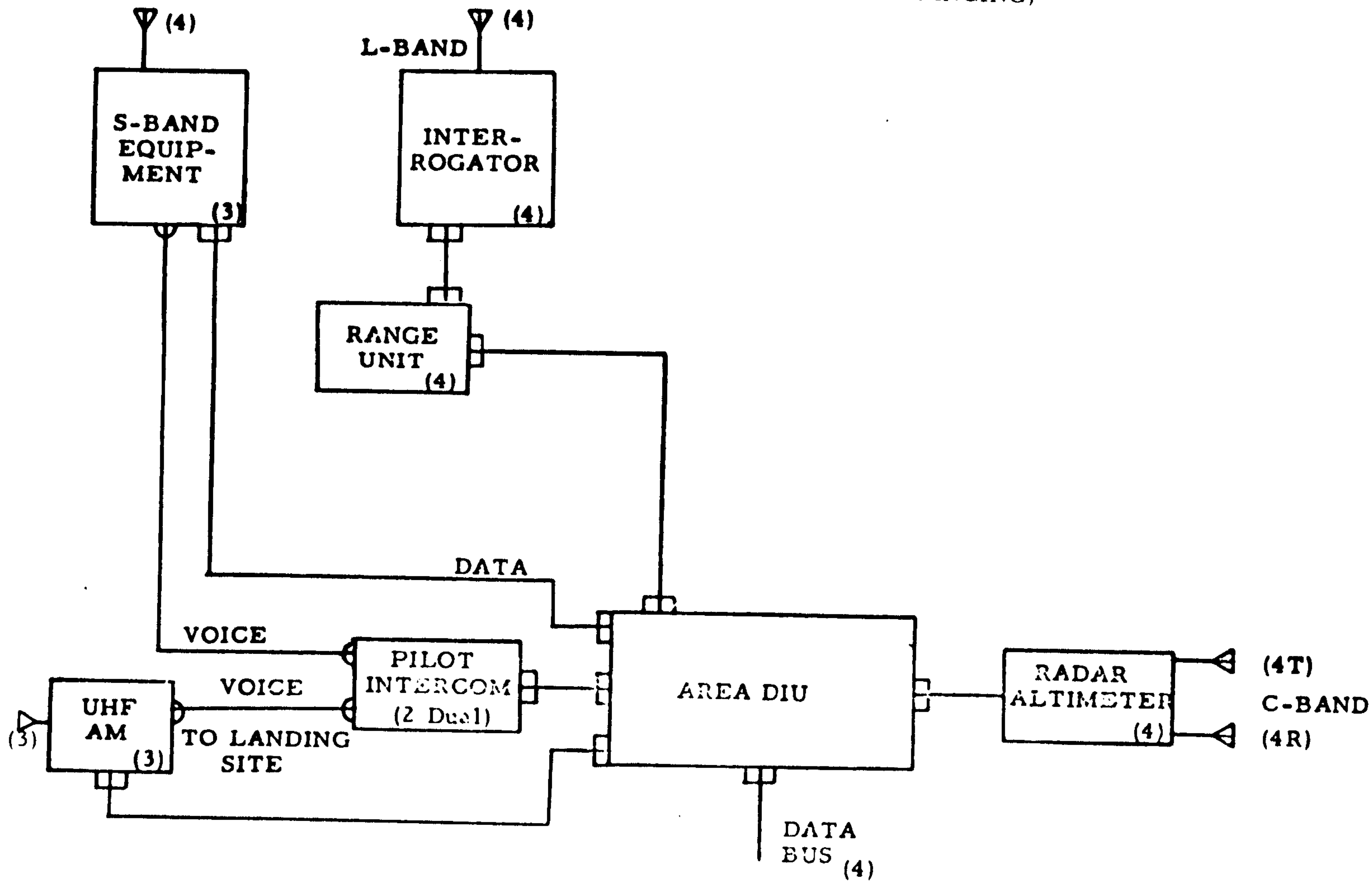
The first alternative to USCANS is to perform the ranging function at a different frequency (say L-band) than S-band. In this case the ranging unit would interconnect to the L-band interrogator rather than the S-band equipment as shown. This configuration has been proposed since some existing multilateration systems operate at L-band.

Utilization of L-band ranging suffers from several deficiencies:

1. Additional antennas (L-band) are required on the shuttle (as well as on the target vehicle).

2. Voice to the control tower must be achieved in some manner such as on the L-band or on UHF in which case more antennas are required or on S-band where the voice link already exists for compatibility with MSFN (S-band antennas and L-band antennas then needed at the landing site).

ONBOARD COMMUNICATION AND
NAVIGATION EQUIPMENT
(S-BAND AND SEPARATE RANGING)

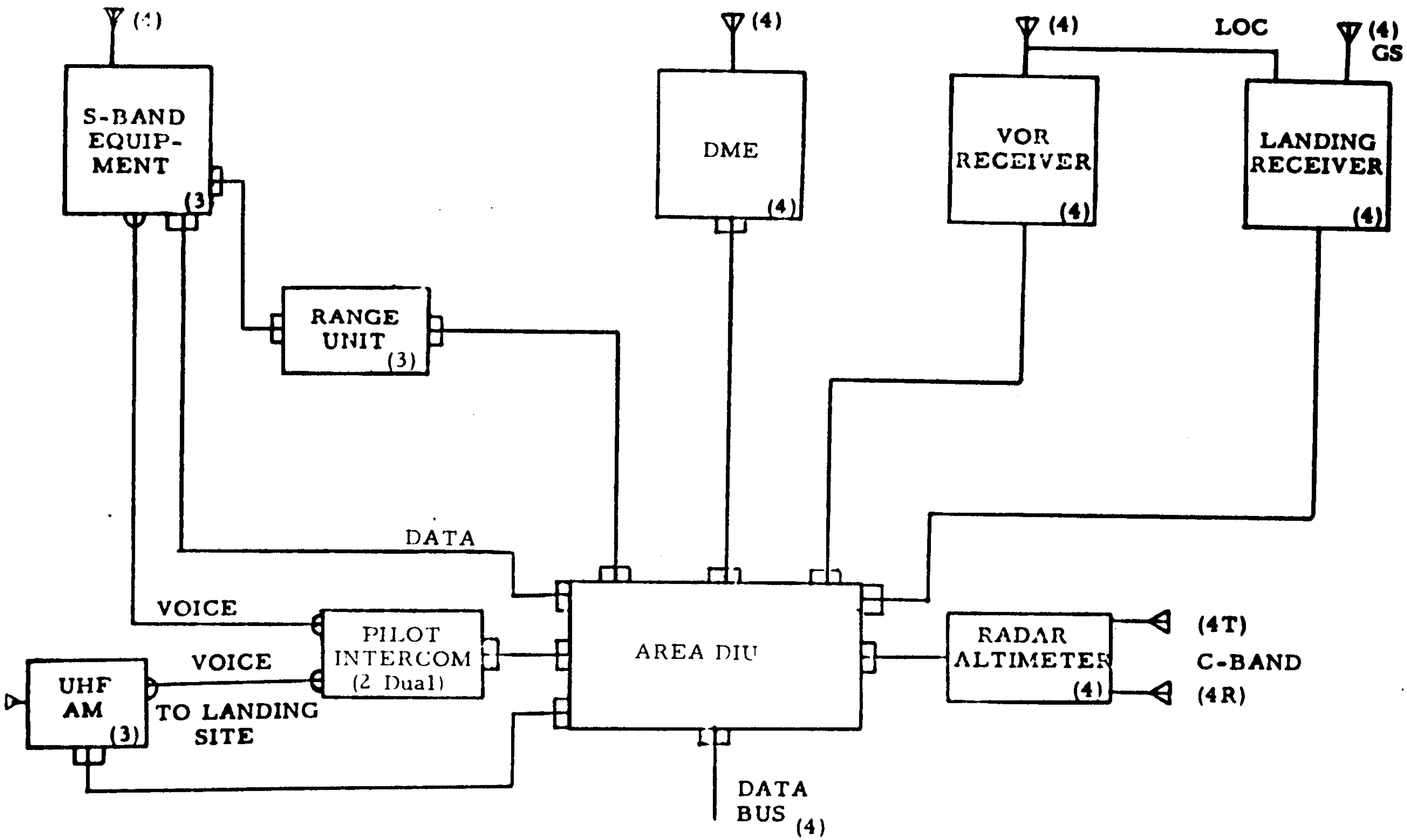


ONBOARD COMMUNICATION AND NAVIGATION EQUIPMENT (FAA COMPATIBLE)

A third alternative is to be compatible with the FAA existing or proposed terminal area and approach navigation equipment. This requires additional onboard equipment as shown. Ranging and voice over the S-band link are still retained for operation with the target satellite.

This configuration has been proposed because of the availability of landing sites around the world with the required equipment installed.

ONBOARD COMMUNICATION AND
NAVIGATION EQUIPMENT
(FAA COMPATIBLE)



SYSTEM CONFIGURATIONS AND COST ELEMENTS

Three systems are configured for cost comparison. This chart shows the equipment used in each configuration. Both orbiter and booster equipment are considered. The cost elements are considered to be conservative estimates based upon experience and informal data from vendors. Antenna costs are considered to be very conservatively estimated.

SYSTEM CONFIGURATIONS AND COST ELEMENTS

ITEM	USCANS	FAA COM-PATIBLE	S-BAND & SEPARATE RANGING	COST $M		WEIGHT (LBS/SET)
				RDT&E	RECUR-RING	
S-BAND EQUIPMENT	4/4	3/0	3/0	6.0	.21	17
ALTIMETER	4/4	4/4	4/4	6.0	.08	21
RANGING UNIT	4/4	3/0		1.0	.03	7
INTERCOM	2/2	2/2	2/2	3.0	.08	5
UHF TRANSCEIVER		3/3	3/3	6.0	.13	30
ILS		4/4		4.0	.07	11
VOR		4/0		3.0	.04	10
DME		4/4		4.0	.08	30
L-BAND VEHICLE EQUIPMENT			3/3	4.0	.20	10
L-BAND GROUND TRANS-PONDERS			24	1.0	.26	
USCANS GROUND TRANS-PONDERS	24			1.0	.42	

ANTENNA COST:

RDT&E $.5M EACH TYPE
ACQUISITION $.05M EA.

ORBITER/BOOSTER

COST COMPARISON

Analysis of the data on this chart indicates a significant cost savings if the USCANS concept is employed. This result occurs because the USCANS equipment is employed in all configurations to achieve compatibility with MSFN. Several costs were not estimated as indicated. Each of these items would tend to favor the USCANS (and the S-band and separate ranging) configuration. The conservative 27% cost savings shown makes USCANS a very attractive candidate.

COST COMPARISON

ITEM OF COST	USCANS	FAA COM-PATIBLE	S-BAND & SEPARATE RANGING
DEVELOPMENT COST			
VEHICLE EQUIPMENT	$17 M	36 M	27 M
GROUND EQUIPMENT	1	0	1
GSE	1	2.0	1
ACQUISITION COST			
VEHICLE EQUIPMENT	17.1M	24.94M	23.48M
GROUND EQUIPMENT	10.2	0	6.3
GSE	2.0	4.0	2.0
TOTAL	48.3 M	66.94M	66.78M
WEIGHT SAVINGS			
ORBITER Δ COST	3.3 M		2.6 M
BOOSTER Δ COST	1.35		.85
Δ TOTAL	4.65M		3.45M

COSTS NOT CONSIDERED:

- POWER SAVINGS
- FUEL DUE TO IMPROVED ACCURACY
- STRUCTURES
- DISPLAYS
- FAA GROUND INSTALLATIONS

PERFORMANCE

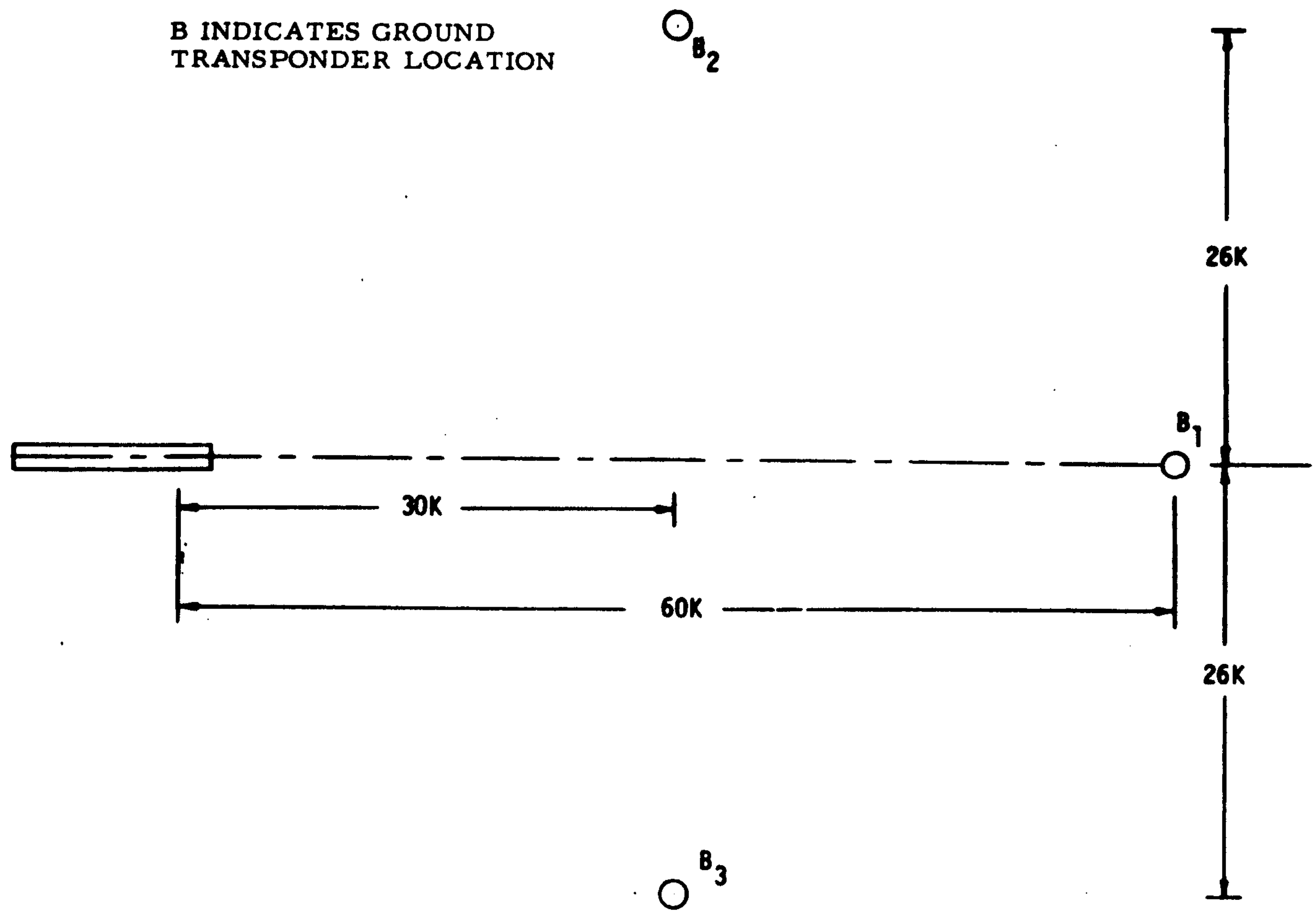
As an indication of the performance achievable with multilateration systems, several cases of landing navigation accuracy are presented. In addition, results of using the ground transponders for aiding the inertial navigation system during ascent into orbit are also presented. This latter capability may be necessary for specific Air Force missions that require high accuracy orbit insertion.

GROUND TRANSPONDER LOCATIONS IN VICINITY OF LANDING SITE

In the landing navigation analysis, three ground transponders were located as shown. In addition to the ground transponders, an IMU and altimeter were employed. The shuttle vehicle was lined up with runway and flew directly over ground transponder B_1 at an approximate altitude of 8000 feet. Landing velocity was approximately 320 feet/second.

GROUND TRANSPONDER LOCATIONS IN VICINITY OF LANDING SITE

B INDICATES GROUND
TRANSPONDER LOCATION



APPROACH AND LANDING ERROR MODEL AND ASSUMPTIONS

Results of two cases are being presented. The error models are presented in the attached chart. To perform the navigation analysis, a 19 state variable recursive filter was employed. The state variables are:

3 Position

3 Velocity

3 Gyro Bias

3 Accelerometer Bias

1 Altimeter Bias

3 Platform Misalignment

3 Range Biases

APPROACH AND LANDING ERROR MODEL AND ASSUMPTIONS

GYRO DRIFTS: 0.1°/HR., (.05°/HR.) 3600 SEC. CORRELATION TIME

ACCELEROMETER BIASES: 100 μg (50 μg)

BAROMETRIC ALTIMETER: 50 FT. BIAS, 0.5% RANDOM WHITE

RANGE MEASUREMENTS: 10 (50) FT. BIAS, 5 (1.6) FT. RANDOM WHITE

UPDATE RATE: 1/SEC.

INITIAL HORIZONTAL POSITION UNCERTAINTIES: 1 N. MI.

INITIAL ALTITUDE UNCERTAINTY: 1000 FT.

INITIAL VELOCITY UNCERTAINTIES: 10 FPS ALL AXES

INITIAL HORIZONTAL PLATFORM TILT UNCERTAINTIES: 0.25 DEG.

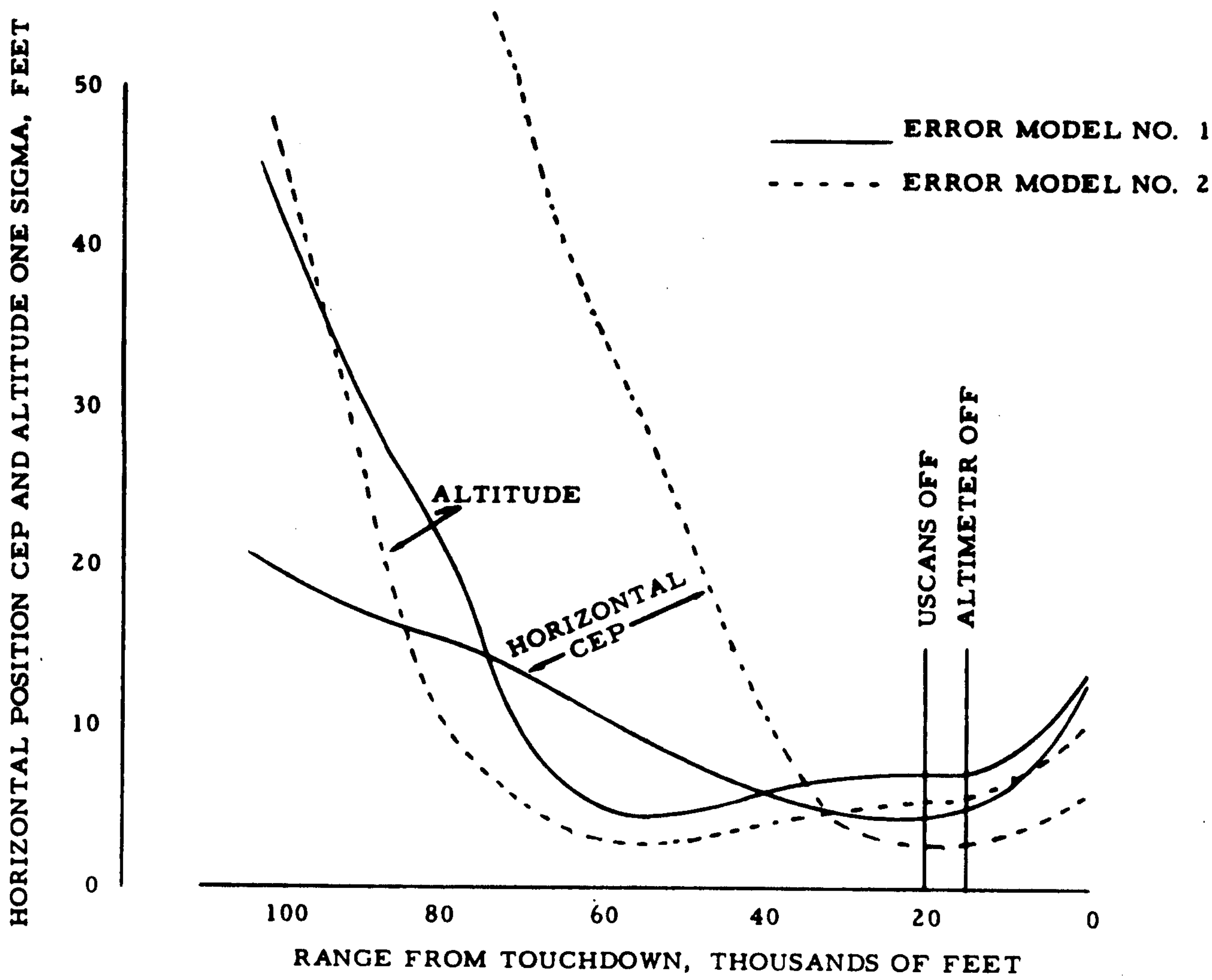
INITIAL AZIMUTH UNCERTAINTY: 1 DEG.

*NUMBERS IN PARENTHESES INDICATE ERROR MODEL NO. 2

POSITION ESTIMATION ERROR HISTORY
(TRANSPONDER CONFIGURATION B)

Position errors are as shown in the following chart. To test the system severely, no information was obtained from the multilateration system within 20,000 feet of the runway. This was done for illustration purposes only and does not reflect an operational restriction. The altimeter was also turned off at 18,000 feet so that from this point on the navigation was performed with the IMU only. Final velocity errors were approximately 0.2 feet/second. It is anticipated that optimum ground system configuration and operational utilization would enable removal of the radar altimeter used for landing flare.

POSITION ESTIMATION ERROR HISTORY
(TRANSPONDER CONFIGURATION B)



ASCENT NAVIGATION ANALYSIS

To achieve very precise orbit insertion cutoff conditions (as required on some Air Force missions), range measurements from the ground transponders may be used to update the inertial navigation system. An analysis has been conducted using the following models to evaluate the navigation improvement potential.

406 second ascent trajectory into a 50 x 100 n. mi. orbit		
39 degree orbit inclination		
IMU system characterized by 0.05°/hr gyros (1σ)		
Ranging system noise	1.6	Ft. (1σ)
Ranging system bias	50	Ft. (1σ)
Tropospheric refraction	5	N units (1σ)
Transponder location error (Cherry Point and Wallops Island only)	30	Ft. (1σ)
Navigation update rate	1	range measurement/ 10 seconds

Four different cases were considered which are distinguished by the number of ground transponders employed. Information from ground transponders was not used when the elevation angle was less than 5 degrees. The navigation accuracy presented is valid at thrust termination. As anticipated, little aid in cross range navigation is obtained from one transponder located at the launch site. Use of out of plane transponders significantly reduces the navigation errors. Utilization of radio aided inertial navigation in this manner during the launch phase implies that IMU quality will be dictated by other phases or operations during the mission.

ASCENT NAVIGATION ANALYSIS

NAVIGATION SYSTEM	ONE SIGMA STATE ERRORS AT THRUST TERMINATION					
	POSITION (FT)			VELOCITY (FT/SEC)		
	DR	CR	UP	DR	CR	UP
INERTIAL NAVIGATION ONLY	420	1310	730	2.5	7.9	5.8
INERTIAL NAVIGATION AND TRANSPONDER AT CAPE KENNEDY	50	1300	240	0.4	7.9	1.9
INERTIAL NAVIGATION AND TRANSPONDERS AT CAPE KENNEDY AND CHERRY POINT	50	140	140	0.3	1.0	1.1
INERTIAL NAVIGATION AND TRANSPONDERS AT CAPE KENNEDY, CHERRY POINT, CARTER CAY AND WALLOPS ISLAND	40	60	60	0.2	0.6	0.7

TRACKING COULD CONTINUE AFTER INSERTION FROM CHERRY POINT AND WALLOPS ISLAND.

OBJECTIONS TO USCANS

The following objections to USCANS have been voiced. Comments for these objections are presented.

1. Use of USCANS implies landing at a limited number of sites. This objection arises because commercial aviation landing fields do not use multilateration systems for landing or S-band for voice. Thus, in the event of an emergency, such fields could not be used for automatic landing or voice communication.

   Considerable amounts of money will be spent on the Shuttle to provide the desired redundancy and reliability levels to obviate such emergencies. To further penalize the shuttle system to be compatible with FAA facilities is not cost effective. Compromise positions do exist, however, such as using multilateration for landing navigation and UHF for voice. This technique does not show all the cost advantages indicated above but is an attractive alternative.

2. Special equipment or procedures must be employed for ferry operations. This objection is similar to the first one in that automatic landing and voice will, in general, not be available at the airports used for ferrying if USCANS is employed. In response, it is suggested that strap-on equipment be employed for this mode just as other equipment (air breathing engines) will be employed. This approach is consistent with not penalizing or compromising the operational system because of the ferry requirements.

3. Time and operations required to qualify a new landing system (multilateration) may be incompatible with the Shuttle Program.

   This objection is currently being investigated and preliminary results indicate that no problems exist. It should be noted that, currently, landing tests with a multilateration system are being conducted at NASA Ames.

OBJECTIONS TO USCANS (CONTINUED)

4. System is potentially incompatible with TDRS. USCANS has been defined based upon current operational concepts. It is true that, if TDRS is employed and USCANS is not compatible with it, a better solution to the problem may exist. On the other hand, it may be that USCANS is still the best answer. These items will not be resolved until the TDRS concept is more fully defined and the design definitized.

OBJECTIONS TO USCANS

- USE OF USCANS IMPLIES LANDING AT A LIMITED NUMBER OF SITES
- SPECIAL EQUIPMENT OR PROCEDURES MUST BE EMPLOYED FOR FERRY OPERATIONS
- TIME AND OPERATIONS REQUIRED TO QUALIFY A NEW LANDING SYSTEM (MULTILATERATION) MAY BE INCOMPATIBLE WITH SHUTTLE PROGRAM
- SYSTEM IS POTENTIALLY INCOMPATIBLE WITH TDRS

SUMMARY

An S-band system has been proposed for all voice, data, and RF navigation functions. This system is compatible with the MSFN and SCN. High performance is achievable with this system, and inherent advantages of redundancy and all runway landing capability are obtained. The most significant feature of this approach is the program cost savings obtained primarily from reducing the amount of onboard equipment and antennas.

SUMMARY

- ALL S-BAND - VOICE, DATA, NAVIGATION
- COST EFFECTIVE SYSTEM
- HIGH PERFORMANCE - INHERENT REDUNDANCY
- COMPATIBLE WITH EXISTING MSFN AND SCN