STI/E-TR-25066
31 May 1983

TRACKING AND DATA ACQUISITION SYSTEM FOR THE 1990's

VOLUME IV

TDAS SPACE SEGMENT ARCHITECTURE

DRAFT FINAL REPORT

Prepared by:
Richard S. Orr

Prepared for:
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

STANFORD
TELECOMMUNICATIONS INC.

6888 Elm Street ■ Suite 3A ■ McLean, VA 22101 ■ (703) 893-3220

(NASA-CR-175212) STUDY OF TRACKING AND DATA ACQUISITION SYSTEM FOR THE 1990'S. VOLUME 4: TDAS SPACE SEGMENT ARCHITECTURE Draft Final Report (Stanford Telecommunications, Inc.) 190 p HC A09/MF A01 CSCL 22A G3/12

N84-19372

Unclas 12593

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

SECTION 1

INTRODUCTION TO TDAS SPACE SEGMENT ARCHITECTURE

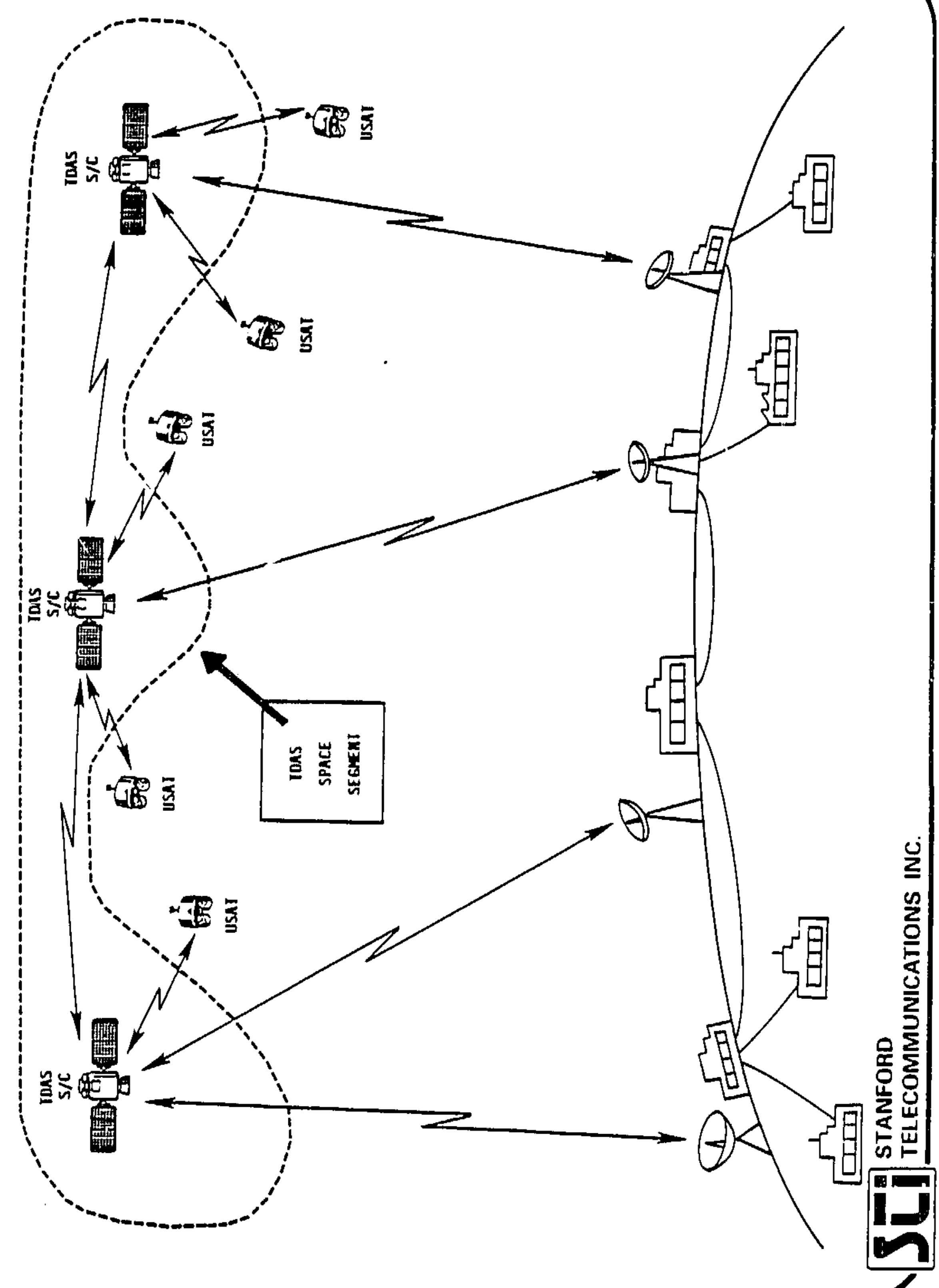
The Tracking and Data Acquisition System (TDAS) is being studied as a 1990's replacement for and upgrade to the NASA Tracking and Data Relay Satellite System (TDRSS). The TDAS will perpetuate the services provided by TDRSS and at the same time offer a variety of new and enhanced services to a second generation of users. The new services must be responsive to the increased demands for channel hours and throughput made by the users of the next decade (Figure 1-1).

Like TDRSS, TDAS is composed of a ground and a space segment. It provides communication, TT&C and navigation services to user spacecraft and links them to the operators and experimenters on earth via a complex of space-to-space, space-to-ground, and terrestrial links. For TDAS to succeed, each segment and subsystem must function smoothly and in concordance with all others. This necessitates that the subsystem and component designs stem from an architecture that shows functional clarity in the assignment of resources.

No single aspect can more directly impact the success of TDAS than the architecture of its space segment. At first look one could infer that this is true by noting how much this architecture comprises: the TDAS spacecraft itself, the constellation into which it is arranged, and the space-to-space and space-to-ground linkages that connect the user satellites (USAT's) to the earth terminals and terrestrial networks. In less a physical but no less an important sense, the architecture also includes the goals for the services to be provided and the provision mechanisms themselves.

But the system impact of the space segment has an origin in other than its magnitude. It is in the space segment that most of the substantial risk is taken. New circuits, subsystems, algorithms, procedures, all of which have been exhaustively validated in theory, on the bench and the

FIGURE 1-1: THE TRACKING AND DATA ACQUISITION SYSTEM (TDAS)



computer, in the test bed and the clean room, are still items of considerable risk until they have been proven repeatedly in space.

The recent experience in the launch of TDRS-E exemplifies this tenet. Even among those who might have held that TDRSS is a risky venture, there are probably very few who would have anticipated the manner in which the early threat to the mission came about.

It cannot be overemphasized that assessment of risk must be a guiding principle in the development of TDAS. It has been so in this architecture study; innumerable alternatives have given way because they have been found to contain some aspect of unacceptable or needless risk. Which is not to say that the endproduct is a risk-free TDAS! Quite to the contrary, our finding is that none of the investigated architectures is simultaneously satisfactory in function and nominally free of risk. There seems to be no path from today to operational TDAS that does not contend with moderate technical risk.

We follow the common practice of researchers facing such a conclusion to formulate their findings in baseline recommendations. A baseline simply states the situation as best we know it at present and is always a candidate for change and improvement. It summarizes knowledge and insignt gained through hard work; it says "this may well be the best approach if ..."

In this light, a baseline becomes much more than a static summary. It is the basis of a development plan that can bring into being needs that are made evident. Where risk items are found, corresponding actions should follow. What actions, and who takes them, are questions that are answered differently in each case — what we would forsee in TDAS is that both NASA and the TDAS contractor should stay abreast of the significant technology developments, and where appropriate, NASA might sponsor supplemental efforts that have direct focus on their applications.

The two year process of work that has led to this volume has followed the path of: developing goals and requirements for the space segment; posing feasible alternatives for its elements and choosing from among these certain ones for detailed evaluation; and using the results of the evaluations on a risk/benefit basis to select and justify a baseline space segment architecture. This work will not be reported historically. We will be selective in the organization of material so that only the analysis of the best contending alternatives is presented. In this regard, readers familiar with briefing charts presented at the TDAS Quarterly Technical Reviews will quite consistently find discrepancies in nomenclature between those charts and the present volume.

This report is Volume IV of nine volumes constituting the final report for the TDAS pre-Phase A study. Volume titles, largely self-explanatory, are given in Figure 1-2.

FIGURE 1-2: TDAS REPORTS

VOLUME I	EXECUTIVE SUMMARY
VOLUME II	TDAS USER COMMUNITY
VOLUME III	TDAS COMMUNICATIONS MISSION MODEL
VOLUME IV	TDAS SPACE SEGMENT ARCHITECTURE
VOLUME V	TDAS GROUND SEGMENT ARCHITECTURE AND OPERATIONS CONCEPT
VOLUME VI	TDAS NAVIGATION SYSTEM ARCHITECTURE
VOLUME VII	TDAS SPACE TECHNOLOGY ASSESSMENT
VOLUME VIII	TDAS FREQUENCY PLANNING
VOLUME IX	TDAS COST SUMMARIES

The program of this volume can be readily grasped. Following this introduction is an Executive Summary (Chapter 2), where the most significant findings contained in the remainder of the report are collected in brief. Chapter 3 prefaces the technical development with several key notions. To begin, TDAS requirements stemming from Volumes II and III are summarized. A statement of guidelines for the architecture development then leads into the identification of goals for the architecture, goals that define new services through which TDAS can achieve the various demands of the mission model. Finally, we present the enhanced TDAS subsystems, each of which would implement one or more new services. These subsystems are considered in some detail; tradeoffs among implementations lead to a recommended approach for each subsystem that will be carried throughout the volume.

Questions of constellation and networking are taken up in Chapter 4. It is because of the strong interrelationship of the constellation and the connectivities between TDAS satellites and the earth terminals that these two subjects are profitably assessed together. Three basic options, all consisting of near-geostationary satellites, are expanded into a total of six suboptions, each of which is described in terms of the satellite locations, the space-to-space and space-to-ground connectivities, and the subsystem enhancements it can support. Data describing the low-orbit coverage of the constellations and their requirements for North-South stationkeeping vs initial inclination are given as inputs to the eventual baseline selection.

Design of the TDAS spacecraft itself occupies Chapter 5 and 6. A prime question about the spacecraft is — where to begin? Three possibilities that differ in the amount of TDRSS heritage they retain are considered, from which emerges the position that an enhanced TDRS, with new TDAS equipment filling the void left by deleting the Advanced Westar package, represents the most apt starting point. A succession of enhancements, each incorporating additional subsystem components, each matched in function to one or more of the constellation/network choices, are developed as candidate spacecraft.

Further development of the spacecraft architecture occurs in Chapter 6 with the discussion of the crosslink subsystem. Issues pertinent to both forward and return crosslinks are discussed: frequency alternatives (60 GHz and laser), onboard processing technique (transponding vs regenerative), and laser implementation (laser type, modulation, direct and heterodyne detection). The impact of the crosslink architecture on other TDAS features is assessed in terms of acquisition and tracking, implications for new TDAS services, and subsystem weight and power estimates. A summary of crosslink technology issues closes the chaper.

Drawing upon all the earlier material, we present the TDAS space Segment architecture baseline system in Chapter 7. The supporting rationale, which is provided, prompts the retention of an alternative for the crosslink subsystem as a hedge against technological risk.

The final chapter provides an overview of issues associated with TDAS security.

SECTION 2

EXECUTIVE SUMMARY OF VOLUME IV

The significant findings about the TDAS space segment architecture are summarized in this chapter. Since the summary does not always correspond sequentially to the volume, section number and figure references are inserted to locate the supporting detail.

2.1 SUMMARY

The TDAS space segment consists of the TDAS spacecraft, the satellite constellation, the links to user spacecraft, intersatellite links between TDAS's (if needed) and space-to-ground links with earth terminals (Figure 2-1). The accomplishment of this volume is to investigate possible architectures for each of these system elements and to select from among these a set that integrates into a baseline architecture.

The TDAS system requirements (3.1) give rise to a set of architecture goals. Prior to stating the goals we formulate some guidelines for our architecture development (3.2.1):

- Meet the communication and navigation requirements of the 1995-2005 period as set forth in Volumes II and III of this report.
- Do not impose significant weight/power requirements on the user spacecraft.
- Let the transition from TDRSS to TDAS be transparent to the TDRSS user.
- Use a single TDAS satellite design for all satellites.

ORIGINAL PAGE IS
OF POOR QUALITY

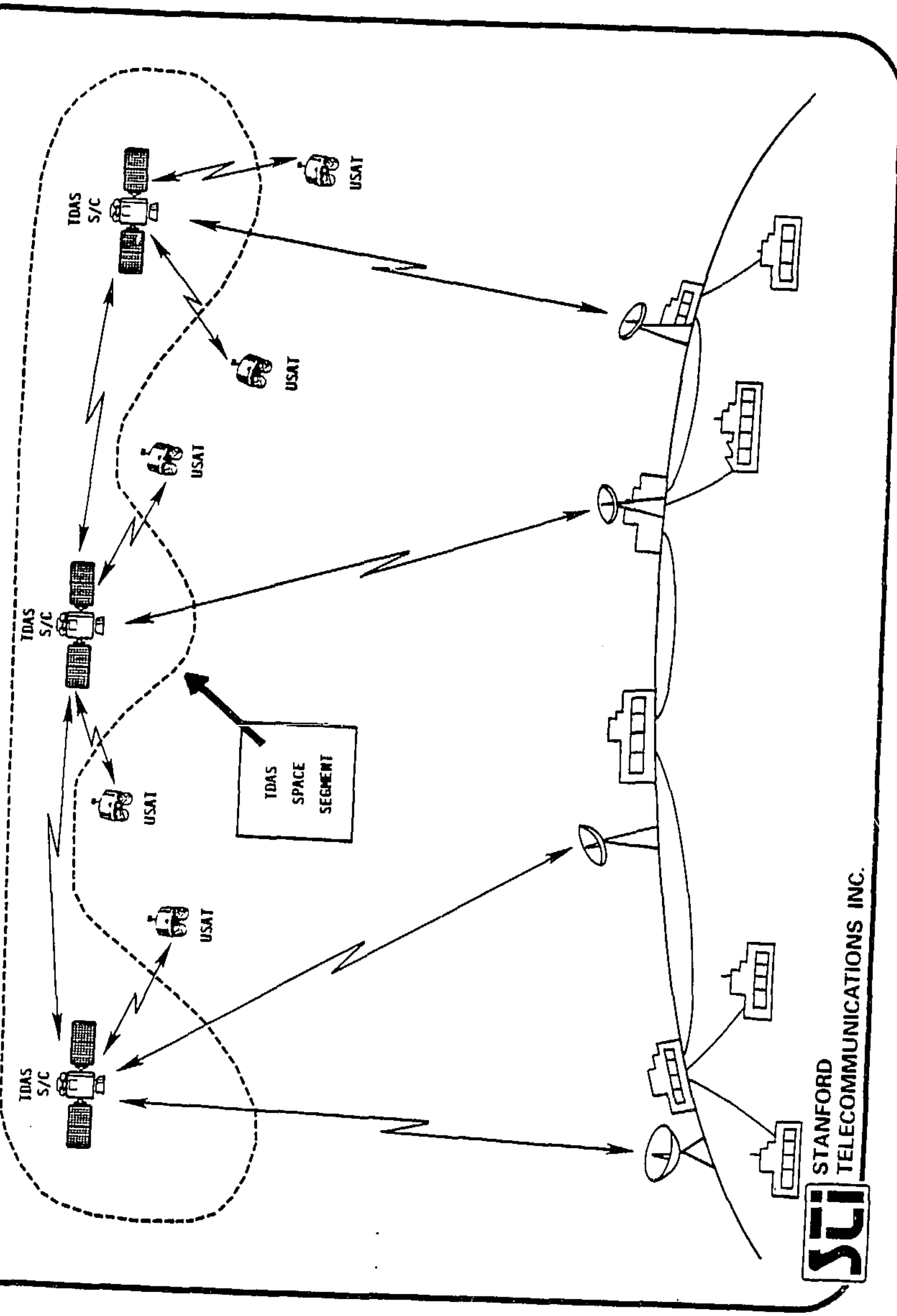


FIGURE 2-1 (1-1): THE TRACKING AND DATA ACQUISITION SYSTEM (TDAS)

- Realize the proposed architectures in terms of "enabling technology" (1988 cutoff).

TDRSS services are the basis of the architecture goals. We add capability beyond that of TDRSS with each one. The requisite subsystem enhancements accompany each gaol in Figure 2-2 (3.2.2).

TDAS reaches its goals through the enhanced subsystems, which are (3.3):

- Improved S-band multiple access (SMA)
- Multibeam antenna (MBA)
- IF Switch
- W-band single access (WSA)
- Laser single access (LSA)
- Crosslink.

Eahc of the space segment configurations under consideration incorporates some or all of these subsystems.

The issues and/or alternatives considered for each of these and the final selections are diagrammed in Figure 2-3. A brief discussion of each subsystem follows, with the exception of the crosslink, discussed in Section 7. In the following, a deep space communications system is also discussed.

Improved SMA (3.3.1)

The SMA module (Figure 2-4) uses a 61-element hexagonal phased array similar to the TDRS 30-element array. The elements are helices with 1.5 dB higher gain than those on TDRS. Two forward link channels per spacecraft are possible with the increased number of elements. Ten channels per spacecraft provide return link service. In the forward direction, one element may be used exclusively to transmit a navigation beacon signal (see Volume VI).

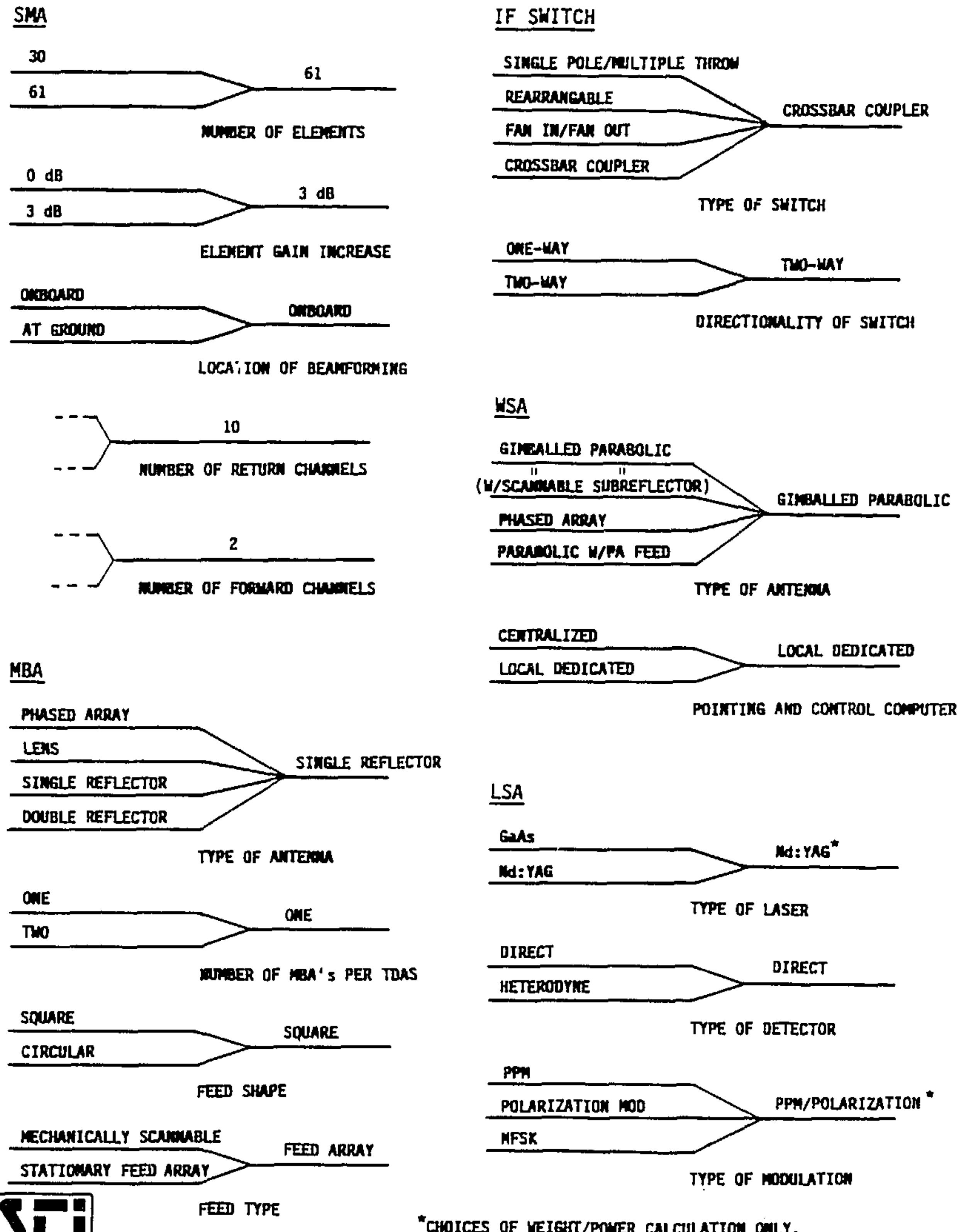
Beamforming is accomplished onboard the spacecraft. This prevents bandwidth expansion of the space-to-ground link due to the increase in number of array

FIGURE 2-2 (3-3): TDAS ARCHITECTURAL GOALS

GOALS	ENHANCEMENTS
IMPROVE SMA SERVICE	• 2-4 SMA FORWARD LINKS • 3 DB IMPROVEMENT ON RETURN LINK
PROVIDE USAT TT&C DATA DIRECTLY TO MISSION CENTERS	• ONBOARD SMA BEAMFORMING
ALLOW USERS TO RECEIVE MISSION DATA AND CONTROL EXPERIMENTS AT 5 OR MORE CONUS LOCATIONS	• MULTIBEAM SPACE/GROUND LINK • ONBOARD SWITCH
PROVIDE INCREASED NUMBER OF HIGH-RATE ACCESSES	• 60 GHz SINGLE ACCESS CHANNELS
PROVIDE ULTRA-HIGH RATE ACCESSES (> 300 MBPS)	• LASER SINGLE ACCESS CHANNEL
PROVIDE 100% COVERAGE	• 60 GHz OR LASER CROSSLINKS

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-3: ENHANCED SUBSYSTEM TRADEOFFS

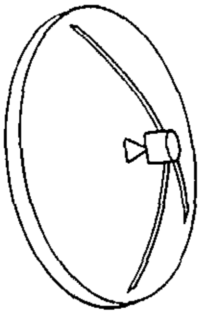


STI

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 2-4: 60 GHz SINGLE ACCESS SUBSYSTEM

- DATA RATES TO 50 MBPS (RETURN LINK)
- 1 M DISH OPTIMUM FOR USER ACQ/TRK
- DEDICATED ANTENNA POINTING AND CONTROL SYSTEM
- MECHANICALLY STEERABLE PARABOLIC DISH
- BODY MOUNTED FOR BETTER S/C ATTITUDE CONTROL
- 500 LBS, 210 W



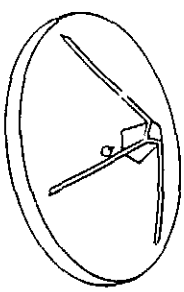
TECHNOLOGY DEVELOPMENT

- 10 W TRANSMITTER
  - TWT OR IMPATT
- 450° K RECEIVER AMP
- LOW INERTIA, SMOOTH REFLECTOR
- 60 GHz LOW LOSS FEED
- ANTENNA POINTING AND AUTOTRACK CONTROL SYSTEM

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-5: 30/20 GHz MULTIBEAM ANTENNA SUBSYSTEM

- 3 METER DISH
- 5 FIXED FEEDS, 4 MOVABLE
- SINGLE REFLECTOR STRUCTURE FOR LIGHT WEIGHT, LOW STOWAGE VOLUME
- SQUARE FEED ARRAY FOR BETTER POLARIZATION AND EFFICIENCY
- 30/20 GHz FREQUENCY
  - BANDWIDTH SUPPORTS HIGH RATE DOWNLINK
  - ONE KU-BAND FEED FOR WSGT
- 205 LBS, 450 W



TECHNOLOGY DEVELOPMENT

- LIGHT WT/RIGID/SMOOTH REFLECTOR
- LOW LOSS/LIGHT WT FEEDS AND WAVEGUIDES
- MECHANICALLY SCANNABLE LONG LIFE FEEDS
- DUAL FREQUENCY/DUAL POLARIZATION FEEDS

STANFORD TELECOMMUNICATIONS INC.

elements. At the same time, beamforming losses are decreased and the need for calibration is minimized or eliminated because the space-to-ground link no longer carries uncombined element signals. In this design the calibration is eliminated because the PN despreading is still relegated to the ground stations. Because of this onboard separation of user signals, selective direct distribution to the various user sites is possible; the needless redundancy that results if all element signals are relayed to each earth station is absent. The improved SMA subsystem weighs 650 lbs and consumes 420 W.

MBA (3.3.2)

The MBA (Figure 2-5) enables TDAS to communicate with multiple ground sites. The operating frequencies in the 30/20 GHz band enable wider bandwidth downlinks than are available in TDRSS. A total of 9 links are available, five to fixed sites - Sunnyvale, White Sands, Colorado Springs, Houston and Greenbelt - and four to variable sites. A single reflector design is preferred to a dual reflector because of lighter weight and lesser volume, despite disadvantages of blockage. This assembly has burden 205 lbs, 450 W.

IF Switch (3.3.3)

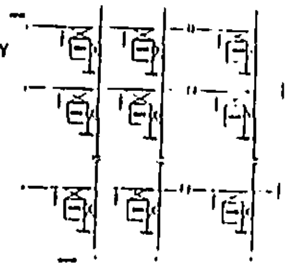
Routing of data between the user channels and the MBA is accomplished by the IF Switch (Figure 2-6). It is a crossbar coupler structure that uses GaAs switch/amplifier elements at the crosspoints. Both one-way and two-way operation are possible by changing the switching element design—two-way operation appears to be preferable. The crossbar is superior to the other alternatives in most respects, but a residual technology issue is the achievement of sufficient bandwidth ($\sim$ 2.5 GHz). A microminiature integrated circuit (MMIC) design for the switch seems feasible within the required time.

WSA (3.3.4)

Five mechnaically steerable 1-m dishes affixed to the spacecraft body and operating at 60 GHz provide the expanded single access services needed by

FIGURE 2-6: IF SWITCH SUBSYSTEM

- 36 x 9 SWITCH
  - ONE-WAY OR TWO-WAY OPERATION
- CROSSBAR COUPLER ARCHITECTURE
- NO FAST SWITCHING REQUIREMENT
- DUAL GATE GaAs MESFET CROSSPOINT SWITCH
- 15 LBS, 10 W

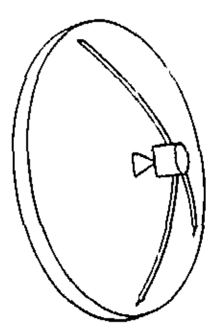


TECHNOLOGY DEVELOPMENT

- BROADBAND SWITCHING ELEMENTS (2.5 GHz)
- BROADBAND DIRECTIONAL COUPLERS
- LOW LOSS, LOW VSWR
- LOW SIZE/WEIGHT

FIGURE 2-7: 60 GHz SINGLE ACCESS SUBSYSTEM

- DATA RATES TO 50 MBPS (RETURN LINK)
- 1 M DISH OPTIMUM FOR USER ACQ/TRK
- DEDICATED ANTENNA POINTING AND CONTROL SYSTEM
- MECHANICALLY STEERABLE PARABOLIC DISH
- BODY MOUNTED FOR BETTER S/C ATTITUDE CONTROL
- 500 LBS, 210 W



TECHNOLOGY DEVELOPMENT

- 10 W TRANSMITTER
  - TWT OR IMPATT
- 450° K RECEIVER AMP
- LOW INERTIA, SMOOTH REFLECTOR
- 60 GHz LOW LOSS FEED
- ANTENNA POINTING AND AUTOTRACK CONTROL SYSTEM

TDAS (Figure 2-7). This placement prevents undue spacecraft attitude perturbations due to steering and requires that the TDRS SMA array and Advanced Westar antenna be removed from the spacecraft body. Each WSA channel accommodates up to 50 Mbps return link with a 450°K receiver (with 10 W into a 0.87 m dish at the user). A dedicated antenna pointing and control system processor (APCS) governs the steering of each separate antenna. The 1 m dish size is near optimum for user acquisition and tracking.

LSA (3.3.5)

Inclusion of a single access laser receiver enables ultra-high rate return link use (30 Mbps - 1 Gbps). The exact form of laser depends on user preferences and is not decided in this study; the most likely candidates are GaAs and Nd:YAG. The GaAs laser has a number of advantages. It is readily modulated in arbitrary fashion at bandwidths well in excess of 1 GHz, and either direct or heterodyne detection can be used. Technology issues in power generation and phase lock receiver technique must be addressed. The Nd:YAG laser, however, could be the choice if military users are so equipped.

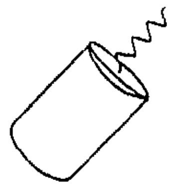
Deep Space Communications (3.3.6)

The Jet Propulsion Laboratory (JPL) has researched the possibility of laser communications from deep space probes to replace the RF links that have in the past served this purpose. To avoid the difficulties of a transatmospheric optical link, JPL postulates an orbiting relay station that intercepts the deep space signal and sends it to earth via RF. With a dedicated relay station up to 25 Mbps could be returned from Jupiter, a data rate 100 or 200 times that now achievable at RF.

TDAS can support the deep space mission by acting as the relay, but the extent of this support is technology dependent. The JPL strawman includes a receiver telescope that has a 4.5 m aperture, nearly that of the TDRS SA antenna! The optical apertures envisioned for TDAS LSA or crosslink, on the order of 30 cm or less, would not support any of the increased data rates. If as much as a 1 m receiver could be accommodated, then up to

FIGURE 2-8: LASER SINGLE ACCESS SUBSYSTEM

- DATA RATES
  300 MBPS - 1 GBPS
- GAAS (OR ND: YAG) LASER
- DIRECT DETECTION
- 25 CM TELESCOPE
- 170 LBS, 135 W*
- BEACON LASER FOR ACQ/TRK
- POTENTIAL DEEP SPACE RELAY CAPABILITY
  - DATA RATES COMPARABLE TO VOYAGER (100 KBPS)



TECHNOLOGY DEVELOPMENT

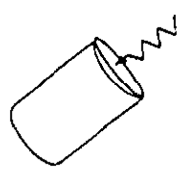
- FEW HUNDRED MW POWER OUTPUT
  - COHERENT OR NONCOHERENT
- IMPROVED FREQUENCY STABILITY OF TRANSMIT LASER
  - FOR FSK MODULATION
- LOW NOISE PHOTODETECTORS
  - 3 TO 5 DB IMPROVEMENT IN AVALANCH MULTIPLICATION NOISE

* SIZING BASED ON ND: YAG LASER

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-9: DEEP SPACE SUBSYSTEM

- INTERCEPTS SIGNALS FROM DEEP SPACE PROBE AND RELAYS TO EARTH
- GAAS LASER RECEIVER
- USING APERTURE, COMPARABLE TO LSA OR LASER CROSSLINK, CAN SUPPORT DATA RATES COMPARABLE TO VOYAGER (100 KBPS FROM JUPITER)
  - ASSUMES 1 W, 1 M SOURCE
- USES 256-ARY PPM
- CHOICE OF ONBOARD DEMODULATION OR TRANSPONDING THE PHOTODETECTOR OUTPUT
- POSSIBLE TO SHARE SOME RECEIVER FUNCTIONS WITH LSA



TECHNOLOGY DEVELOPMENT

- LARGE APERTURE RECEIVER
  - > 1 MBPS WITH 1 M TELESCOPE

STANFORD TELECOMMUNICATIONS INC.

a factor of ten of the data rate increase would be supportable. If technology and the STS payload weight limitations permit, even larger receive lenses could be accommodated, but the ability of JPL to use higher rate probe signals, with either TDAS or dedicated relay support, may have to await breakthroughs in transmitter and receiver technology.

The JPL concept uses a GaAs laser with digital 128-ary pulse position modulation (PPM). Thus the laser frequency may be compatible with the TDAS LSA, but the receiver demodulator, etc., is probably new equipment.

Constellation and Networking (4.0)

Constellations and space/ground networking are treated together because of their strong interrelationship. For ease of tracking, attitude control and scheduling, the satellites for all TDAS constellation candidates are taken to be in circular geosynchronous, near-equatorial (±5° inclination) orbit. Initial inclinations near ±5° require minimal North-South stationkeeping over a 10-year period, whereas progressively more frequent maneuvers are required in the attempt to maintain lower inclinations. Free of the restrictions imposed in TDRSS by the Advanced Westar package, TDAS can use these higher inclinations with only limited concern about coverage or other operational impact.

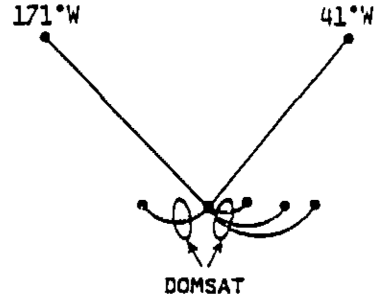
The constellation options and their communication linkages are all shown in Figure 2-10 (4-1). There are three basic options, two of which have sub-options:

- Option 1: Two S/C (plus spare) in view of CONUS
- Option 2: Two S/C (plus spare), one in view of CONUS and one not, with crosslink
- Option 3: Three S/C (plus spare), two in view of CONUS and one not, with crosslink(s)

FIGURE 2-10 (4-1): TDAS CONSTELLATION/NETWORK OPTIONS

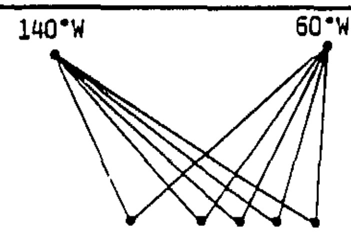
OPTION 1A:

ENHANCEMENTS
SMA
WSA



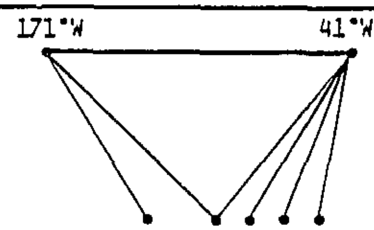
OPTION 1B:

ENHANCEMENTS
SMA
WSA
MBA
LSA



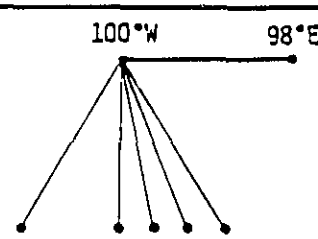
OPTION 1C:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



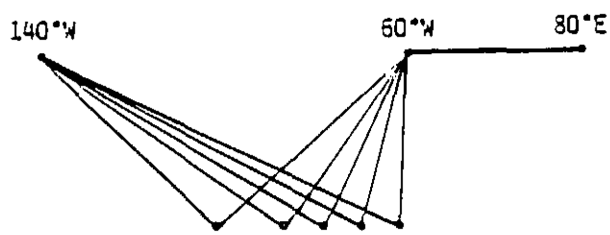
OPTION 2:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



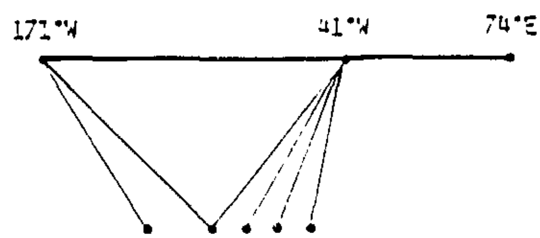
OPTION 3A:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



OPTION 3B:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



STANFORD
TELECOMMUNICATIONS INC.

The suboptions are distinguished by satellite placement and connectivity. In a two-satellite constellation, wider spacing tends to improve coverage monotonically. At the widest spacings there can be some deterioration of user tracking accuracy, indicating that an intermediate spacing may be best. Figure 2-11 (4-16) summarizes the coverage properties. (4.4)

The baseline constellation selection is Option 2, shown in Figure 2-12 (4-6). Key reasons for the selection are summarized below. (7.1)

- Because of the 162° spacing between the satellites, coverage is quite good: 98% at the minimum for any orbit $\geq$ 200 km, and 100% for most orbits.

- Because of the networking and data capacity inherent in this configuration, Option 2 is capable of fulfilling all the TDAS architectural goals.

- Option 2 shares with 3A the minimum crosslink burden among the options that use crosslinking. There is but one high capacity crosslink, as opposed to two in Option 1C and three in Option 3B.

- Tracking is satisfactory in most cases, except for selected low-altitude high-inclination orbits. Because these orbits will rotate relative to the TDAS constellation, the effect is transient and not of great concern.

- The extra investment in a third operational TDAS S/C is believed to not yield sufficient benefit. Option 2 provides good coverage and good navigation in all but a few cases, and it does not seem wide to overdesign for those few exceptions.

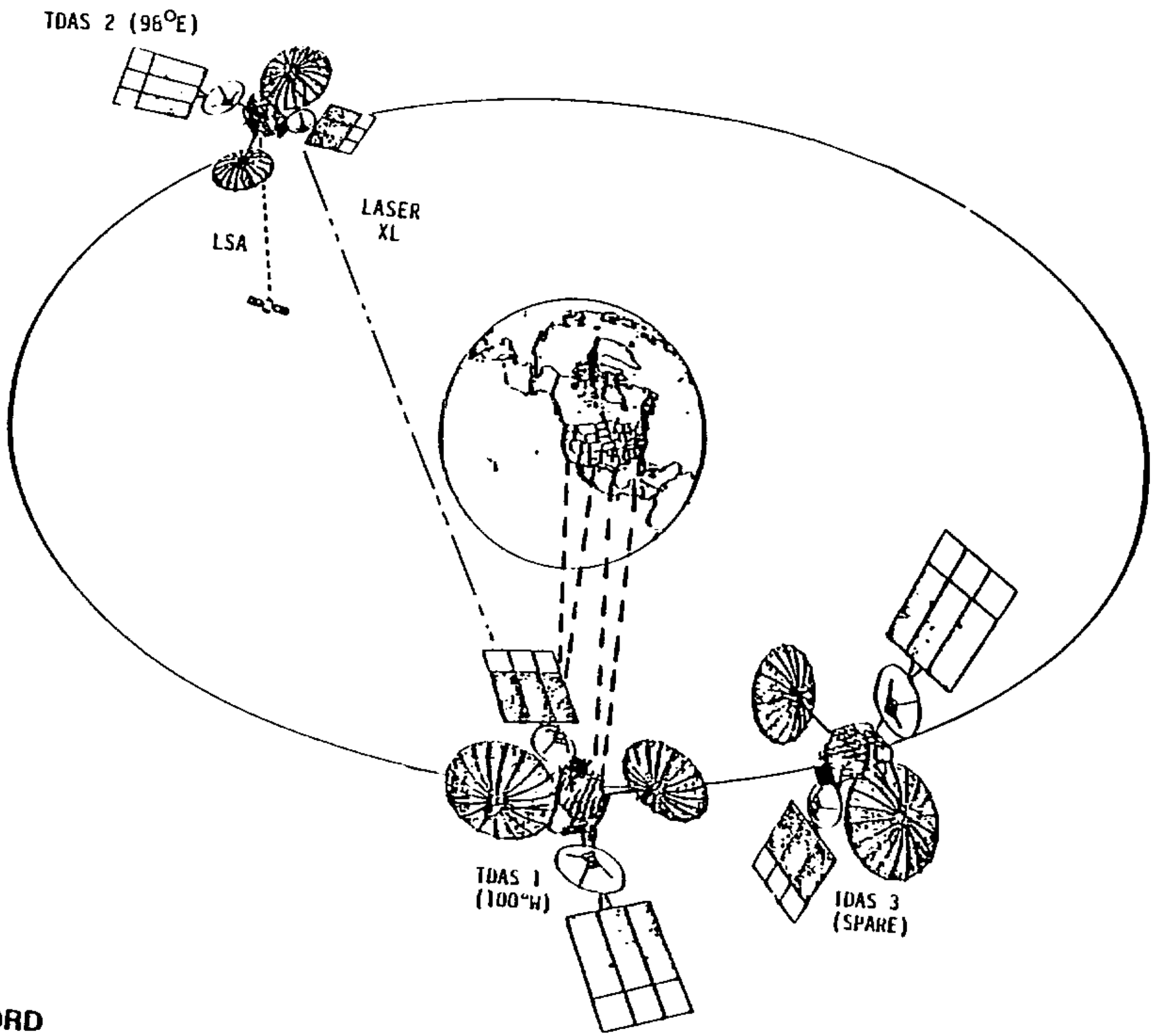
FIGURE 2-11 (4-16): VISIBILITY SUMMARY FOR TDAS CONSTELLATION ALTERNATIVES

CONSTELLATION ALTERNATIVE	ACTIVE S/C		USER COVERAGE* (%)	ACCESS TO/FROM CONUS TERMINALS	
	FRONT SIDE	BACK SIDE		ROUTE	REDUNDANCY
1A	2+	0	85-100	VIA WSGT + DOMSATS	NONE
1B	2++	0		DIRECT	FULL
1C	2+	0	85-100	DIRECT	PARTIAL
2+++	1	1	98-100	DIRECT	NONE
3	2++	1	100	DIRECT	PARTIAL

* MINIMUM ALTITUDE - 200 KM; ANY INCLINATION
+ 130° SPACING
++ 80° SPACING
+++ 162° SPACING

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-12 (4-6): TWO SATELLITE CONSTELLATION



STANFORD
TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

TDAS Spacecraft (5.0)

Three strategies for obtaining the TDAS spacecraft are considered (5.1):

- Expanded TDRS - As the TDRS lifetime nears its end, the TDRS's are replenished and augmented with additional TDRS's. With a constellation of 4-6 active satellites and a second earth terminal identical to White Sands, a number of the TDAS goals could be achieved.

- Enhanced TDRS - The Advanced Westar package is removed from TDRS, and the 1700 lbs, 1170 W that are freed are available for TDAS equipment. The resulting satellite should still fit within the STS payload morphology and weight envelope, although the weight limit (5000 lbs) may be raised for future launches.

- New Bus Architecture - Maximum flexibility in TDAS design results if a new bus architecture dedicated to TDAS is developed. The price of this flexibility, however, is a development program that is both costly and lengthy.

The pros and cons of each strategy have been considered (Figure 2-13 (5-4)), and the conclusion is that enhanced TDRS is recommended. Key reasons are: (5.1)

- TDRS expansion is limited in its ability to satisfy TDAS goals.

- Enhanced TDRS can fulfill all the space segment architecture goals without greatly exceeding the STS payload weight limit.

- A new bus architecture may be overkill in view of the TDRSS compatibility ground rule.

Three enhancements to the TDRS are considered as candidates for the TDRS spacecraft (5.2). These enhancements begin with the stripped-down TDRS spacecraft shown in Figure 2-14 (5-5). The MA array and AW antenna are

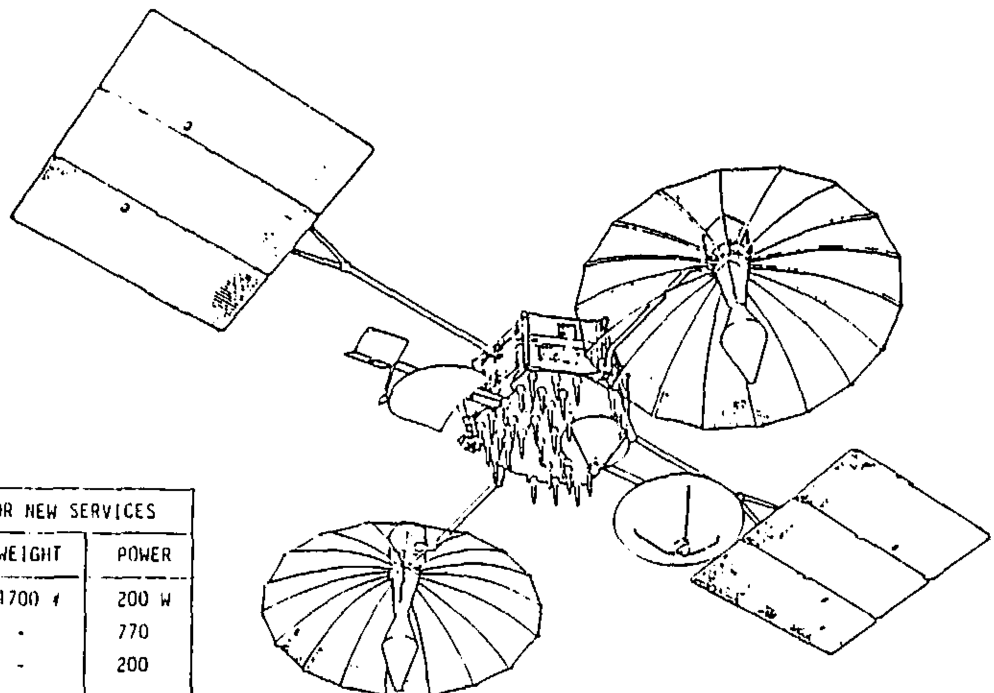
FIGURE 2-13 (5-4): FEATURES OF TDAS SPACECRAFT ACQUISITION STRATEGIES

	EXPANDED TDRS	ENHANCED TDRS	NEW BUS
TDRSS HERITAGE	HIGH	MODERATE	LOW
FLEXIBILITY	LOW	MODERATE	HIGH
TDAS GOALS ACHIEVED	NO MULTIPOINT DISTRIBUTION NO ULTRA-HIGH RATE ACCESS	ALL	ALL
TOTAL COST	HIGH	MODERATE	HIGH
TECHNICAL RISK	LOW	MODERATE	HIGH
TRANSITION PROBLEM	TWO GROUND STATIONS	DIFFICULT BUT FEASIBLE	?
STS COMPATIBILITY	COMPATIBLE NOW	MAY NEED INCREASED WEIGHT LIMIT	?

STANFORD TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 2-14 (5-5): TDRS SATELLITE



CAPABILITY FOR NEW SERVICES		
ITEM	WEIGHT	POWER
AW DELETIONS	1700 #	200 W
EPS ADDITIONS	-	770
TDRS MARGIN	-	200
TOTAL	1700 #	1170 W

removed from the earth-facing side of the spacecraft, as are the internal AW equipments. Each enhancement builds on the previous one until all the enhanced subsystems are incorporated. (5.2)

Enhancement I, pictured in Figure 2-15 (5-6), has the improved SMA and WSA subsystems. The SMA array is mounted opposite the SGL antenna for stability. In Enhancement II (Figure 2-16 (5-9)), the MBA replaces the TDRS SGL antenna, and two laser telescopes are added for the LSA service (one prime, one back-up). Addition of crosslink subsystem yields Enhancement III. Figures 2-17 (5-13) and 2-18 (5-14) show two versions; the former has a 60 GHz crosslink, the latter a laser crosslink. (5.2)

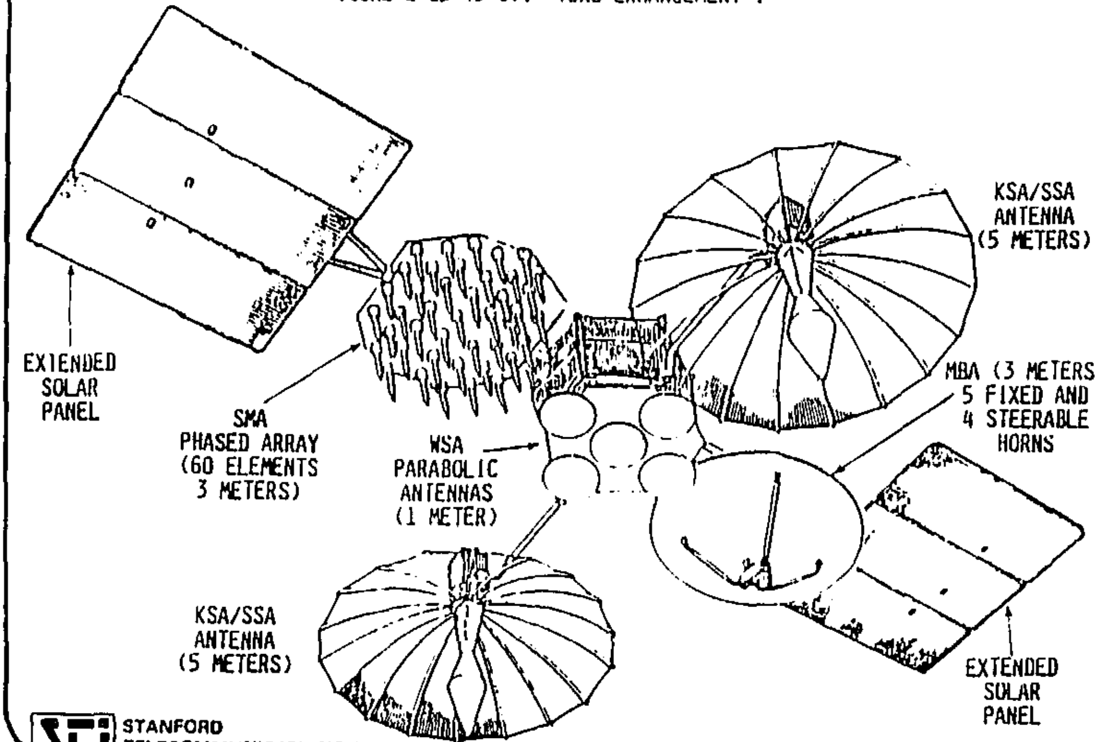
The enhancements are matched to the constellation options as shown below. Each enhancement has exactly the features ascribed to a given constellation/network configuration. (5.2)

CONSTELLATION	ENHANCEMENT
1A	I
1B	II
1C	III
2	III
3A	III
3B	III

Weight/power allocation for the enhancements is summarized in Figure 2-19 (5-13). The figures represent the cumulative enhanced subsystems, not total spacecraft weight and power. In sizing the laser crosslink version of Enhancement III, a GaAlAs laser with heterodyne detection is assumed. (5.2)

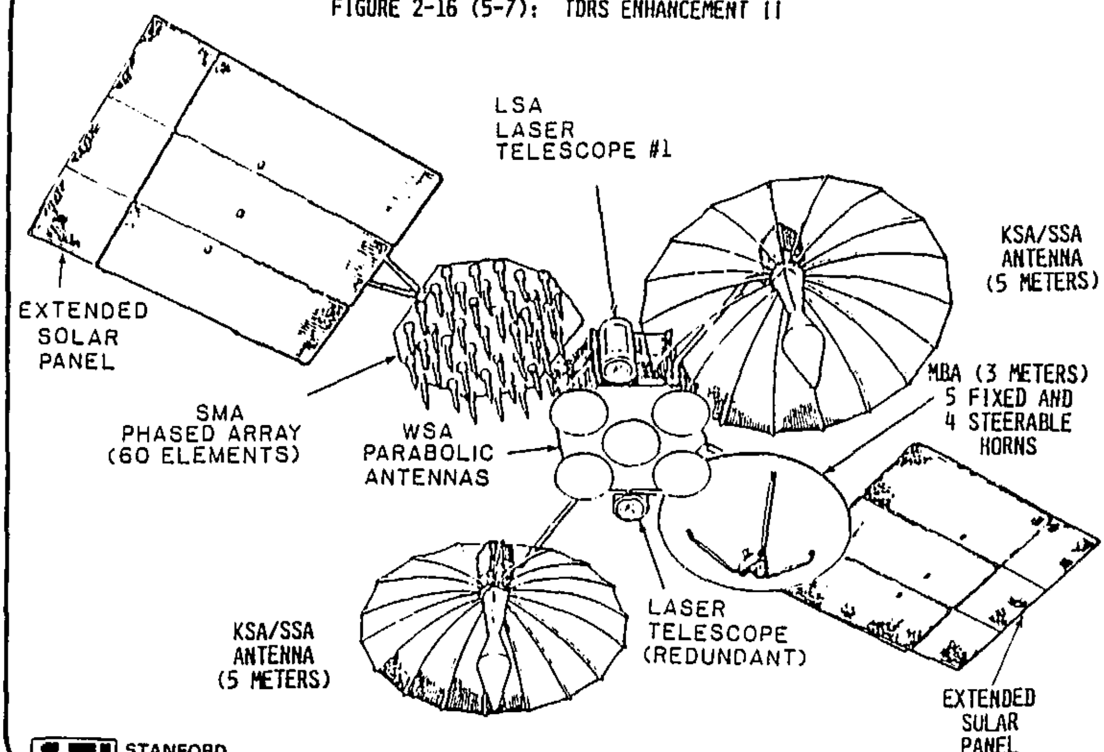
ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 2-15 (5-6): TDRS ENHANCEMENT I



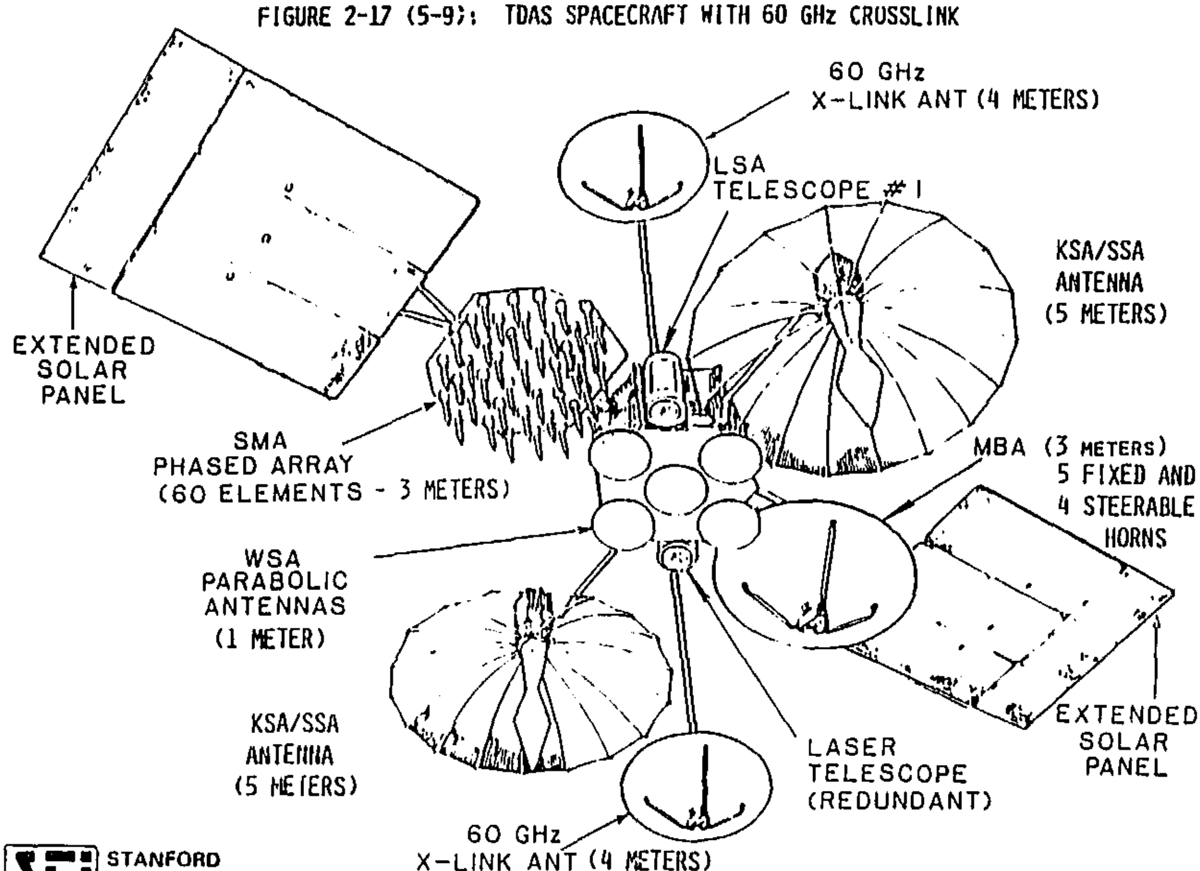
STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-16 (5-7): TDRS ENHANCEMENT II



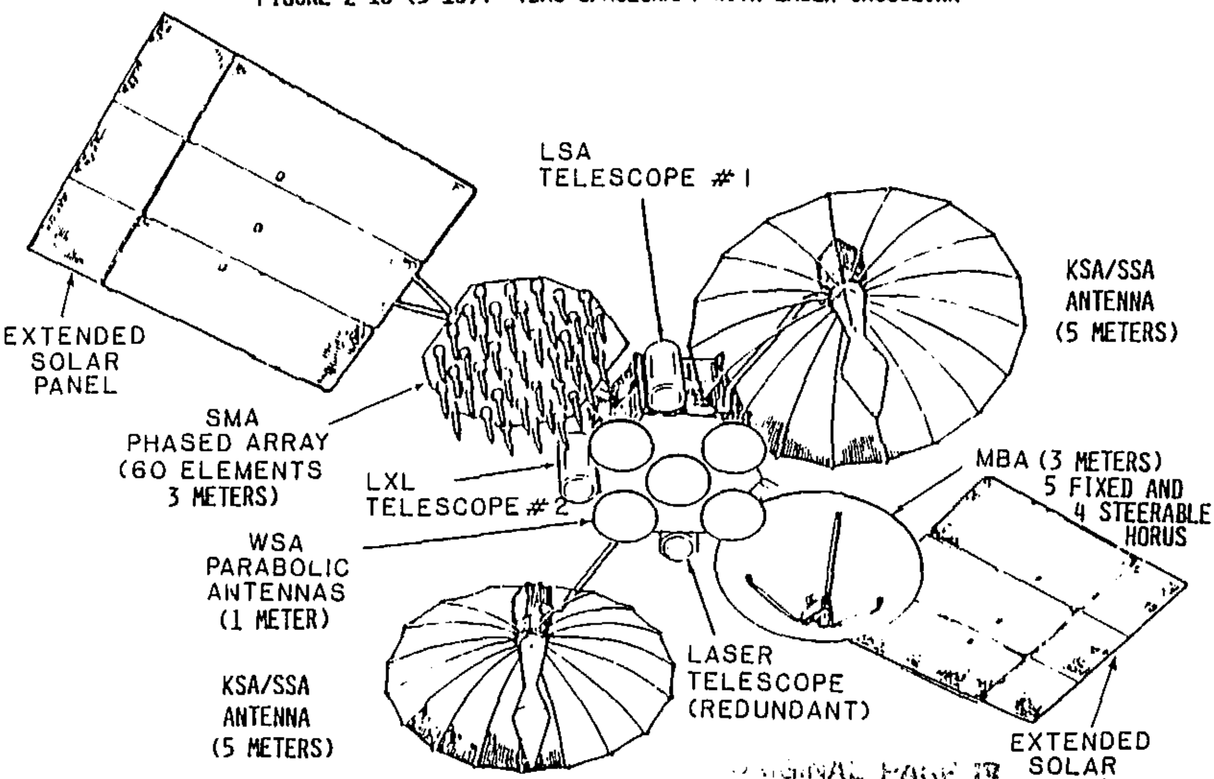
STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-17 (5-9): TDAS SPACECRAFT WITH 60 GHz CROSSLINK



STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-18 (5-10): TDAS SPACECRAFT WITH LASER CROSSLINK



ORIGINAL PAGE IS
OF POOR QUALITY

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-19: TOTAL WEIGHT AND POWER OF THE ENHANCEMENTS

	Δ WEIGHT (lbs)		Δ POWER (W)	
TDRS	0		0	
- MA ARRAY	-230		-140	
+ IMPROVED SMA ARRAY	+650		+420	
+ WSA	+500		+210	
+ SECURE TT&C (BATSON II)	+246		+ 89	
ENHANCEMENT I	+1166		+579	
+ MBA	+220		+460	
+ LSA (Nd:YAG)	+170		+135	
+ SOLAR PANELS	+ 90		0	
ENHANCEMENT II	+1626		+1174	
	GaAs	60 GHz	GaAs	60 GHz
+ XL	+240	+460	+250	+200
ENHANCEMENT III	+1866	+2106	+1424	+1374

STANFORD TELECOMMUNICATIONS INC.

In conjunction with the selection of constellation Option 2, the baseline TDAS spacecraft choice is Enhancement III. The laser implementation is preferred, with the 60 GHz version retained as the alternative. Key reasons for the selection follow. (7.1)

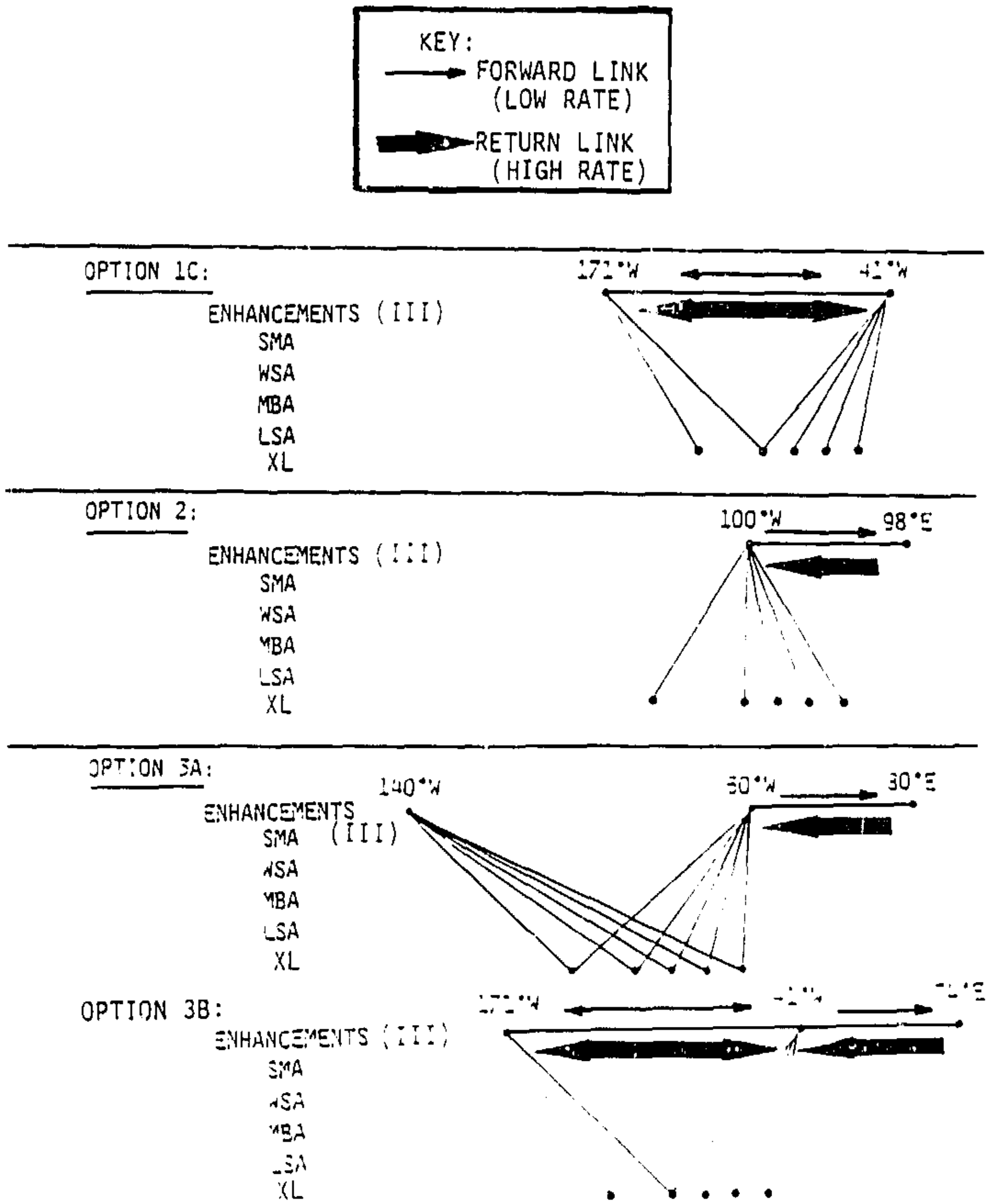
- Use of Enhancement III permits realization of the constellation Option 2 potential to achieve all the TDAS architectural goals.
- Enhancement III, although heavier and more power consuming than the other two, will still fit within the anticipated launch capabilities for the 1990's. Its weight exceeds the current 5000 lb STS payload limit, which would have to be modified to permit STS launch.
- The technological risks in implementing the enhanced subsystems do not seem to be excessive. Ongoing research supplemented by programs that can be put in place soon enough to yield results by 1988 should suffice to provide the technology needs of TDAS.

Crosslink Subsystem

The various constellations that incorporate crosslinks use them differently. The great disparity between the forward and return crosslink throughput requirements creates potential asymmetry on the crosslinks. Depending on configuration, return (or forward) data may flow either unilaterally or bilaterally on a given link, as shown in Figure 2-20. To cope with this, the crosslinks are sized for unilateral data flow and modified to suit the configuration (5.2.3).

The forward crosslink could be at either 60 GHz or laser frequencies. The demands at 60 GHz are far less than those of the WSA service and could be accommodated with a 1 W single impatt device transmitter and 1 ft antennas at both ends. (6.1)

FIGURE 2-20: CROSSLINK DATA FLOW IN THE CONSTELLATION OPTIONS



ORIGINAL PAGE IS
OF POOR QUALITY

Optics and 60 GHz are the alternatives for the return link frequency as well. Three lasers candidates are frequency doubled Nd:YAG (532 nm), CO_2 (10.6 μm) and GaAlAs (832 nm). (6.2.1)

Onboard processing for the return crosslink can run the gamut form transponding to full regenerative repeating (including decoding, editing, reformatting and switching prior to retransmission). Pure transponding and the demodulate/remodulate option are the two techniques considered for the crosslink. (6.2.2)

Laser signals can be received by two different techniques: direct detection and heterodyne detection (Figure 2-21 (6-4, 6-5)). The relative merits of these vary with the application, and not every laser can make use of both. Arguments that favor one receiver over another are presented when the various crosslink options are discussed. (6.2.3)

The four basic crosslink architectures under consideration are: (6.3)

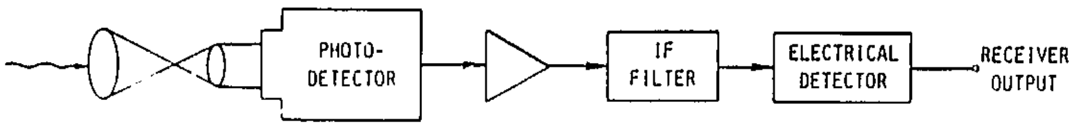
- A: RF transponder
- B: Laser demod/remod
- C: Laser transponder (heterodyne detection)
- D: Laser transponder (direct detection)

Each configuration is diagrammed in the report; only approach C is shown here in Figure 2-22 (6-13). The figure below (Figure 2-23) shows the five applicable combinations of technology and crosslink architectures.

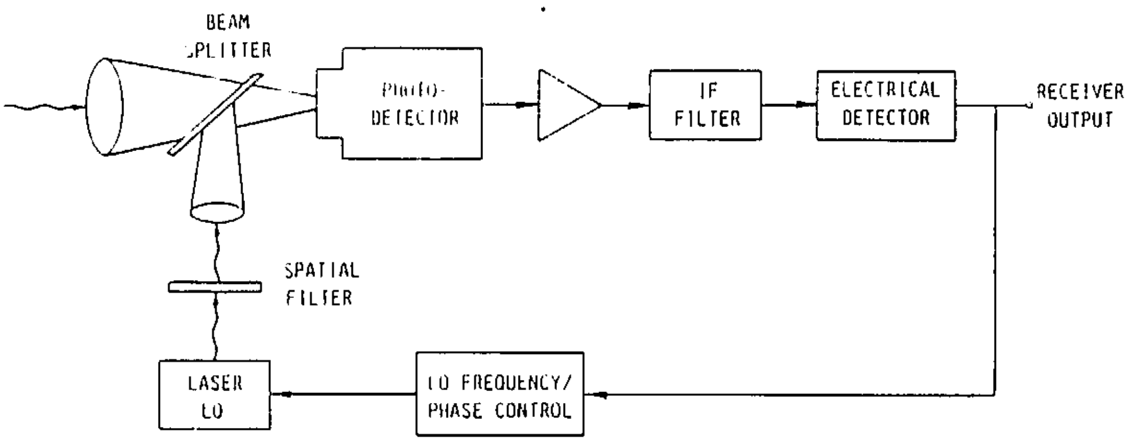
TECHNOLOGY	ALTERNATIVES A	B	C	D
60 GHz RF	√			
Nd:YAG Laser		√		
CO_2 Laser			√	
GaAs Laser			√	√

FIGURE 2-23: APPLICABLE PAIRINGS OF ARCHITECTURES AND TECHNOLOGIES

FIGURE 2-21 (6-4, 6-5): LASER RECEIVERS

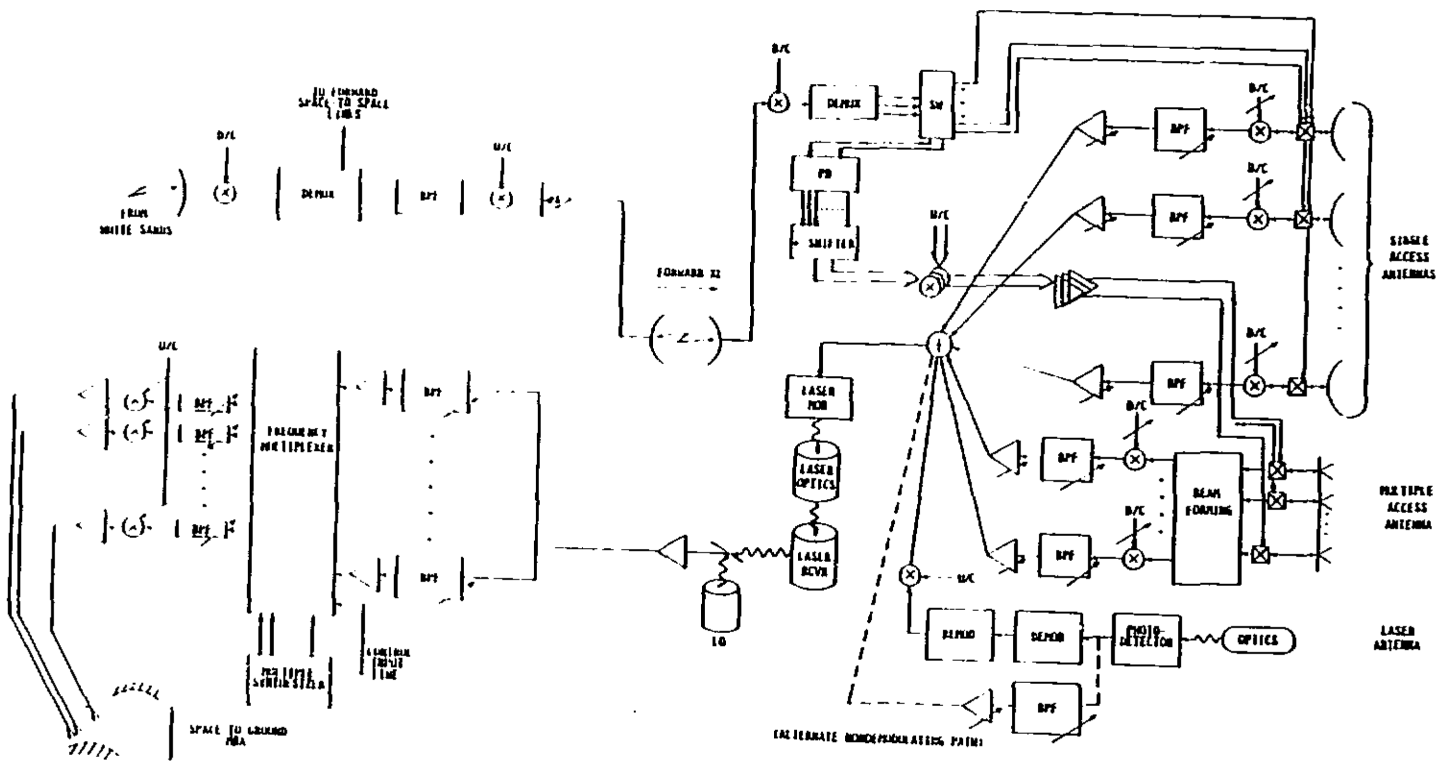


DIRECT DETECTION



HETERODYNE DETECTION

FIGURE 2-22 (6-13): APPROACH C: LASER CROSSLINK WITH HETERODYNE DETECTION



The comparison of acquisition and tracking at 60 GHz and laser frequencies leads to these observations: (6.4)

- Laser acquisition and tracking is the more difficult of the two.
- Techniques differ for heterodyne and direct detection, heterodyne being the more complex.
- A direct detection acq/trk system can be used with heterodyne communications to simplify acquisition.

The capacity to deliver new user services in the TDAS era is dependent in some degree upon the crosslink implementation. Six specific areas in which there is impact are evaluated in Figure 2-24 (6-18). In many cases the distinction among approaches is tied to whether the approach employs demod/remod or transponsing techniques for the crosslink. Dashed entries indicate that the alternative does not restrict new services. (6.5)

Weight and power estimates taken from Volume VII of this report are summarized in Figure 2-25 (6-19). These results highlight the severe penalty of the demod/remod option. GaAs has a slight edge on 60 GHz and CO_2, especially in the heterodyne configuration which is the more link-efficient. (6.6)

Figure 2-26 (6-20) shows the results of an overall assessment of technical risk in implementing the various approaches. (6.7)

On the basis of the data in this report and in Volume VII we have selected Approach C, laser transponder with heterodyne detection as the <u>baseline crosslink architecture</u>. Key supporting reasons are summarized below. (7.2)

- The weight/power penalty of a demodulate/remodulate option is severe and leads to the choice of a transponder technique.

FIGURE 2-24 (6-18): IMPACT OF CROSSLINK ALTERNATIVES ON NEW USER SERVICES FOR TDAS

	APPROACH			
	A (XPDR, 60 GHz)	B (LASER DEMOD/REMOD)	C (LASER XPDR, HETERODYNE)	D (LASER XPDR, DIRECT)
DATA RATES	—	Potentially Restricted	—	—
MODULATION	—	Commonality Preferable	—	—
MULTIPLE ACCESS	—	Onboard despreading required. Could force trade of services vs TDAS burden.	—	—
LASER USER	—	Same laser for user and XL preferable	Same laser for user and XL preferable	Same laser for user and XL preferable
NAVIGATION (ACQ/TRK)	—	Possible differences in services to front and back side users	—	—
SCHEDULING	Flexibility vs TDAS burden	—	Flexibility vs TDAS burden	Flexibility vs TDAS burden

ORIGINAL PAGE IS
OF POOR QUALITY

STANFORD
TELECOMMUNICATIONS INC.

FIGURE 2-25 (6-19): CROSSLINK SUBSYSTEM WEIGHT AND POWER SUMMARY (1 GBPS)

	TRANSMITTER		RECEIVER		MOD/DEMOD		TOTAL	
	LBS	W	LBS	W	LBS	W	LBS	W
60 GHz XPDR	320	170	140	30			460	200
Nd:YAG MOD/DEMOD	250	400	270	300	640	664	1160	1364
CO_2 XPDR	270	270	170	65			440	335
GaAs XPDR* (HETERODYNE)	165	200	75	50			240	250
GaAs XPDR* (DIRECT DET.)	240	300	85	50			325	350

ORIGINAL PAGE IS OF POOR QUALITY

* GaAs WEIGHT AND POWER ESTIMATES MAY BE LESS ACCURATE THAN THOSE FOR THE OTHER TECHNOLOGIES DUE TO DIFFICULTY IN DATA GATHERING.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 2-26 (6-20): CROSSLINK TECHNOLOGY SUMMARY

	OVERALL RISK	RISK ITEMS	IMPACT ON TDAS SERVICES	WEIGHT/ POWER	TECHNOLOGY STATUS
60 GHz	LOW	• LNA • IMPATT POWER COMBINING	LOW, EXCEPT NO CAPACITY FOR HIGHEST DATA RATE USER SERVICE	MEDIUM	ACTIVE
Nd:YAG	MEDIUM	• SPACECRAFT BURDEN • PUMP	HIGH	HIGH	LESS ACTIVE
CO_2	HIGH	• LASER LIFETIME • DETECTOR CRYOGENICS • MODULATOR	LOW	MEDIUM	DORMANT
GaAs (HET)	MEDIUM	• COHERENT POWER COMBINING • HETERODYNE RECEIVER • TRACKING LOOP	LOW	LOW	VERY ACTIVE
GaAs (DIR)	MEDIUM	• POWER COMBINING	LOW	LOW	VERY ACTIVE

STANFORD TELECOMMUNICATIONS INC.

- The risk items for GaAlAs are not insignificant, but they are all areas of quite active current effort, and are very likely to be solved within the required time.

- The transponding approaches have low impact on TDAS services (except at 60 GHz, where there is difficulty achieving the ultra-high rate access), whereas the demod/remod technique has substantial adverse impact on the communication and navigation services.

- The GaAlAs system has the lowest projected weight and second lowest power consumption of the alternatives.

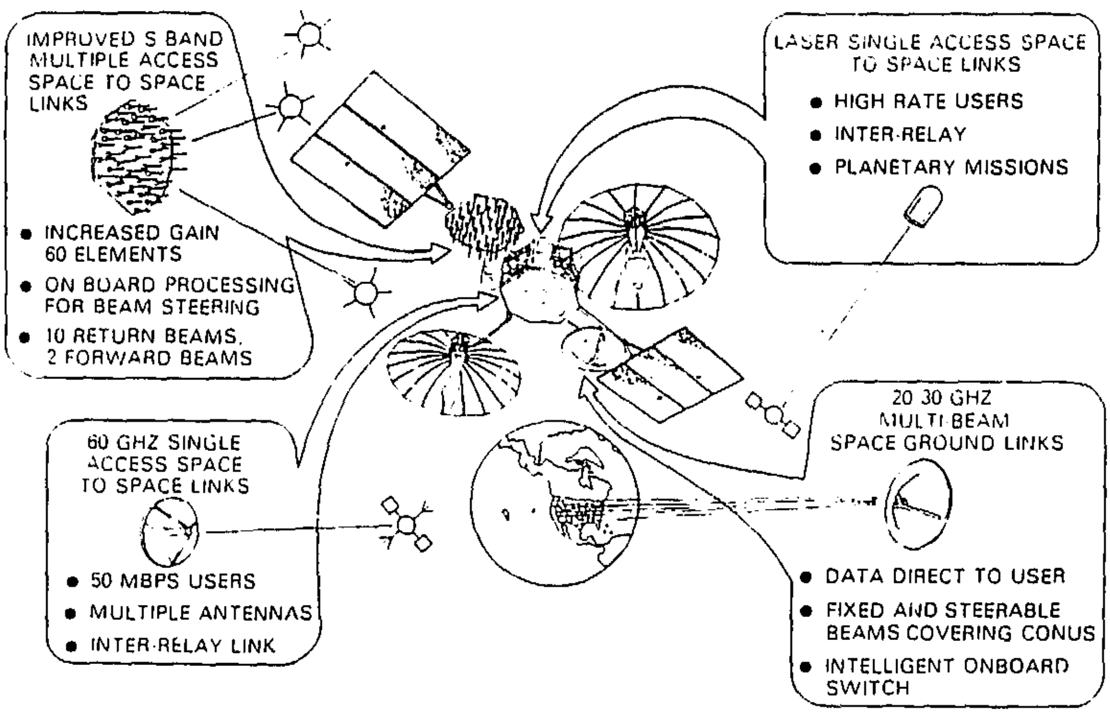
A 60 GHz crosslink is also a strong contender, and we recommend that it be retained as the alternative to the laser. NASA should watch closely and also participate in the development of both technologies over the next few years, and in this way be ready to pursue whichever becomes the better course.

The full baseline TDAS space segment architecture is summarized in Figure 2-27. This baseline realizes all the enhancements proposed at the outset; the TDAS spacecraft drawing in Figure 2-28 indicates how each has been incorporated. (7.1) Figure 2-29 summarizes the TDAS technology assessment.

CONSTELLATION/ NETWORK	TDAS SPACECRAFT	CROSSLINK
2	III	C
• TWO SPACECRAFT, ONE FRONTSIDE (100° W) ONE BACKSIDE (98° E), WITH CROSSLINK	• ENHANCED TDRS WITH: SMA, WSA, MBA, LSA, AND XL	• GaAlAs LASER TRANSPONDER WITH HETERODYNE DETECTION

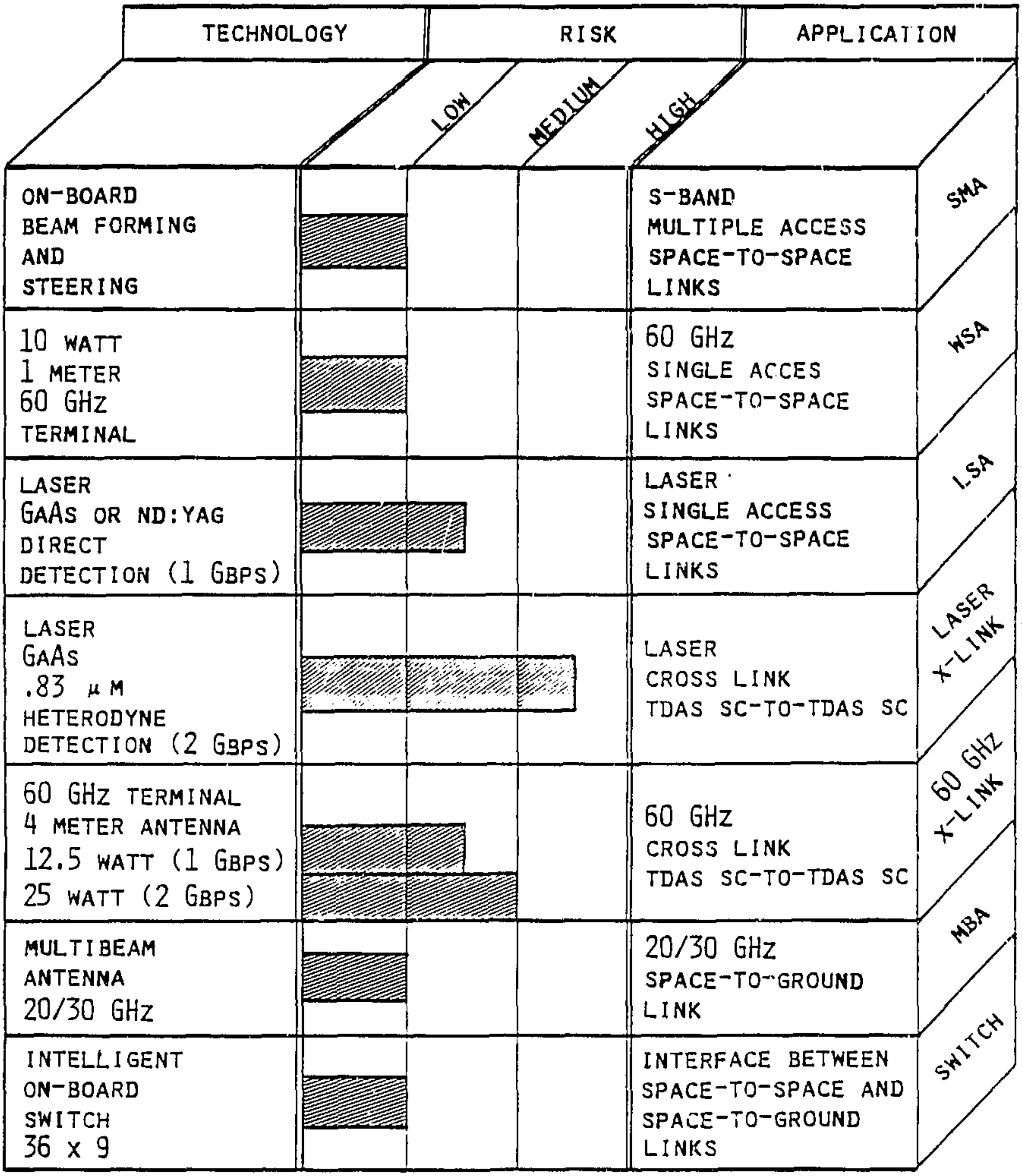
ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 2-28: BASELINE TDAS SPACECRAFT AND SERVICES



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 2-29: TDAS TECHNOLOGY ASSESSMENT



STANFORD TELECOMMUNICATIONS INC.

TDAS Threat Model

Preliminary analysis of jamming threats to TDAS have been carried out. In the table display in Figure 2-30, entries denote whether potential jamming susceptibilities are found on the various links. These susceptibilities may be found negligible with further study, or may require implementation within TDAS of security features not proposed in the baseline.

FIGURE 2-30: LINK SUSCEPTIBILITY VS FREQUENCY

	S BAND	K BAND	W BAND	LASER
USAT/TDAS	✓	✓	X	X
TDAS/TDAS	N/A	N/A	X	✓
TDAS/GROUND	✓	✓	N/A	N/A
GROUND/TDAS	✓	✓	N/A	N/A
TDAS/USAT	✓	✓	X	N/A

✓ = Potential Susceptibility

X = No Identified Susceptibility

SECTION 3

SPACE SEGMENT ARCHITECTURE ISSUES

TDAS, whether it evolves smoothly from TDRSS or comes about in a more dramatic fashion, is basically a new system. To discuss architecture of its space segment presupposes some considerable thought about its functions and some partitioning of those thoughts into requirements and goals, "musts" and "ought to's." Beyond that lies the realm of defining the services that will meet the perceived needs. It is at this point that architecture considerations can come to play.

Volumes II and III of this report serve to define the TDAS mission as best we can know it today. TDAS requirements that have been drawn up using the mission model as a basis are summarized herein. After studying the requirements, it became evident that certain realizations of TDAS would have more desirable features than others. These desirable features have been preserved as goals of the architecture. Based on our summary of the system requirements we will trace the development of these goals in this section

The identified goals for the most part center on describing the services that should be provided to various TDAS user satellites. It is then a short step to determining frequencies, EIRP's, receive G/T's, etc., and the equipments that will provide them. Each user service specifically associated with the TDAS space segment will be identified and described briefly in this section; this is the real beginning of the TDAS architecture specification.

The step from services to architecture entails consideration of the major subsystems of TDAS: the satellite constellation and the associated ground network, the TDAS spacecraft, and the crosslink between TDAS spacecraft. Chapters 4-6 of this report will be devoted to these three subsystems, where the resolution of the pertinent issues will be discussed.

3.1 TDAS REQUIREMENTS

The survey of future user requirements attempted to characterize the engineering and science data to be returned to earth from the various experiments and missions. Total volume, dump rate and contact times were determined where possible. In some cases generic experiments were postulated where details of actual future efforts were unavailable. Figure 3-1 shows a result of the survey; it depicts NASA-only (no military) predicted requirements for a busy day in 2000 A.D.

Using data of the sort shown in Figure 3-1, requirements for channel hours per day in various data rate regimes were generated, as shown in Figure 3-2. These requirements include both NASA-only and various combinations of joint NASA/military usage. For the 50 kbps to 300 Mbps range of rates, the requirements are also parameterized in units of TDRS per-satellite capacity, and we note that the NASA requirement alone is by 2000 projected to be double the capacity of the TDRS-E/TDRS-W system soon to be emplaced, and the military projections double the total yet again.

The preceding figures show two novel features beyond the indicated capacity increase. The first is the appearance of users having data rate requirements in excess of 300 Mbps; the second is full period contact times, as in the case of all engineering data and the STS science data. Each of these features will turn out to have considerable impact on the space segment architecture.

3.2 TDAS ARCHITECTURAL GOALS

3.2.1 Guidelines

To make the goal formation process concrete, we will operate under some guidelines. The first of these is to:

- Meet the communication and navigation requirements of the 1995-2005 period as set forth in Volumes II and III of this report.

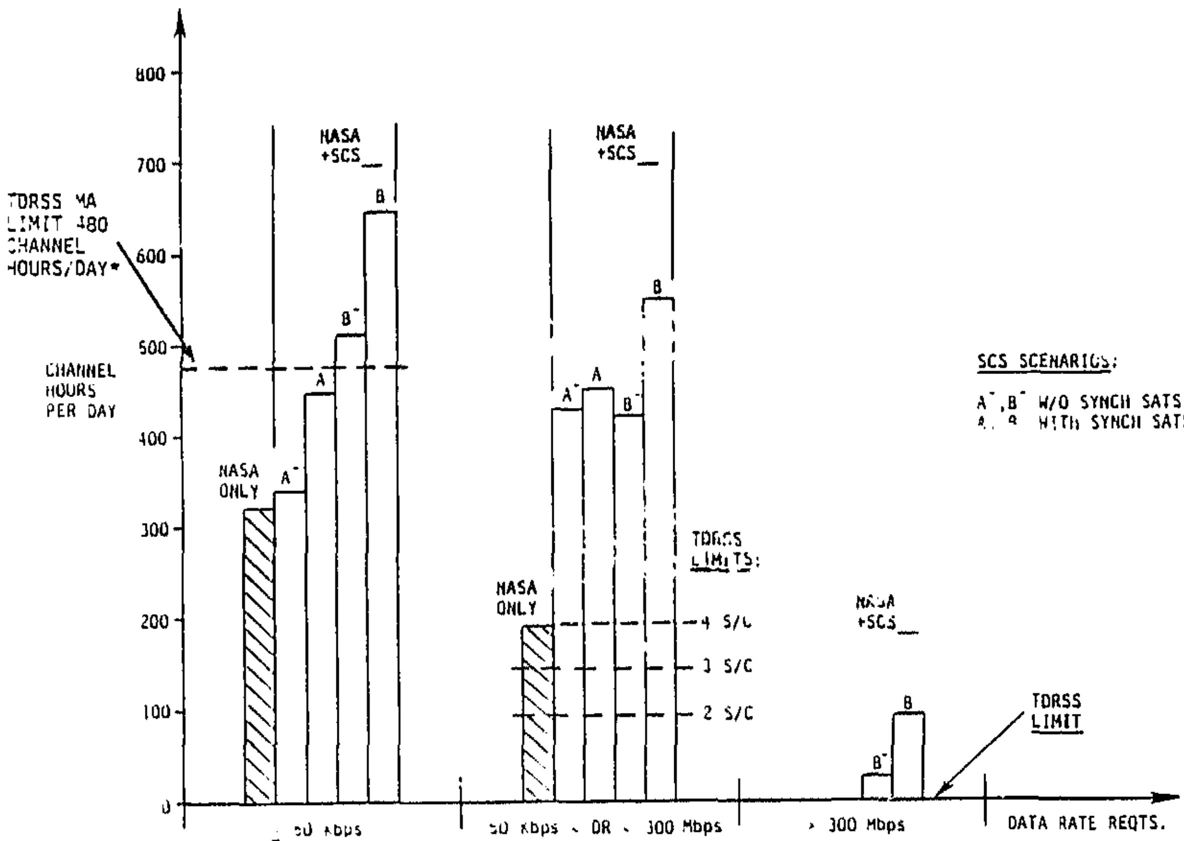
MISSIONS	SCIENCE DATA			ENGINEERING DATA	
	VOLUME (BITS/DAY)	DUMP RATE	CONTACT HOURS*	DUMP RATE	CONTACT HOURS (REAL TIME)
AG-3	5×10^8	35 Kbps	5.3	2 kbps	24
EG-5	7×10^8	48	5.3	2	
ADV. TM	3×10^9	200	5.3	2	
SG-1	5×10^9	350	5.3	2	
METEOROLOGY (2)	6×10^{10}	665	3.6 x 2	8.3	
LARGE OPT/UV	10^{10}	700	5.3	2	
AXAF	10^{11}	7 Mbps	5.3	4	
COSMIC/100-m	10^{11}	7	5.3	2	↓
SHUTTLE	—	50	24	192	**
EG-3	2×10^{12}	300	2.4	2	24
SG-2	3×10^{12}	300	3.6	2	
RG-1	1.5×10^{13}	300	5.3	2	
HLLV				15	
SHUTTLE				192	
OTV				6 Mbps	
TMS				15	
MOTV				15	
SPACE STATION/ PLATFORM	1×10^{13}	300	3.5	50	↓

* ASSUMES 16 CONTACTS/DAY, 15 MINS/CONTACT AND 75% SHCEDULING EFFICIENCY. EXCEPTIONS: SG-2 AND METEOROLOGY ARE BASED ON 10 MINS/CONTACT AND EG-3 ON 7 MINS/CONTACT.

** ENGINEERING DATA ASSUMED TO BE MULTIPLEXED WITH SCIENCE DATA.

FIGURE 3-1: The table shows NASA data service requirements for TDAS. Both science and engineering data are included for a mix of actual and generic experiments. By examining the contact time and dump rates, specific channel availability requirements vs data rate can be forecast.

STANFORD TELECOMMUNICATIONS INC.



* Based on ground station receive capability of 20 channels total.

FIGURE 3-2: Daily channel hour requirements for NASA and NASA/military users forecast for 2000 A.D. Military scenarios are designated SCS (Satellite Control Satellite) for the study in which these requirements evolved. SCS A is a lighter loading than SCS B. Both A and B are depicted in versions including and excluding synchronous user satellites.

STANFORD TELECOMMUNICATIONS INC.

A second guideline is imposed to ease the transition from TDRSS to TDAS:

- Do not impose significant weight/power requirements on the user spacecraft.

Architecture configured under this guideline will support the transition with minimal impact on the user community. Experimenters will not find the spacecraft needed to work with TDAS to be necessarily more complex nor to have a greater fraction of its burden diverted from science usage and instead dedicated to relay compatibility. And in fact, we want to go a step farther in making the guideline more stringent:

- Let the transition from TDRSS to TDAS be transparent to the TDRSS user.

This latter version implies that all TDRSS services are maintained within TDAS. For our purposes these are the communication (KSA, SSA, MA) and navigation (range and doppler tracking) services. The architectural approaches presented in this adhere to the stringent form of the guideline.

The fourth guideline is:

- Use a single TDAS satellite design for all satellites.

This guideline precludes a configuration choice that requires parallel development and procurement of different satellite types, or the inclusion of options that may or may not be present in individual satellites. To adopt this guideline could possibly impose a weight/size/power burden on the TDAS, and therefore a judicious choice among the posed alternatives will be one the tends to minimize this burden.

Finally:

- Realize the proposed architectures in terms of "enabling technology" (1988 cutoff).

Some difficulty due, of course, to the subjective element in defining an enabling technology, can be anticipated in determining whether this guideline is being met in the alternatives. An enabling technology is one that can be addressed to an application without appreciable research and development in the technology itself, but in only the details of application. The architectural elements of the baselines recommended in this volume have, wherever possible, a supporting technology that can be considered as "enabling" by 1988 standards.

3.2.2 Goals

The principal TDAS architectural goals are shown in Figure 3-3, and the corresponding system enhancements (relative to TDRSS) are given alongside. Each of these is discussed in turn.

3.2.2.1 Improved SMA Service. TDRSS provides an S-band multiple access (SMA) service via a 30-element array onboard the satellite. Each satellite can receive 20 return link channels. although the TDRSS ground station can accommodate no more than 20 channels in total. Multiple access is achieved via pseudonoise code-division (PN/CDMA). All thirty antenna elements are used for the formation of each channel, and therefore all element signals are frequency multiplexed onboard and downlinked to the ground station where beamforming and calibration is performed for each channel. The forward SMA link service consists of a single channel formed onboard the TDRS using 12 of the elements.

To maintain TDRSS user compatibility, TDAS must replicate these services, retaining the PN/CDMA format. Additional forward links will accommodate flexibility in scheduling the increased number of users. Nothing indicates that either the maximum MA return data rate or the number of channels per spacecraft need be increased.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 3-3: TDAS ARCHITECTURAL GOALS

GOALS	ENHANCEMENTS
IMPROVE SMA SERVICE	• 2-4 SMA FORWARD LINKS • 3 DB IMPROVEMENT ON RETURN LINK
PROVIDE USAT TT&C DATA DIRECTLY TO MISSION CENTERS	• ONBOARD SMA BEAMFORMING
ALLOW USERS TO RECEIVE MISSION DATA AND CONTROL EXPERIMENTS AT 5 OR MORE CONUS LOCATIONS	• MULTIBEAM SPACE/GROUND LINK • ONBOARD SWITCH
PROVIDE INCREASED NUMBER OF HIGH-RATE ACCESSES	• 60 GHz SINGLE ACCESS CHANNELS
PROVIDE ULTRA-HIGH RATE ACCESSES (> 300 MBPS)	• LASER SINGLE ACCESS CHANNEL
PROVIDE 100% COVERAGE	• 60 GHz OR LASER CROSSLINKS

STANFORD
TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

An attempt to increase the forward link capacity of the TDRS array is not likely to meet with success. Although the element requirement for two forward links (24 elements) could be met, it is less clear that the appropriate distribution of elements on the array face could be obtained. In order to form, for any user location, a beam with well-controlled lobe structure, the location of the elements to be used must evidence a certain symmetry. In order to minimize both beam broadening and pattern sensitivity to phase error, it is best if the full aperture is utilized.

These demands are better met with an array containing a greater number of elements. Doubling the array to 60 elements permits an easier choice of 24 elements for the two forward links, and even third and fourth links can be contemplated. Another benefit of doubling the elements is the 3 dB increased signal-to-noise ratio in the return link beam. The increased margin will be beneficial to multiple access signals that are transponded over a crosslink.

3.2.2.2 Distribution of USAT Data. TDRSS employs a single ground station at White Sands, NM, to which all downlink transmissions are directed. If this configuration were perpetuated in the TDAS era, the downlink load to this station would be greatly increased, and there would be a corresponding increase in the distribution of user data and telemetry via NASCOM, DOMSAT, or fiber cable links to the user mission centers or POCC's. An alternative is to directly distribute the data to a number of ground terminals which would be local nodes to which the mission centers and POCC's connect. In doing so the redistribution burden is considerably eased.

The alternative has many implications for the space segment, of which only one is considered here and the others deferred to paragraph 3.2.2.4. In order to distribute MA user data to several ground sites, a TDRS-type satellite would add downlink antenna capability and send each element signal to each site, where beamforming and extraction of relevant data would occur. This method entails a great waste of downlink capacity in sending to each ground station signals containing much irrelevant data. A selective retransmission scheme at the relay satellite could, however, be implemented if the MA beamforming were performed onboard instead of at the ground. At the same time this eliminates needlessly redundant equipment from the ground sites. Thus the system enhancement question relates to the technology of onboard beamforming and calibration. Calibration becomes easier, and possibly unnecessary, because the downlink is eliminated from the calibration loop.

3.2.2.3 User Experiment Control. To go along with direct downlink distribution of data is the notion that uplink commands to user spacecraft or onboard experiments could also be uplinked from diverse sites. In TDRS, the mission center generates commands which are passed to the NCC and then to White Sands via NASCOM. This system could be replaced by direct commanding that bypasses White Sands: user commands can be generated at the mission center, linked to the earth station, and uplinked to the TDAS satellite that will handle the relay to the user spacecraft. Direct control of the spacecraft or experiment package on it (e.g., USAT antenna pointing) is thus accomplished.

The TDAS satellite that can handle this mode of operation will have several enhancements relative to TDRS. For both the uplink and downlink, a multibeam space-to-ground antenna (MBA) is needed. To properly interconnect the space/space and space/ground signals will require an onboard switch that is configured by TDAS command. The technologies associated with the switch are key to this goal.

3.2.2.4 Increased High Rate Accesses. Within the TDAS era, channel-hour requirements for high rate traffic (50 kbps-300 Mbps) will double or quadruple those of TDRSS. To meet this need, additional single access (SA) capacity is required. The attempt to provide it at S- or K-band stresses bandwidth availability and requires additional antenna aperture at least equalling that of the TDRSS single access dishes (4.9 m diameter). At higher frequencies, equivalent or better links can be obtained with smaller antennas, making possible a large number of SA channels per spacecraft. The move to a higher frequency, while promising from the antenna viewpoint, causes difficulties in RF power generation that must be reckoned with.

3.2.2.5 Ultra-High Rate Access. TDRSS offers no service at data rates above 300 Mbps. With the advent of ultra-high data rate users, another new service must be added. Its frequency should be at least as high as that of the new single access channels: both RF and optical frequencies are possible. At data rates of 1 Gbps, laser links may be the only practical solution.

Choice of implementation of the ultra-high rate access channel is not an isolated concern. We shall see that it interacts strongly with the other single access channels and the crosslink.

3.2.2.6 Visibility and Number of Ground Stations. Requirements for full period coverage of some users have been shown. This cannot be accomplished with the TDRSS or any other two-satellite constellation. Various possibilities will exist with constellations of three or more satellites.

Several issues arise in considering the constellation design for the TDAS. The first is 100% visibility. Of equal importance are the location of satellites with respect to the ground terminals, the TDAS satellite capability, the need for ground terminals outside the continental United States, and the need for crosslinks between the TDAS satellites. Accuracy of user and TDAS navigation also varies with the constellation.

The subjects of constellation/networking, TDAS spacecraft design, and crosslink design are of sufficient importance that each is the subject of full chapter of this report. The remainder of this chapter describes the enhanced TDAS subsystems that have been selected for TDAS. It is on the basis of these subsystems that the architecure tradeoffs can be made.

3.3 ENHANCED TDAS SUBSYSTEMS

Each enhanced subsystem that is considered for TDAS is described below. In Chapter 5 of this report, we see how various combinations of these are integrated into design alternatives for the TDAS spacecraft.

3.3.1 S-Band Multiple Access (SMA)

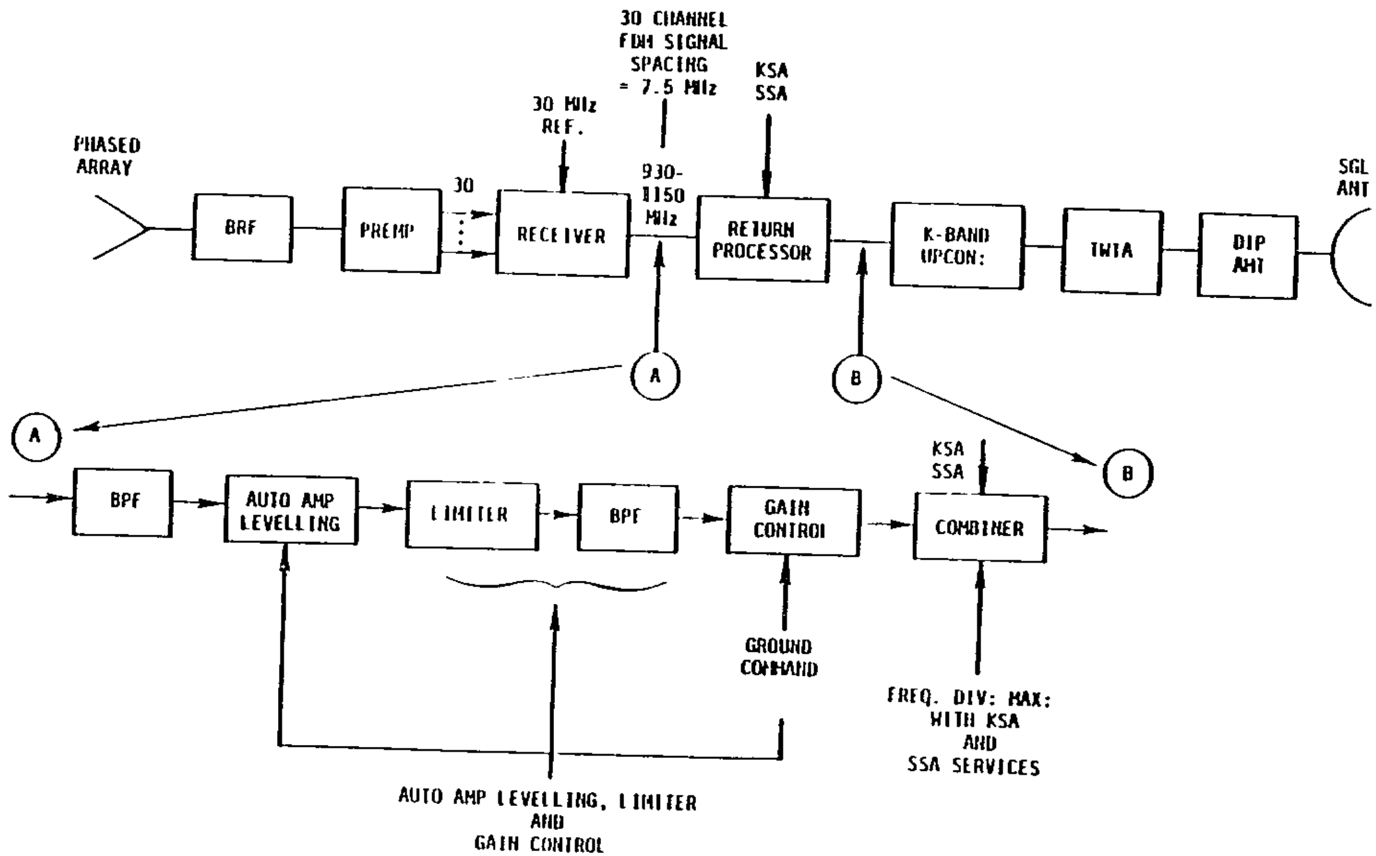
A functional block diagram of the existing TDRS SMA return channel is shown in Figure 3-4. Because the beams are formed at the ground, the signal transfer characteristics are critical to performing the beamforming with reasonable losses. Low loss is controlled by automatic amplitude leveling, signal limiting and gain control at the ground station processor. This permits the return channel TWTA to operate in its preassigned backoff mode, maintaining the correct relative levels of the various signals and allowing the MA array element signals to radiate to ground without appreciable amplitude and phase distortion. The return channel is periodically calibrated to remove any effects due to frequency dispersion in the downlink (the element signals are transmitted FDM) and the satellite channel. Calibration requires a despread signal and must be performed at the ground.

SMA subsystem requirements for a new TDAS SMA service are listed in Figure 3-5. In the technology studies it has been shown that a theoretical increase of 1.5 dB element gain is achievable with a helix element that retains the 26° FOV; 1 dB of this is expected to be realized. By doubling the number of elements in the array to 60, a 3 dB array gain increase is achieved. This array, shown in Figure 3-6, has 61 elements hexagonally packed in four concentric rings. Its diameter is 1.75 m, about 74% smaller than the TDRS array (the TDRS array must give up space to the Advanced Westar antenna).

Beamforming in space simultaneously conserves downlink bandwidth, permits efficient distribution to multiple sites, and decreases beamforming loss. Figure 3-7 summarizes the impairments to beamforming within both the onboard and ground equipments. About 1 dB of beamforming loss is due to ground equipment that would not be present in the onboard beamformer; TDAS will have as a result a 1 dB enhancement.

The functional block diagram (Figure 3-8) shows how the pieces fit. The return link front end assembly consists of the array elements, filters and preamps. Behind the elements used for the two forward links are

FIGURE 3-4: FUNCTIONAL BLOCK DIAGRAM (EXISTING TDRS SMA RETURN CHANNEL)



ORIGINAL PAGE IS
OF POOR QUALITY

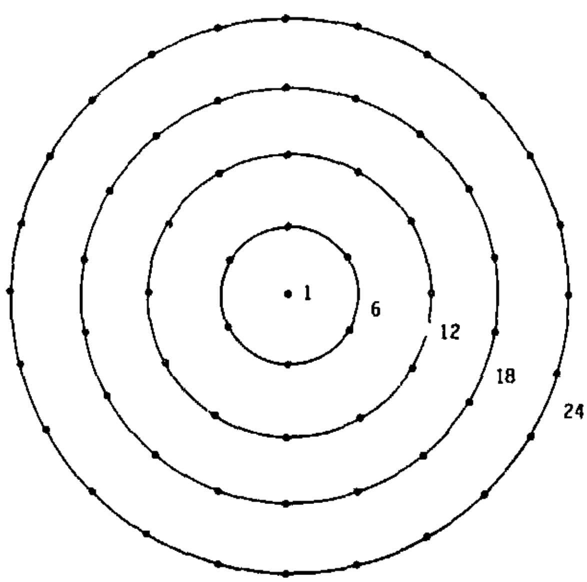
STANFORD
TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 3-5: SMA SUBSYSTEM REQUIREMENTS FOR TDAS

- CHANNELS:
  - FORWARD - 2 (EACH TIME SHARED)
  - RETURN - 10
- FOV: 25° CONICAL
- TRAFFIC CAPABILITY: 10 USER S/C SERVED SIMULTANEOUSLY (AVERAGE PER S/C)
- PERFORMANCE ENHANCEMENT:
  - 3 DB INCREASED ARRAY GAIN
  - REDUCED BEAM FORMING LOSSES
  - ENHANCED PHASED ARRAY ELEMENT GAIN

FIGURE 3-6: PHASED ARRAY ANTENNA WITH 60 ELEMENTS



STANFORD TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

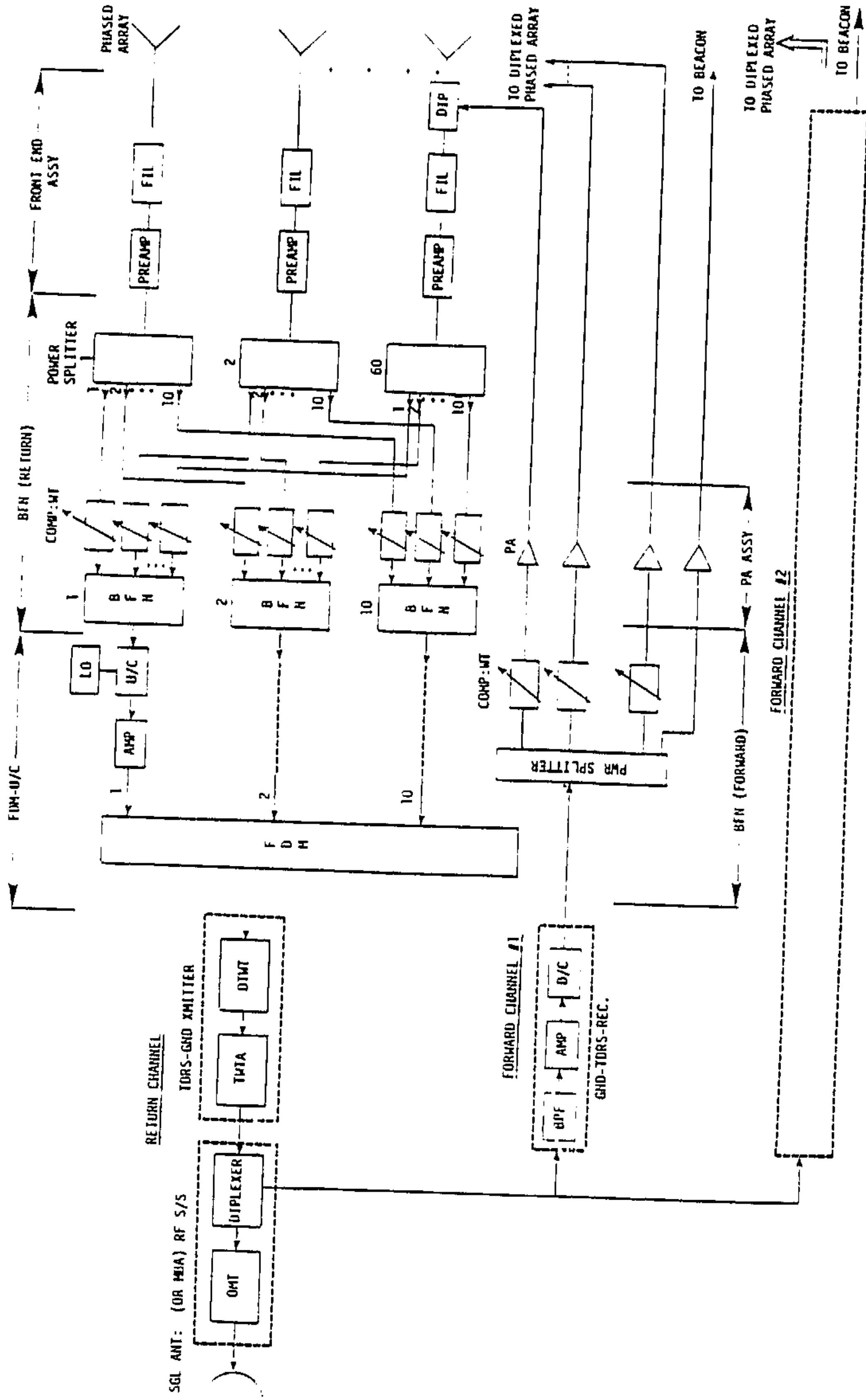
FIGURE 3-7: APPLICABLE CAUSES OF BEAM FORMING LOSS

APPLICABLE BEAM FORMING IMPAIRMENT	COMPONENT	GAIN IMPAIRMENT (DB)			PHASE IMPAIRMENT	
		LINEAR PK PK	PAR PK	RIPPLE PK-PK	TOTAL PHASE NONLINEARITY (DEG)	DIFFERENTIAL PHASE STABILITY (DEG)
ON GROUND BEAM FORMING (↕ all components); ON BOARD BEAM FORMING (↕ MA ANTENNA to RECEIVER)	MA ANTENNA					± 5
	CABLE (ANT-DIP)					± 1
	(MA DIPLEXER (OR BRF)			0.2	± 0.5	± 4
	CABLE (DIP-PREAMP)					± 0.5
	PREAMP			0.2	± 2.0	± 6
	CABLE (PREAMP-REC)					± 3.6
	RECEIVER		1.5	0.7	± 0.5	± 0.0
	RETURN PROCESSOR		0.2	0.1	± 0.3	± 5
	AUTO: AMP LEVEL/ LIMITER/GAIN CONTROL			0.2	± 0.5	
	UPCONVERTER		0.1	0.2	± 1.6	± 4
	TWTA	0.1		0.2	± 0.8	± 3
	DIPLEXER (SGL)					± 2
	MISMATCH			0.2		
	FILTER (SGL)			0.1	± 1.1	

REDUCTION IN BEAM FORMING LOSS = 1 DB

STI STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-8: FUNCTIONAL BLOCK DIAGRAM OF SMA MODULE



STANFORD TELECOMMUNICATIONS INC.

diplexers. Each element signal is power split ten ways and switched into a beamforming network (BFN) through a variable weight that controls amplitude and phase. The output of each BFN is upconverted (each beam to a separate frequency) and amplified prior to presentation to the frequency multiplexer. The multiplexer creates composite outputs for each downlink port of the space-to-ground antenna and passes them to the radio chain.

The two forward channels consist of receivers, each tuned to the appropriate band, followed by power dividers, the weighting circuitry, and power amplifiers. The power amp outputs are sent to the phased array diplexer.

A weight and power breakdown for the SMA module (Figure 3-9) shows 650 lbs, 420 W. A comparable figure for TDRS is 230 lbs, 140 W.

3.3.2 Multibeam Antenna (MBA)

Implementation of direct distribution of user data and direct experiment control by the mission centers requires that the TDAS satellite have an MBA for its space-to-ground link. A survey of possible sites for TDAS ground terminals turned up five that are assured to be at or near mission centers. These are Greenbelt, MD (GSFC), Houston, TX (JSC), White Sands, NM (WSGT/NGT), Sunnyvale, CA (SCF), and Colorado Springs, CO (CSOC). Figure 3-10 shows the LAT/LONG coordinates of these sites relative to a TDAS at 97°W. These sites would be accommodated by fixed feeds on an MBA. The pointing offset for each station is shown in the figure. For other sites that are either fixed, but not requiring full period coverage, or are mobile, movable feeds can be added. Four such feeds accommodate another four sites.

Requirements for the MBA subsystem are shown in Figure 3-11. In considering alternatives to meet these requirements, we have looked at the number of MBA's per TDAS, the antenna types (phased array, lens, single and dual reflectors), and feeds (aperture shape and clustering). In deciding between one or two MBA's per spacecraft, it was concluded a single MBA is preferable because of lighter weight and stowage volume, even though the performance and implementation ease of the dual array may be slightly superior.

FIGURE 3-9: WEIGHT/POWER BREAKDOWN-ENHANCED SMA MODULE

SUBSYSTEM	WEIGHT(LBS)	POWER(W)
RF S/S	6	—
TDRS-GND XMTER	50	60
FDM-U/C	60	50
BFN (RETURN)	100	80
FRONT-END ASSY	60	40
PHASED ARRAY (60 ELEM)	135	--
PA ASSY	50	50
BFN (FORWARD)	70	60
GND-TDRS RECEIVER	100	60
MISC:	19	20
TOTAL	650	420

FIGURE 3-10: FIXED FEED LOCATIONS

GROUND STATION	LATITUDE	LONGITUDE	ANGLE BETWEEN BORESIGHT AND THE STATION
GSFC MD	39°N	77°W	2.58°
HOUSTON TX	29°N	95°W	1.36°
WS NM	32°N	106°W	1.6°
SUNNYVALE CA	37.5°N	122°W	3.26°
COLORADO SPRINGS CO	39°N	106°W	1.19°

ASSUMPTIONS:

- THE MECHANICAL BORESIGHT OF THE ANTENNA IS POINTING TO (LATITUDE = 39°N, LONGITUDE = 97°W)
- FREQUENCY = 25 GHZ
- SATELLITE LOCATION 97° WEST LONGITUDE (ANT. PERFORMANCE PRACTICALLY INSENSITIVE TO SAT. LOC. CHANGE OF ± 20 DEG)

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-11: MBA REQUIREMENTS

FREQUENCY	30/20 GHZ
GAIN	> 45 DB @ 20 GHZ
POLARIZATION	DUAL
COVERAGE	CONUS LOCATIONS
FEEDS	5 - FIXED FEEDS 4 - SCANNABLE FEEDS

STANFORD TELECOMMUNICATIONS INC.

Among antenna types, the phased array showed a number of disadvantages that clearly eliminated it as the choice — the complication of multiple beam-forming networks at two frequencies and the problems associated with elimination of grating lobes are two such disadvantages. In comparing lens and reflector antennas, it was noted that some lens designs could incur weight and tolerance penalties, especially in a wide scan angle configuration. The reflector is free of grating lobes, is comparatively lightweight and efficient, and has many alternative configurations that can be tested for suitability, and is therefore the preferred choice.

The central tradeoff in the MBA reflector is cost/complexity vs good electrical performance. A dual reflector with a main and subreflector has the better performance potential, but its alignment and manufacturing tolerances are more difficult to meet. Technology of front fed single reflectors is better e tablished and more capable of achieving design goals, but the blockage and scan degradation losses are larger and cannot be eliminated. It is our judgment that the technology trade favors the single reflector because of its inherent predictability. Its structure is more like that of the space-to-ground link antenna it replaces and is more likely to be easily integrated into a "busy" spacecraft bus.

The MBA feed system can consist of either a mechanically scannable single feed or a stationary feed array. The feed elements themselves may be square or circular. A scannable feed is preferable to an array in terms of blockage loss and distortion, but it is limited to single link operation with a single feed. With scanning, arbitrary ground sites can be picked up, however. In order to cover nine sites, a nine feed array in a square grid is believed to be feasible. Triangular grids, which have advantages of lower overlap loss and a potentially simpler beamforming network, are less well suited to the geometry.

Square elements are preferred to circular because of better polarization alignment and orthogonality and higher efficiency. Thus a 3 x 3 square grid of square elements is the recommended feed structure.

Four mechanically scannable feeds cover each quadrant of CONUS (NE, NW, SE, and SW) to pick up the variable sites. Each such feed needs steering of 2° E-W and 1° N-S. The backup capability could be provided by having overlapping coverage from the four scannable fc , in which case they back each other up, or by designing all nine feeds to ... ıvable, in which case the fixed and mobile site feeds mutually back up one another.

The MBA module shown in Figure 3-12 takes user inputs either directly or via crosslink. These are downconverted with level adjustments under control of a microcomputer and passed at IF to the switch. The switch, discussed in detail in the next section, properly interconnects the inputs to outputs and passes its outputs to an upconverter bank and the TWTA's. Each amplified signal is couples to the proper feed line. In the receive direction, the elements signals are diplexed and sent to the forward or crosslink processor.

Weight and power estimates in Figure 3-13 total to 220 lbs, 460 W.

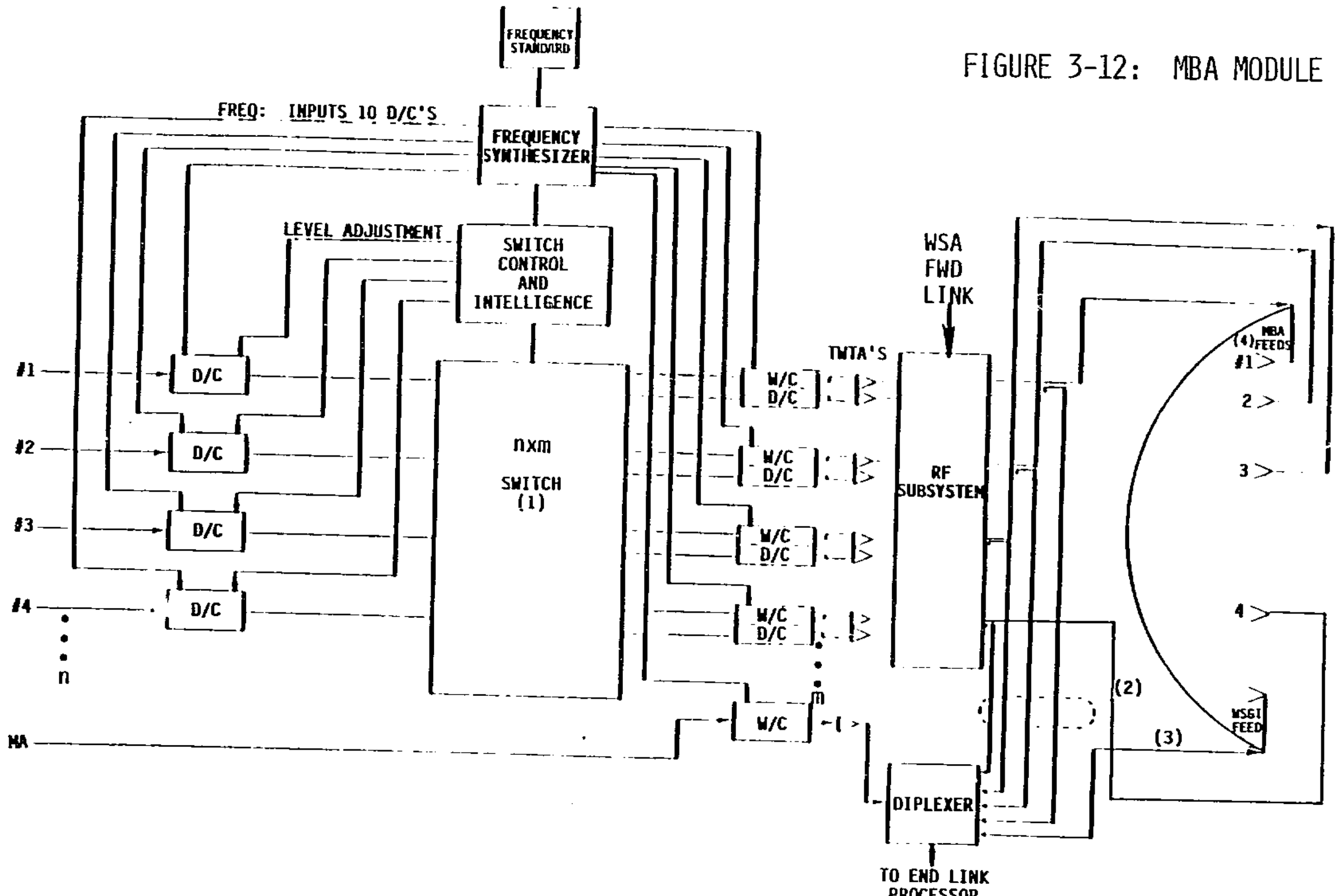
3.3.3 IF Switch

The IF switch shown in Figure 3-13 is a 36-input, 9-output switch. A single two-way switch can be used, or separate unidirectional switches can handle the incoming and outgoing traffic separately. The switch operates at an IF bandwidth of at least 1 GHz.

Four switch architectures were investigated: single pole/multiple throw, rearrangeable switch, fan in/fan out, and coupler crossbar. Figure 3-14 summarizes the findings of the technology study and indicates the preference for the crossbar as the TDAS switch. Its only disadvantages are that there is less isolation between the lines than in the other types, and that couplers that can sustain up to 2.5 GHz bandwidth require development.

The coupler crossbar arrangement is shown in Figure 3-15. It provides switching of N TDAS signals to M MBA beams (switching of M uplink signals to N TDAS outputs in the case of a 2-way switch). The crossbar architecture has input and output transmission lines forming a matrix with N x M

FIGURE 3-12: MBA MODULE



NOTES:
(1) THE SWITCH IS NOT RESTRICTED TO 4x4 (nxm SWITCH CAN BE IMPLEMENTED; n>4, m > 5).
(2) PROVIDES WSGT KNOWLEDGE THAT VARIOUS CONUS LOCATIONS ARE RECEIVING DATA.
(3) ABILITY TO SWITCH WSGT TO OTHER FEED IN CASE OF FAILURE IS NOT SHOWN.
(4) MOVEABLE FEEDS NOT SHOWN.

ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 3-13: WEIGHT/POWER BREAKDOWN — MBA MODULE AND IF SWITCH

SUBSYSTEM	WEIGHT (LBS)	POWER (W)
ANTENNA SUBSYSTEM (INC: FEEDS, REFLECTORS & SUPPORTS)	70	-
RF SUBSYSTEMS	15	-
TWTA'S	60	400
UPCONVERTERS	35	30
SWITCH AND SWITCH CONTROL-INTELLIGENCE	15	10
DOWNCONVERTERS	15	10
MISC:	10	10
TOTAL	220	460

FIGURE 3-14: ALTERNATE SWITCH MATRIX ARCHITECTURES

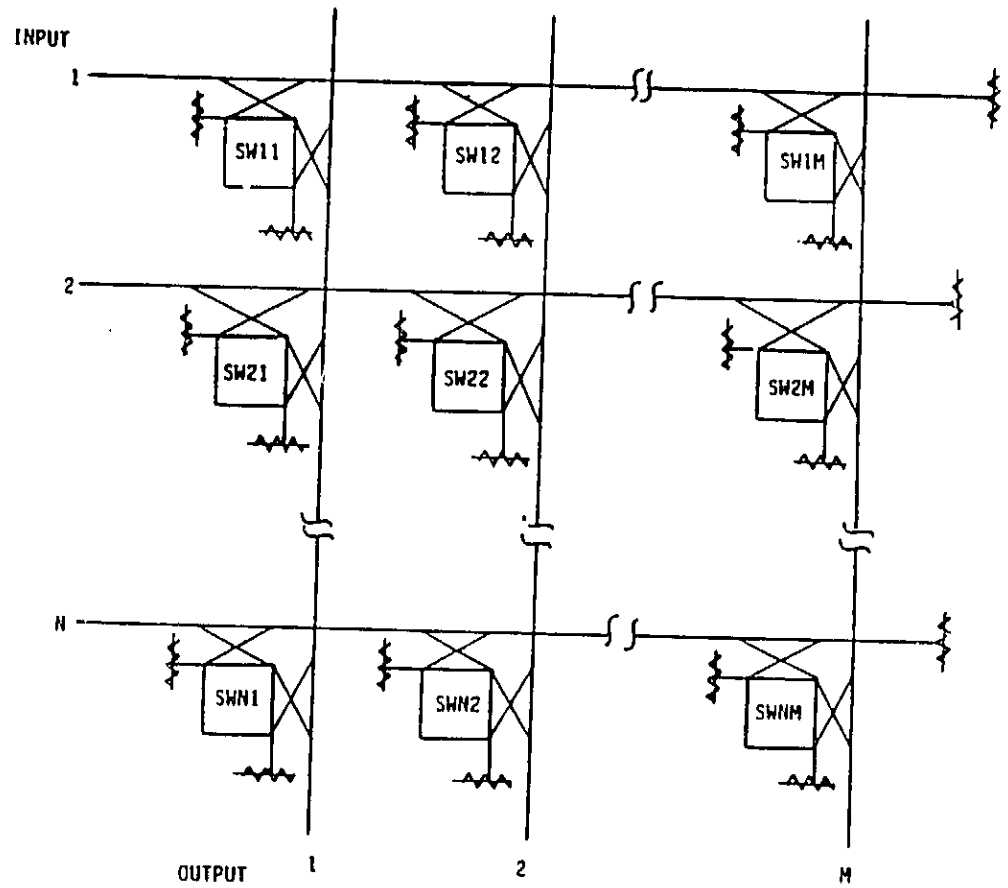
TYPE	ADVANTAGES	DISADVANTAGES
SINGLE POLE MULTIPLE THROW	LOW INSERTION LOSS	POOR RELIABILITY
REARRANGEABLE SWITCH	LOW INSERTION LOSS LESS SWITCHES NEEDED	POOR RELIABILITY CONTROL ALGORITHM COMPLICATED
FAN OUT/FAN IN	RELIABLE	HIGH INSERTION LOSS HIGH INPUT VSWR
COUPLER CROSS/BAR*	COMPACT RELIABLE LOW INSERTION LOSS POSSIBLE LOW VSWR LEAST SIZE/WEIGHT	LOW ISOLATION BROADBAND (≃ 2.5 GHZ) COUPLERS REQUIRE DEVELOPMENT

* PREFERRED CHOICE.

REF: SPACECRAFT IF SWITCH MATRIX FOR WIDEBAND SERVICE APPLICATIONS IN 30/20 GHZ COMMUNICATION SATELLITE SYSTEMS.
INTERIM TASK I REPORT: CONTRACT NO. NAS3-22501 NAS/LEWIS RESEARCH CENTER.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-15: COUPLER CROSSBAR SWITCH



crosspoints. At each crosspoint there is one appropriate switching device for 1-way/2-way design. For example, a dual gate GaAs MOSFET switching device provides gain and at the same time performs switching. If the switch is closed at a crosspoint, the coupled signal is amplified and directionally coupled to the corresponding output transmission link. If the switch is open, the signal is reflected into the load at the other end of the first coupler and is not coupled to the output link. The coupling coefficients of input and output couplers are adjusted such that the power at the input to the dual gate MOSFET is constant for all crosspoints. Because of this adjustment, the power at the output ports of the matrix is also constant, and the insertion loss of the matrix is constant and independent of the connection path. A signal on the input line can be simultaneously connected to any number of output lines with no change in the output power level. At each crosspoint, the amount of IF power extracted from the input and transmitted to the switching element is independent of switch status (ON or OFF). When ON, the signal is amplified and transferred to output coupler; when OFF, power is dissipated into the termination of the first coupler and no power is transferred to the output coupler.

The crosspoint design differs according to whether the switch is one- or two-way. The basic one-way design shown in Figure 3-16 functions according to the above description. Its modification for two-way operation is shown in Figure 3-17. The input/output couplers and the amp/switches are replicated on both arms to make the crosspoint I/O symmetric.

For either one-or two-way operation, the crossbar coupler is the implementation choice. The two-way switch appears to be feasible; a compact microminiaturized integrated circuit design using dual gate GaAs MOSFET switching elements may prove to be most suitable.

The weight and power estimate for the switch, 15 lbs and 10 W, was included in the MBA summary (Figure 3-13).

FIGURE 3-16: ONE-WAY CROSSPOINT DESIGN

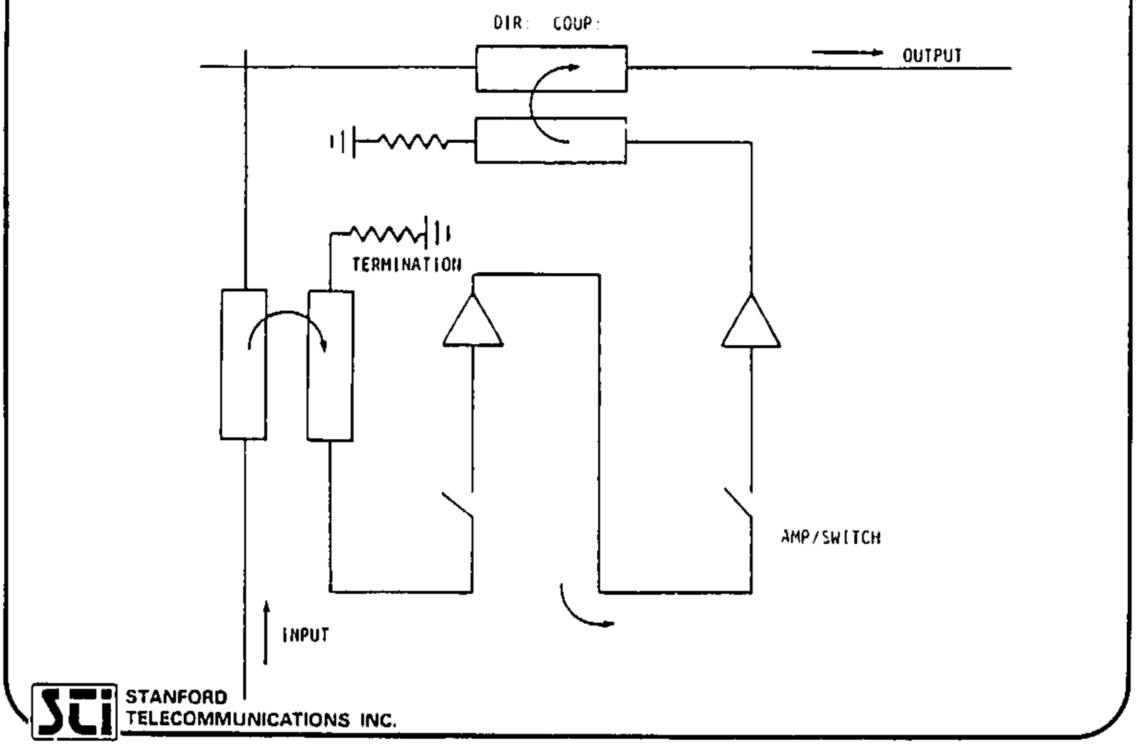
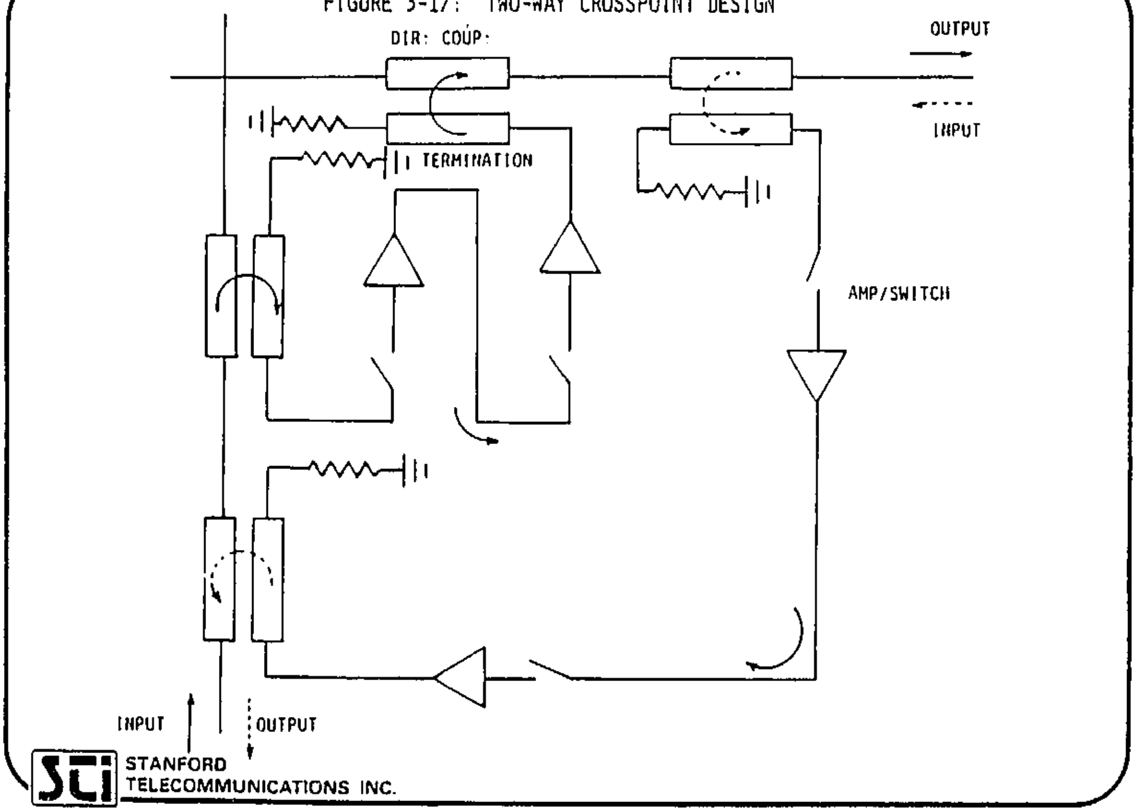


FIGURE 3-17: TWO-WAY CROSSPOINT DESIGN



3.3.4 W-Band Single Access (WSA)

The W-band single access service has the requirements shown in Figure 3-18. These can be met in a configuration such as that shown in Figure 3-19. Each of the five WSA antennas is diplexed and is controlled by an antenna pointing and control system (APCS). On the receive side, each signal is filtered, amplified, downconverted and amplified. The signals are FDM'ed at IF and presented to the MUX at the IF switch input where the other services going to a particular destination (ground terminal or crosslink) are multiplexed in.

In the forward direction, IF from the crosslink or uplink is demuxed, switched, upconverted, and RF amplified. This signal enters the antenna via the diplexer.

Four antenna candidates were investigated: gimballed parabolic, gimballed parabolic with scannable subreflector, phased array, and parabolic with phased array feed. Examing the relevant capabilities of each alternative in Figure 3-20 shows that the fixed feed gimballed parabolic antenna is superior to the other alternatives in all respects except acquisition/tracking power requirement and torque noise. It is believed to be the choice most likely to satisfy the requirements with minimal complexity and risk.

Antenna control and pointing can be executed either at the TDAS central onboard computer (OBC) or by dedicated processors physically adjacent to the antenna they control. In comparing the two approaches, we could find no evidence that centralized processing has any benefits to offer. As Figure 3-21 makes clear, the central processor may be unavailable or unable to respond in a timely manner when needed for a real-time computation or there may be conflicting demands from the set of antennas. Full prelaunch checkout is much more difficult for a multipurpose computer than a small special purpose one. Thus the APCS's shown in Figure 3-19 are necessarily dedicated units installed near the antenna.

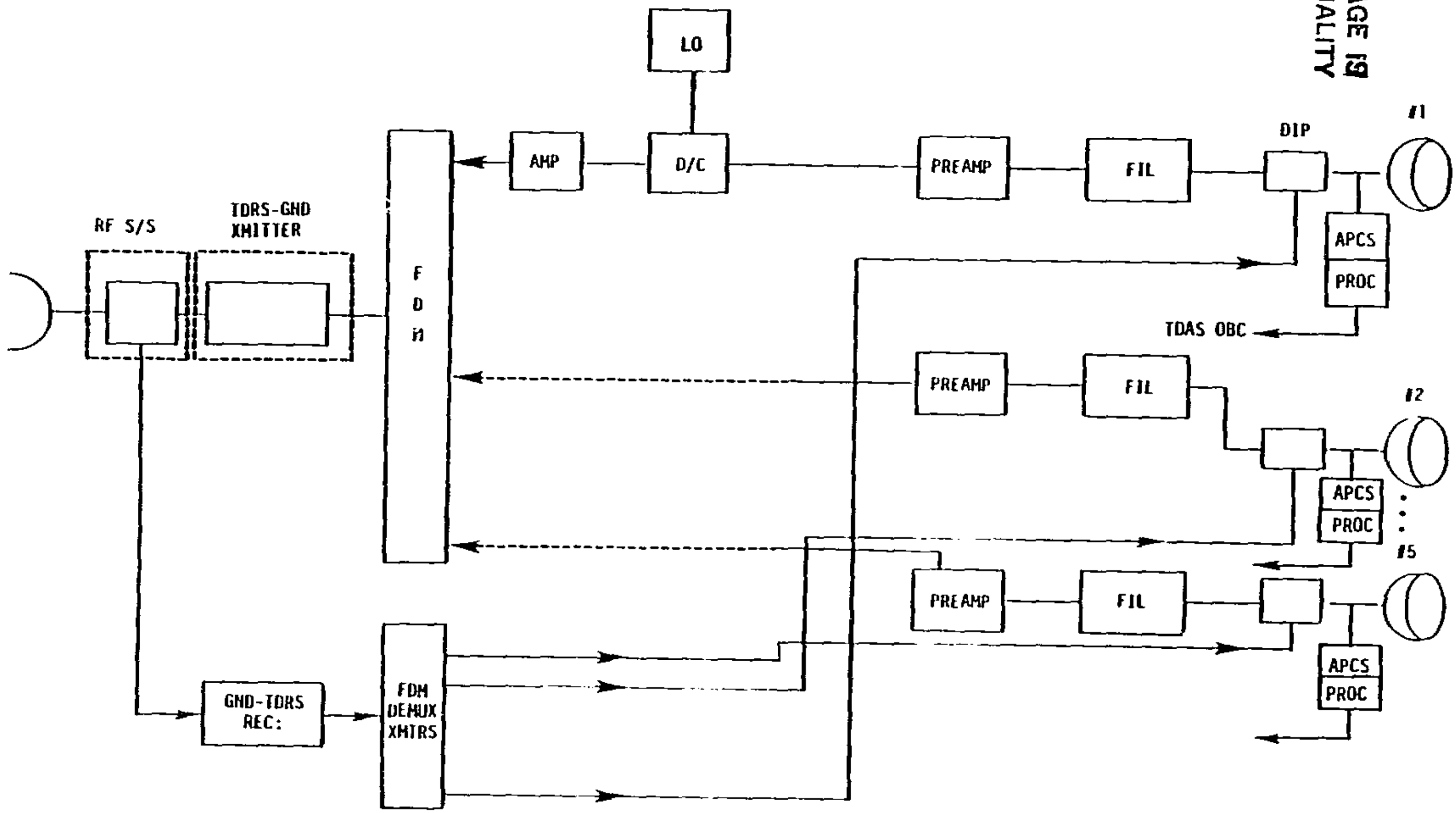
FIGURE 3-18: DISCRETE ANTENNA WSA MODULE REQUIREMENTS FOR TDAS

FREQUENCY	60 GHZ
COMMUNICATION LINKS	TDRS-TO-USER S/C USER S/C-TO-TDRS
USER ACCOMODATION	5 RETURN } PER S/C 5 FORWARD }

STANFORD
TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 3-19: FUNCTIONAL BLOCK DIAGRAM - WSA MODULE



APCS: ANT: POINTING AND CONTROL SYSTEM
PROC: PROCESSOR
OBC: ON-BOARD COMPUTER

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-20: WSA ANTENNA DESIGN ALTERNATIVES

TYPE	GAIN	DATA RATE CAPABILITY	ACQ/TRK POWER REQMT	TORQUE NOISE	POINTING ACC.	COMPLEXITY	RELIABILITY
GIMBALLED PARABOLIC*	HIGH	HIGH	HIGH	HIGH	HIGH	LOW	HIGH
GIMBALLED PARABOLIC WITH SCANNABLE SUBREFLECTOR	LOW	LOW	MED	LOW	LOW	HIGH	LOW
PHASED ARRAY	LOW	LOW	LOW	NEGLIGIBLE	MED	HIGH	LOW
PARABOLIC WITH PHASED ARRAY FEED	LOW	LOW	LOW	NONE	MED	MED	MED

* PREFERRED CHOICE: IS OPTIMUM FOR SATISFYING REQUIREMENTS WITH LEAST COMPLEXITY AND RISK.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-21: APCS PROCESSOR ALTERNATIVES

TYPE	ADVANTAGES (+1)/DISADVANTAGES (-)
CENTRAL PROC. (TDAS OBC)	- HANDLES OTHER S/C FUNCTIONS AND PROC. MAY NOT BE AVAILABLE WHEN NEEDED BY APC'S
	- PROC. MAY BE OVERBURDENED WHEN ALL FIVE APCS FUNCTIONS ARE INCLUDED
	- DEMANDS PLACED UPON PROC. BY APC'S MAY CONFLICT
	- CHECKING OUT ALL PROC. FUNCTIONS EARLY IN DESIGN PHASE NOT POSSIBLE
DEDICATED PROC.*	+ PROVIDES AUTONOMOUS PROCESSING FOR EACH APCS
	+ HIGH PROCESSING SPEED AVAILABLE FOR FREQUENT ANTENNA POSITION UPDATES
	+ APCS PROC. FUNCTIONS CAN BE CHECKED OUT EARLY IN DESIGN PHASE

* DEDICATED PROCESSORS APPEAR NECESSARY.

STANFORD TELECOMMUNICATIONS INC.

A weight/power breakdown for the ASP is shown in Figure 3-22. This data is taken from Volume VII of the report.

The APCS must be augmented by an autotracker that provides data inputs from from which pointing updates are periodically calculated. Because of the narrower beamwidths attainable at 60 GHz, the autotracking problem is somewhat different than for TDRSS, and has been examined in some detail.

<u>60 GHz Autotracking</u>

The objective of the 60 GHz autotrack study was to assess acquisition performance at 60 GHz, its impact on the user's system, the potential risks, and the tradeoffs that would ameliorate those risks. Of particular interest is the comparison with the TDRSS 15 GHz autotrack function.

Acquisition is the process whereby the TDAS antenna initially points at the user spacecraft. Autotracking is the maintenance of that pointing during relative motion of the two vehicles.

Figure 3-23 illustrates the fundamental acquisition problem. The user satellite position will be known by TDAS to within some initial uncertainty. For the TDRSS and TDAS K-band system, the angular uncertainty of the user as viewed from the relay spacecraft exceeds the 3 dB beamwidth of the single access antenna. A spatial search is required to initially point at the user spacecraft.

Requirements have been assigned to the autotrack process based on the TDRSS K-band autotrack. When the TDAS W-band service meets these requirements, summarized in Figure 3-24, its performance will be equivalent to TDRSS K-band autotracking.

Acquisition begins with TDAS attempting to acquire a signal of specified power and bandwidth radiated by the user. Both antennas are initially open loop pointed based on common user position data. In the analysis it is assumed that the resulting pointing errors (due to uncertainty in relative position) are equal at each antenna.

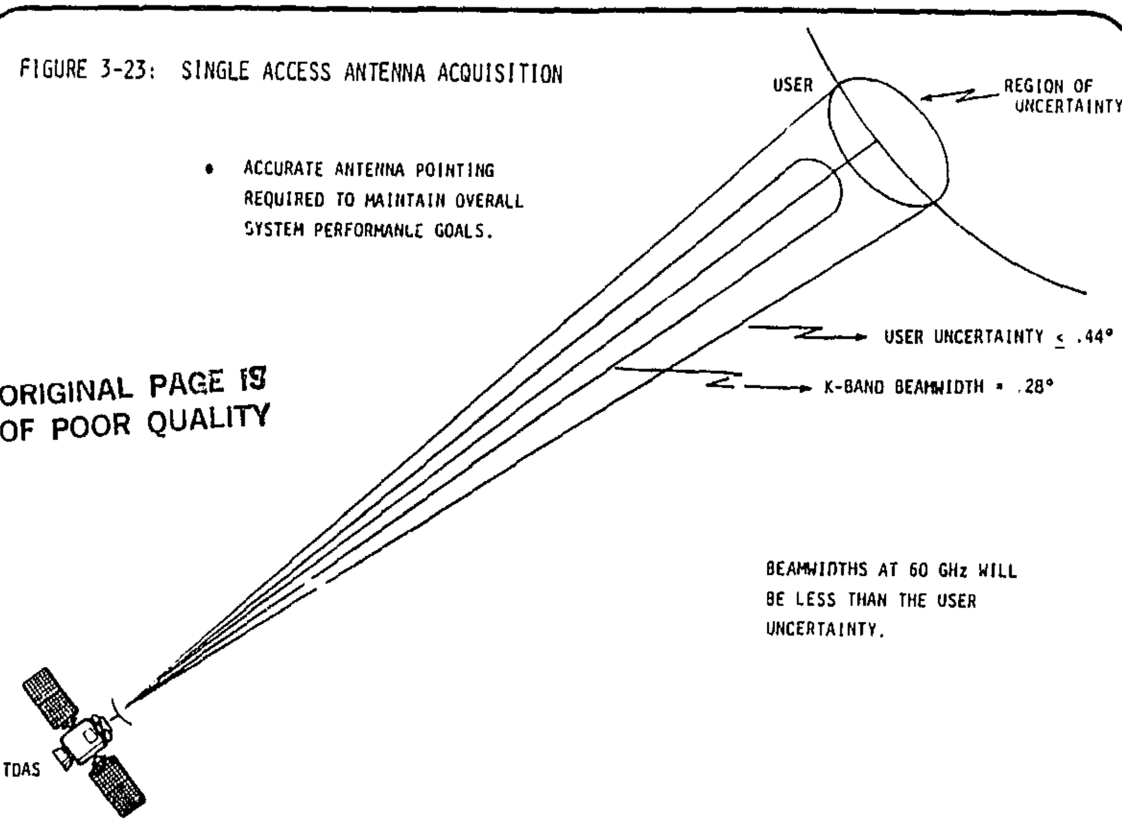
FIGURE 3-22: WEIGHT/POWER BREAKDOWN — DISCRETE ANTENNA WSA (5 1-M WSA's)

SUBSYSTEM	WEIGHT(LBS)	POWER(W)
RF S/S	4	--
TDRS-GND-TRANSMITTER	10	15
FDM-DC	75	25
FRONT-END ASSEMBLY	36	12
GND-TO-TDRS RECEIVER	10	18
FDM DEMUX	5	3
POWER AMP: ASSEMBLY	25	60
DISHES (5)	120	--
GIMBAL ASSEMBLIES (5)	180	60
MISCELLANEOUS	35	17
TOTAL:	500	210

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-23: SINGLE ACCESS ANTENNA ACQUISITION

- ACCURATE ANTENNA POINTING REQUIRED TO MAINTAIN OVERALL SYSTEM PERFORMANCE GOALS.



BEAMWIDTHS AT 60 GHz WILL BE LESS THAN THE USER UNCERTAINTY.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-24: REQUIREMENTS FOR W-BAND AUTOTRACK SIGNAL DETECTION PERFORMANCE

- BOTH ENERGY DETECTOR AND AUTOTRACK SIGNAL DETECTOR YIELD A SIGNAL PRESENCE OR ABSENCE INDICATION EVERY $\frac{1}{2}$ SECOND.
- THE PROBABILITY THAT ONE OF THE DETECTORS INDICATES A FALSE ALARM DURING A 15 MINUTE PERIOD IS LESS THAN .005.
- THE PROBABILITY THAT ONE OF THE DETECTORS INDICATES A FALSE DISMISSAL FOR ANY $\frac{1}{2}$ SECOND INDICATION IS LESS THAN .01.

TDAS ANTENNA ACQUISITION PERFORMANCE AT 60 GHz WILL BE EQUIVALENT TO TDRSS ANTENNA ACQUISITION PERFORMANCE AT 15 GHz.

STANFORD TELECOMMUNICATIONS INC.

The proposed autotrack sequence, again based on the TDRSS procedure, is shown in Figure 3-25. The TDAS antenna begins a search of the user position uncertainty volume. One branch of the receiver samples integrated energy in the attempt to detect signal presence. When signal is detected, the antenna is slewed at a constant rate toward the direction of the user. Direction is determined from the sign bit in the receiver's error channel. When the error becomes small enough, the closure rate is decreased; slewing is disabled when the error crosses through zero, and tracking mode is entered.

During acquisition there will be signal loss due to offpointing of both antennas. Minimization of this loss by selection of the two antenna apertures is desirable, as long as it does not impose any other unreasonable constraints on the antenna design. Design values for the TDAS and user antenna sizes were obtained by looking at the worst case total pointing error that arises when each antenna is offpointed by the maximum user uncertainty (0.22° for TDRSS).

The product of the two antenna diameters is constrained to take on a value that equalizes the TDRSS 15 GHz link and the new 60 GHz link under the assumption of equal transmit power in the two cases. Thus as the TDAS antenna diameter increases, the user diameter decreases, and vice versa. A large diameter antenna will have high directivity, i.e. mainbeam gain, but will lose gain rapidly at offsets because of its narrow beamwidth. The small aperture antenna has low directivity but less sensitivity to offpointing.

Figure 3-26 summarizes the tradeoff of TDAS vs user aperture. The optimum sizing to minimize pointing loss under worst case offset occurs at the minimum of the curve, where both antennas have 0.93 m diameter and 4.37 dB pointing loss (8.74 dB total loss). A nearby point is taken as the design choice (TDAS antenna 1.0 m, user 0.87 m) at which the total loss is only 0.1 dB above minimum. By comparison, the TDRSS 15 GHz service, to which the above has been equated, has 4.9 m dishes on TDRS and 0.7 m at the user. Handled in this manner, the introduction of a 60 GHz SA service does not greatly change the user requirements.

FIGURE 3-25: WSA ANTENNA ACQUISITION SEQUENCE

1. OPEN-LOOP POINTING USING USER POSITION DATA - SIGNAL DETECTION PROCESSES INITIATED.

2. SIGNAL PRESENCE DECLARED - CLOSED-LOOP DIRECTION CONTROL AT A FIXED CLOSURE RATE (.02°/SEC) USING THE SIGN OF THE ERROR SIGNAL.

3. MAIN BEAM SIGNAL PRESENCE INDICATED:

   - INTEGRATION TIMES REDUCED TO $\frac{1}{2}$ SEC.
   - BEGIN CHECKING MAGNITUDE OF ERROR SIGNAL.

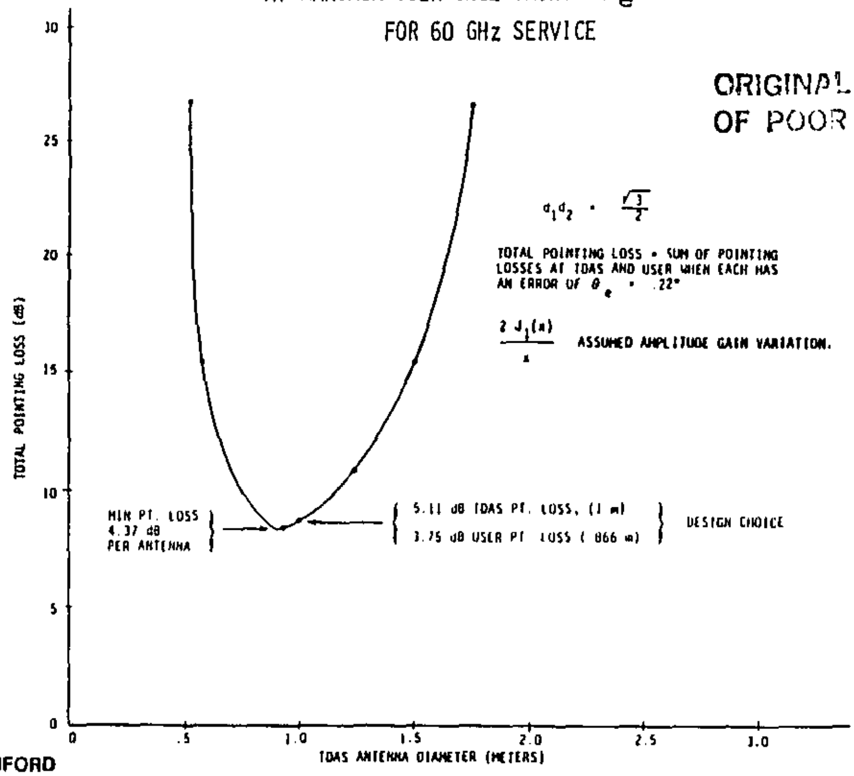
4. ANGULAR CLOSURE RATE REDUCED (TO .003°/SEC) WHEN ERROR SIGNAL IS .075°.

5. ANGULAR CLOSURE RATE REDUCED TO 0 AND FINE POINTING CONTROL INITIATED WHEN ERROR SIGNAL CHANGES SIGN (TRACKING MODE).

THE STEPS AND THE QUANTITIES ARE BASED ON ANTENNA ACQUISITION AT 15 GHz FOR TDRSS.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-26: TOTAL POINTING LOSS VS TDAS ANTENNA DIAMETER AT MAXIMUM USER UNCERTAINTY (θ_e = .22°) FOR 60 GHz SERVICE



STANFORD TELECOMMUNICATIONS INC.

FIGURE 3-27: POINTING LOSS VS POINTING ERROR

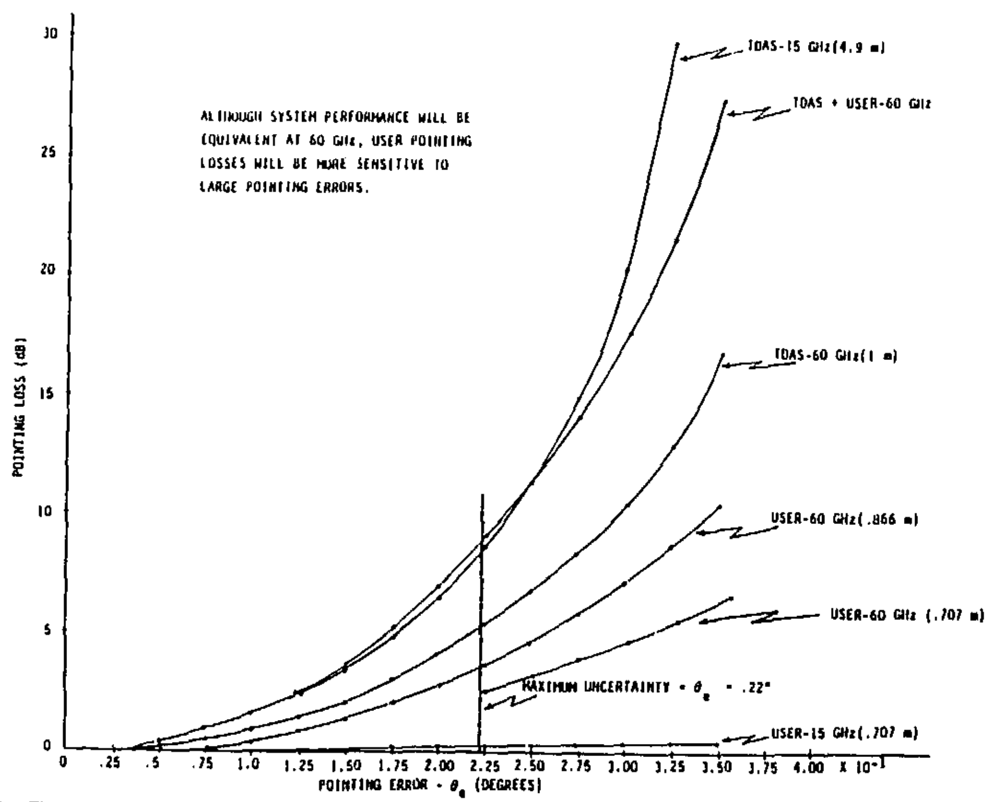


Figure 3-27 shows the total pointing loss as a function of error for several cases. One can see from the curve that in TDRSS, the pointing loss is almost entirely the result of the TDRS SA antenna, whereas for the TDAS result just calculated, the errors are fairly evenly split between TDAS and user. This is to be expected because of the disparity in antenna sizes in the former case that is not present in the latter.

The autotrack function imposes user EIRP requirements in addition to those arising from data transmission. Figures 3-28 and 3-29 show user EIRP vs bit rate (bandwidth) at 15 and 60 GHz, respectively. In both cases autotrack is the more stringent requirement at low bandwidths, where data signal power can be low. The crossover point is between 10^5 and 10^6 HZ in each case.

The autotrack EIRP requirement is about 14 dB greater at W-band than K-band. The increase in gain going from 0.7 m at K-band to 0.87 m at W-band is 13.8 dB, indicating that the user power requirements are not increased by the proposed W-band autotrack.

The user pointing loss of 3.8 dB can be decreased slightly by reducing the TDAS system noise figure. Figure 3-30 shows the magnitude of the effect. Starting with our nominal design, a decrease in noise figure permits the user to decrease his antenna size and consequently his maximum pointing loss. A 3 dB decrease to about 500°K gains back 2 dB pointing loss. Further decrease of the noise temperature engenders technological risk and provides increasingly limited improvement.

In TDRSS, user signal detection and error-signal estimation is performed at the ground station. The tracking error signal is downlinked as a low-index AM component that is extracted at the ground station. A calibration loop is included in the extraction to normalize out channel effects.

Incidental AM on the downlink can be an appreciable error source in the tracking data. For TDAS we propose to avoid this by doing all signal

FIGURE 3-28: USER EIRP REQUIREMENTS - 15 GHz
VS
BIT RATE OR MEASUREMENT BANDWIDTH

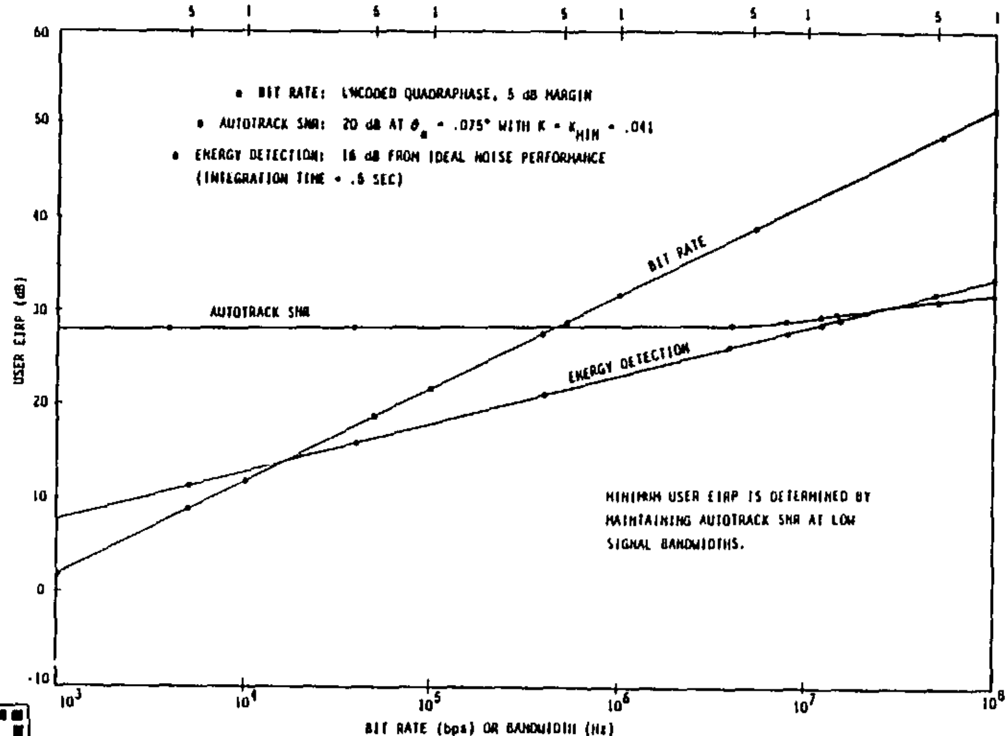
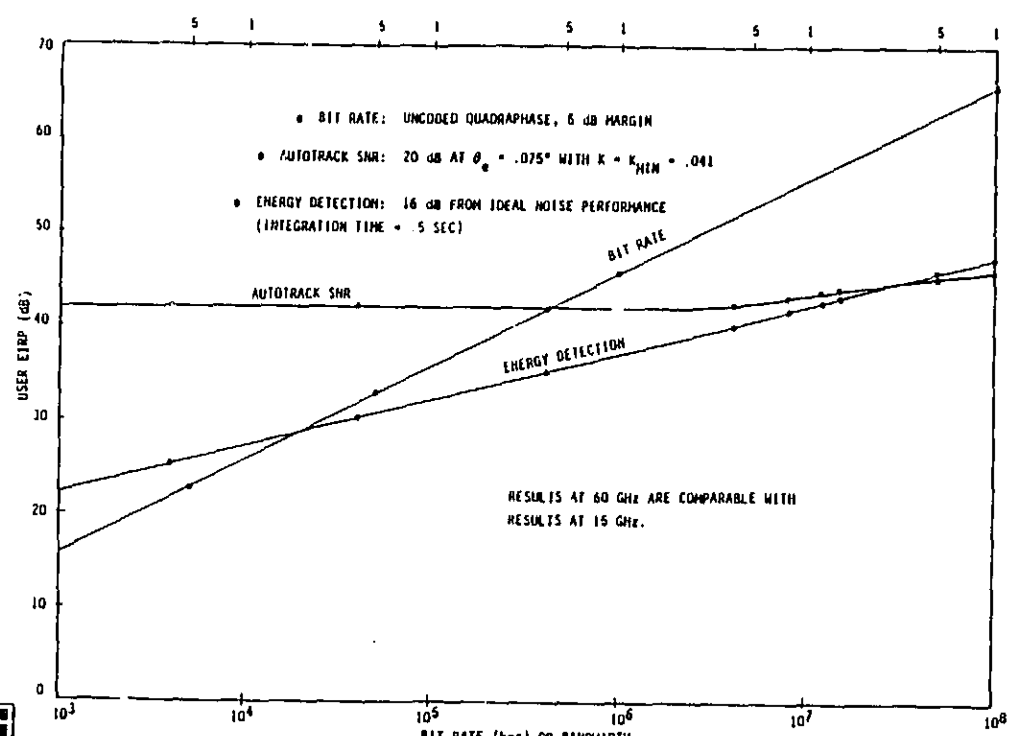
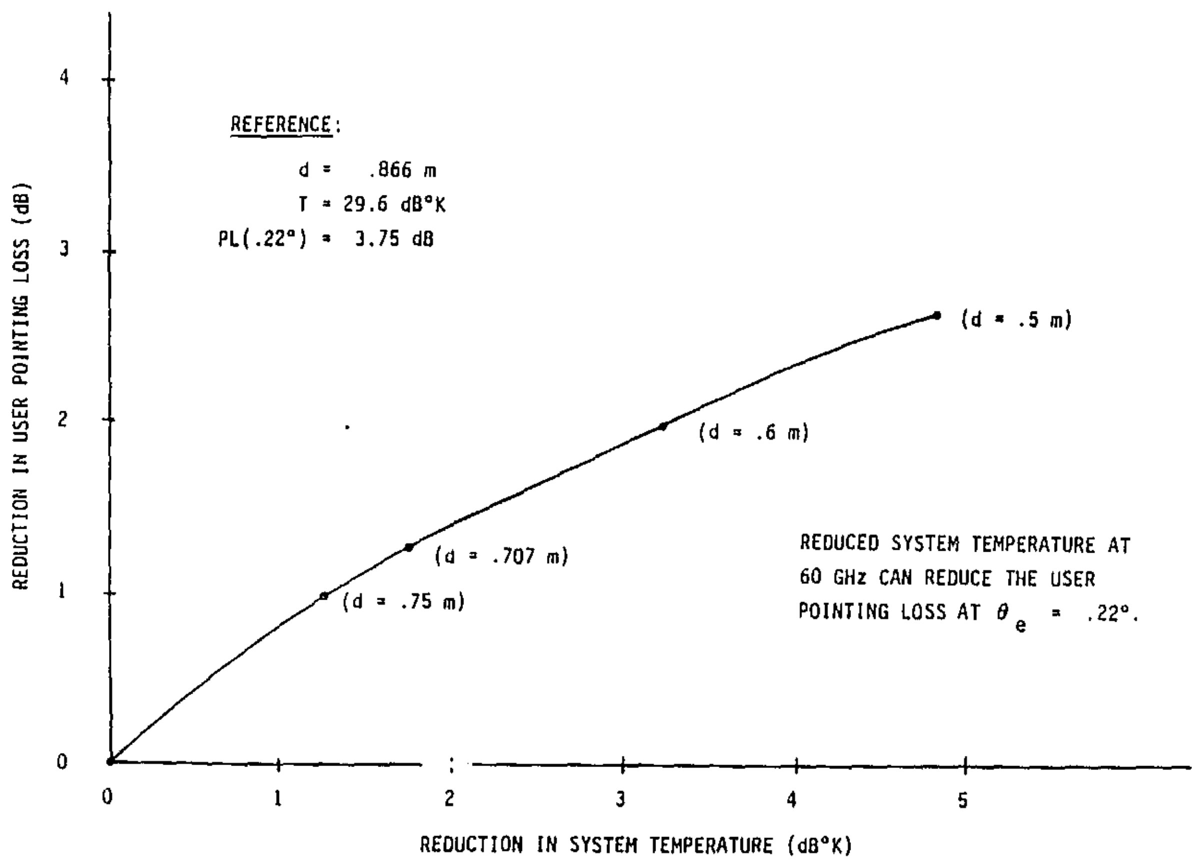


FIGURE 3-29: USER EIRP REQUIREMENTS - 60 GHz
VS
BIT RATE OR MEASUREMENT BANDWIDTH



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 3-30: USER POINTING LOSS
VS
TDAS SYSTEM TEMPERATURE
60 GHz SERVICE



STANFORD
TELECOMMUNICATIONS INC.

detection and error estimation onboard the spacecraft. Tracking data is extracted within the dedicated ACPS and control commands are issued locally. No round trip delays or additional error sources need be involved.

We conclude the 60 GHz acquisition discussion by summarizing the important findings:

- Antenna acquisition performance at 60 GHz in terms of user EIRP and time to acquire will be equivalent to the performance at 15 GHz:

    - Energy detection will achieve required detection performance goals at operational levels of user EIRP and expected user uncertainty.

    - A minimum user EIRP of 42-44 dB will be required to initiate (and maintain) high accuracy antenna tracking at 60 GHz.

- User antenna pointing requirements are more stringent at 60 GHz than at 15 GHz; beamwidths are reduced by a factor of 4 and user pointing losses are more sensitive to large pointing errors. This will result in an operational impact rather than affecting user equipment complexity, i.e., in TDAS there will be more reacquisition attempts when uncertainty in user position data exceeds specified bounds.

- Increasing the TDAS antenna diameter beyond 1 meter to ameliorate user sensitivity at 60 GHz results in appreciable system pointing losses for the expected maximum user uncertainty (16 dB at 1.5 m vs 9 dB at 1 m) and is therefore discouraged.

- Decreasing TDAS system noise temperature at 60 GHz can reduce user pointing loss (at the maximum expected user uncertainty) by 1 or 2 dB.

- Signal-detection and error-signal estimation processing functions can be performed onboard the TDAS spacecraft rather than on the ground. This eliminates the need to calibrate and derive the error-signals from small-index AM modulated signals with their attendant sensitivity to incodental AM.

3.3.5 <u>Laser Single Access (LSA)</u>

The laser single access (LSA) service accommodates high data rate (300 Mbps - 1 Gbps) users, all of whom are as of this writing non-NASA users. In discussing this service we rely heavily upon the laser technology material found in Volume VII of this report and the crosslink discussion of this volume (Chapter 6). Recall from the summary (Chapter 2) that the baseline candidate for a TDAS crosslink is a GaAs laser system used in a coherent transponding mode with a heterodyne detection receiver. An alternate is also given, which is a 60 GHz crosslink. In conjunction with the baseline system there are symbiotic reasons to prefer a GaAs LSA, but with 60 GHz there are no external forcing functions (other than the Deep Space link service, which is discussed in Paragraph 3.3.6). Thus we will first cover the possibilities for a GaAs link, but will then look at the other laser technologies as well. The discussion is brief to avoid needless replication of the material in Volume VII.

3.3.5.1 <u>GaAs LSA</u>. Solid state lasers of GaAs compounds (e.g., GaAlAs) are small, lightweight and low in power consumption. They are readily modulated in arbitrary fashion — analog or digital, pulsed or full duty factor — at data rates well beyond 1 GHz. These features make GaAs an attractive candidate for many space applications.

There are outstanding technical issues about GaAs lasers, but there is little doubt that the many current efforts in GaAs lasers will yield solutions to these. Power generation to meet high data rate needs is an issue, but recently numerous sources have been reporting optical outputs from single chip devices in the several hundred milliwatt region. Coherent combining of disjoint devices is being pursued as another solution.

Specific modulation formats for GaAs LSA have not been addressed in this study. There is an important distinction between two applicable classes of modulations; there are those that can be supported by a direct detection receiver and those that require heterodyne detection. This distinction basically corresponds to modulations that require a local coherent phase or frequency reference (e.g., MPSK or MFSK) vs those that do not. Coherent modulation can result in a considerably more efficient link because it is possible to operate a heterodyne receiver for GaAs very near the theoretical performance limit, known as the quantum limit. The photodetectors in a direct detection receiver (avalanche photodiodes) have an excess noise factor associated with them that keep performance some 10 dB from the quantum limit.

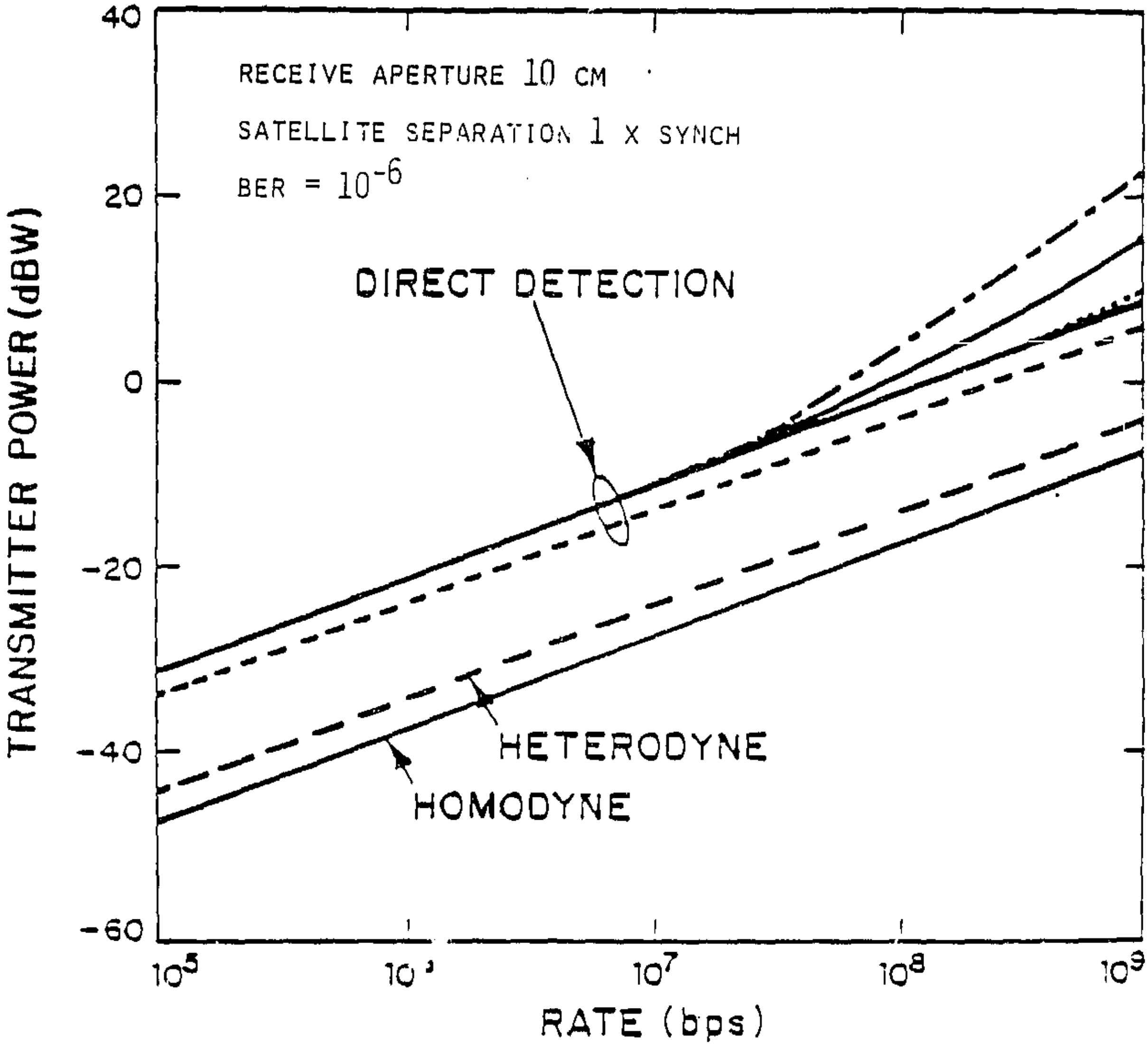
For the near term, modulation that requires phase tracking (PSK or coherently demodulated FSK) is probably not feasible for the LSA, because the received signal level will not support phase tracking, even for data rates as high as 1 Gbps. This is a result of the broad line width of the GaAs laser, on the order of a few MHz, which necessitates a very wideband tracking loop. Although future developments that narrow line widths could ameliorate the problem, a better near term approach is to use frequency tracking, whose requirements are much less stringent, with modulation such as noncoherent MFSK. Large alphabet MFSK is quite efficient and does not require a coherent phase reference from symbol to symbol. For a direct detection system, PPM, possibly combined with polarization modulation, is the only apparent choice.

Figure 3-31* shows performance curves for both cases, and homodyne detection (baseband heterodyne) as well. Heterodyne is seen to have a 10 dB advantage over a direct detection system over a wide range of data rates. Homodyne is 3 dB better than heterodyne because of the recov 'y of both sidebands in going to baseband.

---

* Taken from F.W. Floyd, Space Data Relay Networks, M.I.T. Lincoln Laboratory Technical Report 572, 3 December 1981, Lexington, MA.

FIGURE 3-31: DATA RATE VS LASER TRANSMITTER OUTPUT POWER FOR DIRECT DETECTION, HETERODYNE AND HOMODYNE DETECTION TECHNIQUES



STANFORD TELECOMMUNICATIONS INC.

The advantages of heterodyne detection must be weighed against features that tend to offset them. A heterodyne receiver is more complex in having a local oscillator and a phase tracking loop, neither of which is present in direct detection. But because the baseline crosslink system uses heterodyne, there is potential savings. The laser receiver that accepts the crosslink signal in a front side TDAS could be designed so as to be usable for the single access link on a blind side satellite. Of course a second receiver is necessary to accommodate both crosslink and LSA at the front side, but these receivers could be identical or nearly so.

3.3.5.2 Nd:YAG LSA. The frequency doubled Nd:YAG laser has considerable development behind it, and can provide a quite efficient digital link up to 1 Gbps. The technology is fairly mature and is not expected to show drastic improvements in the near term. All the impetus for Nd:YAG lasers has come from Air Force programs, and so much of the argument for or against YAG for TDAS may ultimately revolve around the military's decision whether to use YAG. Should there emerge a number of NASA users with ultra-high data rate requirements, the issue could reopen.

The best developed form of modulation for Nd:YAG is digital pulse quatenary modulation (PQM), which is a combination of binary PPM and binary polarization modulation. No coherent options have been developed because heterodyne detection is not well suited to the 532 nm wavelength and there has been no development of a CW reference oscillator.

3.3.5.3 Other Options. During the investigation of laser crosslink technology, CO_2 lasers were considered. Although they have many attractive features, a major drawback for space applications proves to be laser lifetime. The problem of obtaining more than 1-2 year lifetime is as yet unsolved and is not currently an area of active research. Detector cryogenics and high rate modulators are other technology needs for CO_2. Progress in these areas would have to be shown before CO_2 became a viable condidate for LSA.

3.3.5.4 LSA Weight and Power. Weight and power estimates for a Nd:YAG laser that appear in Volume VII of this report are shown in Figure 3-32. The totals are 170 lbs and 135 W.

3.3.6 Deep Space Communications

The Jet Propulsion Laboratory (JPL) has been researching the possibility of laser communications from deep space probes to replace the RF links that have in the past served this purpose. A direct optical link from deep space to an earth station is subject to adverse propagation effects in the atmosphere: clouds, haze, smog, or any form of aerosol scatters appreciable amounts of radiation; clear air turbulence induces random refractive index variations that spawn scintillation (amplitude variations), tremor disk (phase variations), and image wander (arrival angle variations). A relay system that exoatmospherically intercepts the deep space signal and returns it to earth by RF is free of these problems and in position to benefit from the advantages of optical transmission.

In the JPL concept there is an orbiting relay satellite to intercept the deep space signals. The time frame associated with optically equipped deep space probes is no sooner than the early 1990's, raising the possibility that TDAS could be a prime candidate for the relay. Thus the ability of TDAS to provide that support is at issue here.

JPL has considered a number of possibilities for laser techniques and signal format. In the matter of direct vs heterodyne detection, the preference is for direct detection on the grounds that heterodyne detectors, because of the Gaussian nature of the resulting quantum-limited channel, have a capacity limit of 1.44 bits per detected photon, whereas no such theoretical limit exists for direct detection (background rather than signal-dependent noise becomes the limiting factor). Because of the great distances involved, deep space signals will no doubt be weak at the receiver, and a high capacity per detected photon becomes desirable. Direct detection is further advantageous in that large, nondiffraction limited receiver optics can be used.

FIGURE 3-32: WEIGHT/POWER SUMMARY — LSA MODULE — Nd:YAG LASER

SUBSYSTEM	WEIGHT (LBS)	POWER (W)
TRANSMITTER	50	15
RECEIVER	20	50
ACQ & TRACKING S/S (1)	35x2=70	60
TELESCOPE (1)	10x2=20	
MISC:	10	10
TOTAL	170	135

NOTE: (1) REDUNDANT TELESCOPE AND ACQ & TRK S/S ARE ALSO PROVIDED.

STANFORD
TELECOMMUNICATIONS INC.

A signalling scheme involving high order pulse position modulation (PPM) and Reed-Solomon coding is the most promising alternative that JPL has offered. M-ary PPM with $M = 2^8$ is used to carry an 8-bit word in each transmitted symbol. Because of the low received signal levels and the Poisson process nature of the photon statistics, there is appreciable probability that no photon will be detected in any of the 256 time slots. This constitutes an erasure, the effects of which are overcome by encoding the binary data in the Reed-Solomon Code (8 bits/symbol).

In an experimental laboratory setup, JPL has verified that this system can produce low error rates (10^{-6}) at a data rate equivalent to 2.5 bits per detected photon. For a probe near Jupiter, this translates to 25 Mbps using a 1 W source, 1-meter transmitting optics and a 4.5 m receiver. These data rates at RF are roughly 250 times those achieved at RF by the Voyager spacecraft (100 kbps).

The JPL experiment uses a GaAlAs laser. Because of the rapid increases in achievable output power, it is likely that they will continue to advocate GaAs as the transmit laser. The transmitter (1 W, 1 m) envisioned in the example given above (due to JPL) seems quite reasonable for space applications, but the 4.5 m receive aperture, while conceivable for a future dedicated relay spacecraft, would be a severe burden to TDAS. To put this number in perspective, the Space Telescope optics has a 2.4 m aperture, and the astronomical telescope at the Mount Palomar Observatory measures 5 m. A receiver aperture better suited to TDAS compatibility, for example, a 50 cm lens, would support 300 kbps, and a 1 m could support more than a megabit. Since aperture is largely a technology issue, TDAS can attempt to support whatever is feasible in its era.

To provide this support, each TDAS would require a direct detection receiver. Were the LSA service provided by GaAs with direct detection, a shared resource with scheduled support becomes feasible. The receive electronics would differ if the deep space data were to be demodulated and decoded onboard TDAS. An alternative, one being considered by JPL for their relay spacecraft, is to photodetect the input signal and transmit the photodetector output waveform to ground via RF. In the latter case, one receiver with variable filtering might suffice for both services. Of course, if the LSA service is absent or uses a different laser, then the deep-space package becomes an add-on having no overlap with the other systems.

There also exists the possiblity that the deep space reception could be carried out by the GaAs crosslink receiver, but this would necessitate modifications. A direct detection receiver could be added behind the receiver optics, or perhaps, if a direct detection beacon receiver were used for the crosslink, it could be adapted to the deep space channel. The latter alternative initially seems unlikely since the requirements of the beacon link and the deep space link may differ appreciably.

Scheduling issues arise from shared usage of the deep space and crosslink receivers. Although the crosslink receiver on a blind side TDAS could be devoted to deep space, its visibility to the probe could have diurnal variations. The front side satellite could only support the probe when it had no crosslink to receive, an event that might never occur.

In summary, then, JPL aspires to increase its data rates from deep space by a factor of 100-250 using optical signalling. With today's technology, TDAS could support a factor of 3 to 10 of this increase. A much greater factor may be possible if the technology of large aperture optics for space matures by 1988. The compatibility of this support would be greatly enhanced if the TDAS crosslink, the LSA and the deep space optical system were all to employ GAAs lasers.

SECTION 4

CONSTELLATION AND NETWORKING OPTIONS

The TDAS constellation and the supporting ground network, two of the system's major architectural elements, are so profoundly related that it is almost impossible not to treat them together. The orbital slot of each TDAS dictates the regions of earth and space with which it can communicate; the location of the ground stations then implies the space-to-ground connectivity and says something about the terrestrial links as well.

Many combinations of constellation and network have been considered throughout the course of the study. The results of these considerations can be summarized effectively by grouping the configurations into three options. These options have in common that all satellites are in circular geosynchronous, near-equitorial (±5°) orbit. They are distinguished as follows:

- Option 1: Two S/C (plus spare) in view of CONUS
- Option 2: Two S/C (plus spare), one in view of CONUS and one not, with crosslink
- Option 3: Three S/C (plus spare), two in view of CONUS and one not, with crosslinks.

The spacecraft are in geosynchronous orbit for the same reasons that TDRS is so placed: ease of tracking, attitude control, and scheduling. Orbital inclination up to ±4.5° can provide adequate coverage. Inclinations near 4.5° considerably ease the burden of North-South stationkeeping maneuvers required to sustain low inclinations. The same is true of TDRSS; it was only the original inclusion of the commercial Advanced Westar package, now defunct, that put stringent demands (±0.1°) on the North-South stationkeeping of TDRSS. Without the commercial service, it too could sustain inclinations up to 4.5°.

Figure 4-1 illustrates these options (including suboptions for Options 1 and 3) and their interconnections to ground. The five ground terminal sites shown in the figure refer to Sunnyvale, White Sands, Colorado Springs, Houston, and Greenbelt. The pertinent subsystem enhancements are given for each.

Each option will be discussed in detail, following which some comparative assessments will be made, and a baseline will be selected. Figure 4-2 summarizes the major issues for TDAS Constellation selection.

4.1 OPTION 1: TWO S/C IN VIEW OF CONUS

4.1.1 Option 1A

Perhaps the most logical candidate to begin the investigation is one which most closely resembles TDRSS. In Option 1A (Figure 4-3), the two satellites are placed in the TDRSS orbital slots of 41°W and 171°W (spacing 130°), with a spare around 100°W. Each satellite has a single downlink to White Sands, from which data is distributed to the other four sites via domsat or other means (possibly a fiber optics net in the 1990's).

This option could sustain the enhanced SMA service and the new WSA. Downlink capacity constraints argue against including the LSA.

4.1.2 Option 1B

By pulling the satellites closer to the center of CONUS, it is possible for each to have coverage of the five ground sites. Satellites at 60° W and 140°W (intersatellite spacing 80°) will achieve this (see Figure 4-4). This option trades coverage on the back side for flexibility of downlink data distribution. In addition to the SMA and WSA enhancements, onboard SMA beamforming, the MBA, and the IF switch are required. Because of the multibeam space-to-ground link, the LSA service can be accommodated. Option 1B incorporates five of the six TDAS goals.

Figure 4-1 illustrates these options (including suboptions for Options 1 and 3) and their interconnections to ground. The five ground terminal sites shown in the figure refer to Sunnyvale, White Sands, Colorado Springs, Houston, and Greenbelt. The pertinent subsystem enhancements are given for each.

Each option will be discussed in detail, following which some comparative assessments will be made, and a baseline will be selected. Figure 4-2 summarizes the major issues for TDAS Constellation selection.

4.1 OPTION 1: TWO S/C IN VIEW OF CONUS

4.1.1 Option 1A

Perhaps the most logical candidate to begin the investigation is one which most closely resembles TDRSS. In Option 1A (Figure 4-3), the two satellites are placed in the TDRSS orbital slots of 41°W and 171°W (spacing 130°), with a spare around 100°W. Each satellite has a single downlink to White Sands, from which data is distributed to the other four sites via domsat or other means (possibly a fiber optics net in the 1990's).

This option could sustain the enhanced SMA service and the new WSA. Downlink capacity constraints argue against including the LSA.

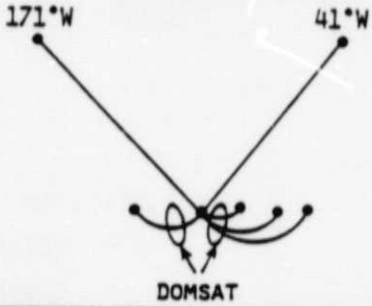
4.1.2 Option 1B

By pulling the satellites closer to the center of CONUS, it is possible for each to have coverage of the five ground sites. Satellites at 60° W and 140°W (intersatellite spacing 80°) will achieve this (see Figure 4-4). This option trades coverage on the back side for flexibility of downlink data distribution. In addition to the SMA and WSA enhancements, onboard SMA beamforming, the MBA, and the IF switch are required. Because of the multibeam space-to-ground link, the LSA service can be accommodated. Option 1B incorporates five of the six TDAS goals.

FIGURE 4-1: TDAS CONSTELLATION/NETWORK OPTIONS

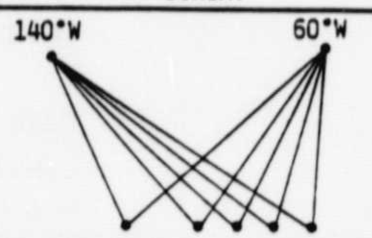
OPTION 1A:

ENHANCEMENTS
SMA
WSA



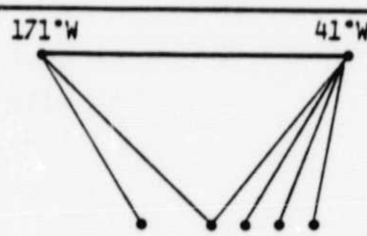
OPTION 1B:

ENHANCEMENTS
SMA
WSA
MBA
LSA



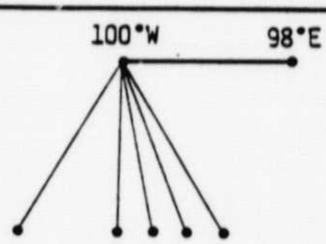
OPTION 1C:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



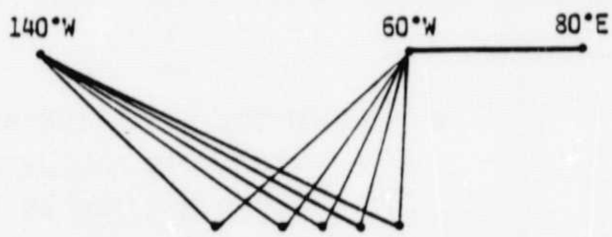
OPTION 2:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



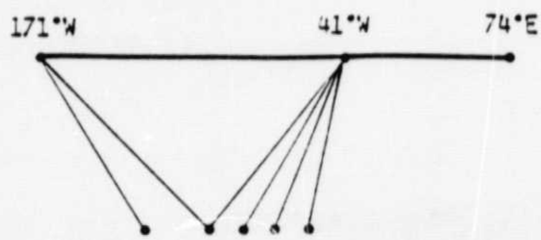
OPTION 3A:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



OPTION 3B:

ENHANCEMENTS
SMA
WSA
MBA
LSA
XL



STANFORD TELECOMMUNICATIONS INC.

FIGURE 4-2: TDAS CONSTELLATION CONSIDERATIONS

- CONUS UP/DOWN LINKS
  - REDUNDANT, DIRECT LINKS TO EAST AND WEST CONUS FROM EITHER FRONT-SIDE SATELLITE REQUIRE A LONGITUDINAL SPACING <80°
  - USER ACCESS TO EAST OR WEST CONUS WITH A LONGITUDE SPACING OF 130°, AS IN TDRSS, REQUIRES A TDAS-TDAS CROSSLINK
- USER COVERAGE
  - WITH TWO TDAS SATELLITES:
    - 85 - 100% FOR 130° LONGITUDE SPACING (BOTH FRONTSIDE)
    - 70 - 95% FOR 80° LONGITUDE SPACING (BOTH FRONTSIDE)
    - 98 - 100% FOR 162° (MAX) SPACING (ONE BACKSIDE)
  - WITH THREE TDAS SATELLITES (ONE BACKSIDE)
    - 100%
- NORTH-SOUTH STATION-KEEPING
  - TO AVOID MANEUVER REQUIREMENTS OVER A 10 YEAR MISSION AN ORBIT INCLINATION > 4.5° AND APPROPRIATE ASCENDING NODE PLACEMENT IS REQUIRED

STANFORD TELECOMMUNICATIONS INC.

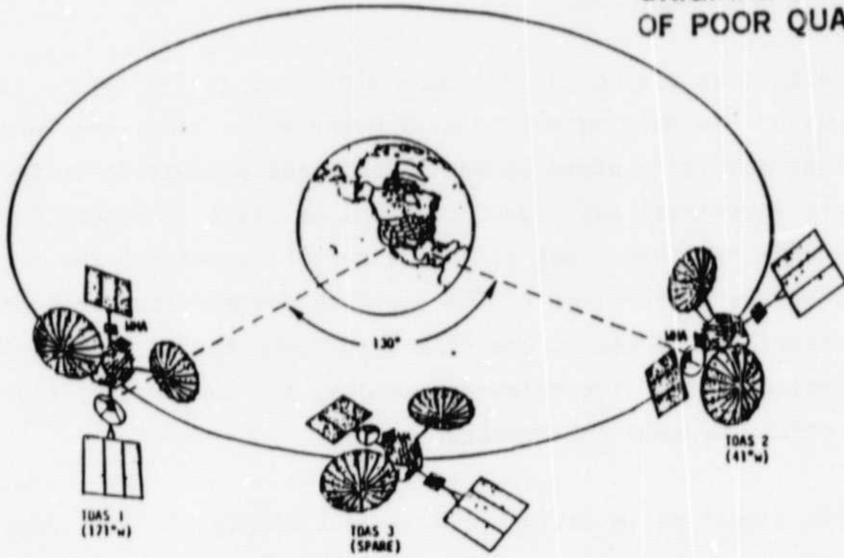
FIGURE 4-2: TDAS CONSTELLATION CONSIDERATIONS

- CONUS UP/DOWN LINKS
  - REDUNDANT, DIRECT LINKS TO EAST AND WEST CONUS FROM EITHER FRONT-SIDE SATELLITE REQUIRE A LONGITUDINAL SPACING <80°
  - USER ACCESS TO EAST OR WEST CONUS WITH A LONGITUDE SPACING OF 130°, AS IN TDRSS, REQUIRES A TDAS-TDAS CROSSLINK
- USER COVERAGE
  - WITH TWO TDAS SATELLITES:
    - -- 85 - 100% FOR 130° LONGITUDE SPACING (BOTH FRONTSIDE)
    - -- 70 - 95% FOR 80° LONGITUDE SPACING (BOTH FRONTSIDE)
    - -- 98 - 100% FOR 162° (MAX) SPACING (ONE BACKSIDE)
  - WITH THREE TDAS SATELLITES (ONE BACKSIDE)
    - -- 100%
- NORTH-SOUTH STATION-KEEPING
  - TO AVOID MANEUVER REQUIREMENTS OVER A 10 YEAR MISSION AN ORBIT INCLINATION > 4.5° AND APPROPRIATE ASCENDING NODE PLACEMENT IS REQUIRED

STANFORD TELECOMMUNICATIONS INC.

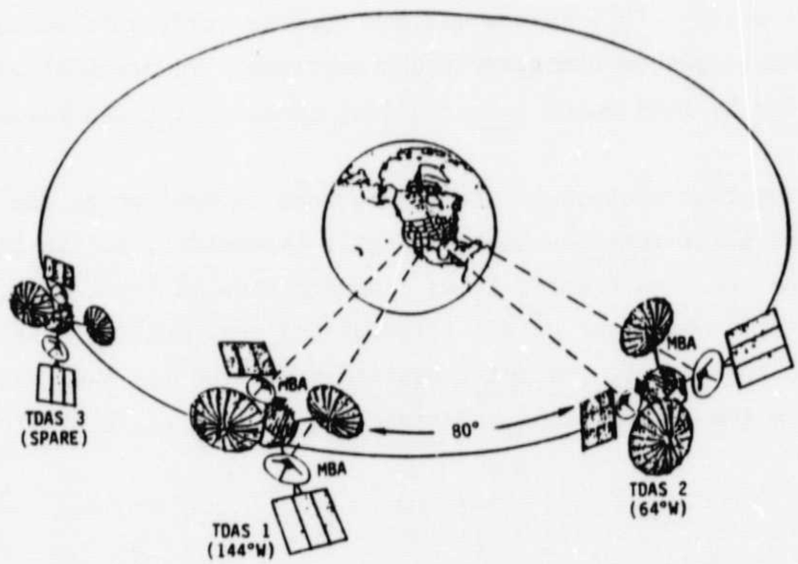
FIGURE 4-3: TDAS CONSTELLATION 1A (ENHANCEMENTS: SMA + WSA)

ORIGINAL PAGE IS
OF POOR QUALITY



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 4-4: TDAS CONSTELLATION 1B (ENHANCEMENTS: SMA, WSA, MBA, LSA)



STANFORD
TELECOMMUNICATIONS INC.

4.1.3 Option 1C

Satellites placed in the TDRSS slots, as in Option 1A, can be netted in many ways. The West satellite will cover White Sands and Sunnyvale, and the East satellite picks up White Sands and everything to the East. By linking the satellites and ground stations as shown in Figure 4-5, the TDRSS coverage is retained. But without a crosslink between the two TDAS's, scheduling would be constrained by the space-to-ground link arrangement, with each USAT restricted to use of the TDAS that connected to its mission control center. Emplacement of the crosslink removes all such restrictions and allows this option the same enhancements as 1B.

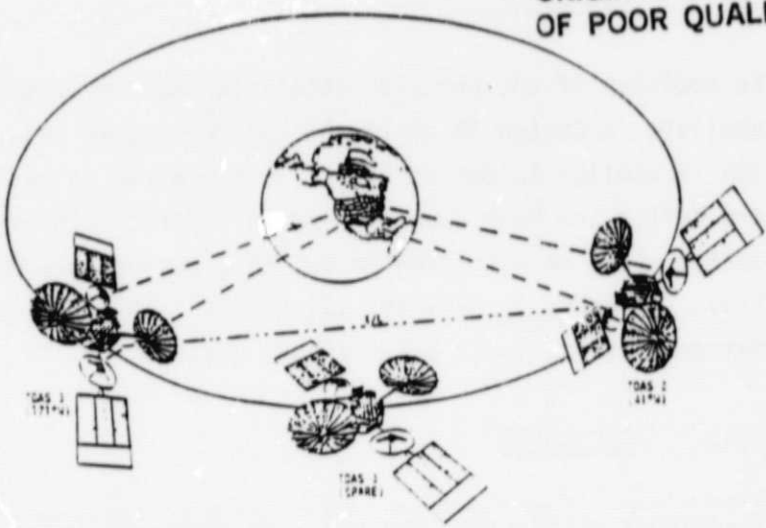
The crosslink in Option 1C must be a bilateral, high capacity link. LSA return traffic, for example, could flow either way on the link. The forward crosslink usage is bilateral also, but at lower data rate.

4.2 OPTION 2: TWO S/C WITH CROSSLINK

Option 2 is a fundamentally different strategy from any version of Option 1. Now, according to Figure 4-6, a satellite is positioned over central CONUS (100° W) and the second satellite almost diametrically opposite (162° to the West). This is the maximum spacing achievable without encountering earth blockage or atmospheric degradations. Coverage of at least 98% is achieved by this means. A crosslink connects the two spacecraft.

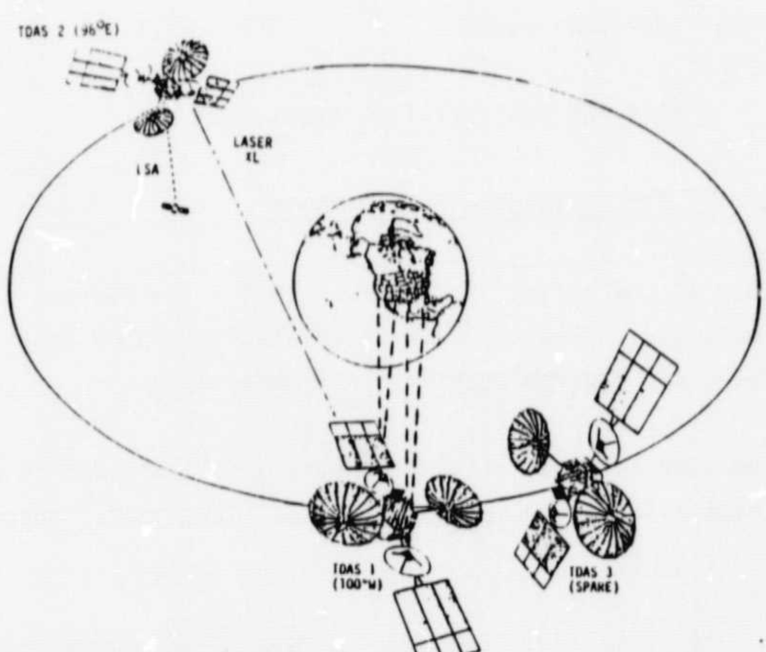
All data distribution to and from ground is handled by the 100°W satellite. The crosslink function becomes highly asymmetric, unlike the case of Option 1C. Return link traffic flows from backside to front only; the reverse flow is forward link only. Although the peak return crosslink load could exceed that of 1C, the net crosslink burden on the two TDAS spacecraft is less in the present case. Option 2 is capable of fulfilling all TDAS goals.

FIGURE 4-5: TDAS CONSTELLATION 1C (ENHANCEMENTS: SMA, WSA, MBA, LSA, XL)



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 4-6: TWO SATELLITE CONSTELLATION



STANFORD
TELECOMMUNICATIONS INC.

4.3 OPTION 3: THREE TDAS SATELLITES

4.3.1 Option 3A

The addition of one backside satellite that is crosslinked to the 60°W satellite in Option 1B yields Option 3A (Figure 4-7). The crosslink function is similar to Option 2; it is asymmetric in having low-capacity forward trffic and high capacity return traffic. In either direction the loading would be less than in Option 2 because of the two frontside satellites. Coverage is 100% for all orbits. This constellation has all the enhancements and meets all the TDAS goals.

4.3.2 Option 3B

By adding a third satellite and a crosslink to Option 1C, we arrive at Option 3 (Figure 4-8). Both the frontside pair and the backside satellite are spared. This option achieves 100% coverage and can realize all the TDAS objectives.

To determine the value to the system of either 3A or 3B, an assessment of benefits vs complexity must be made. In Option 3B, one satellite, to raise a single issue, must support two crosslinks simultaneously, a feature absent from the other options.

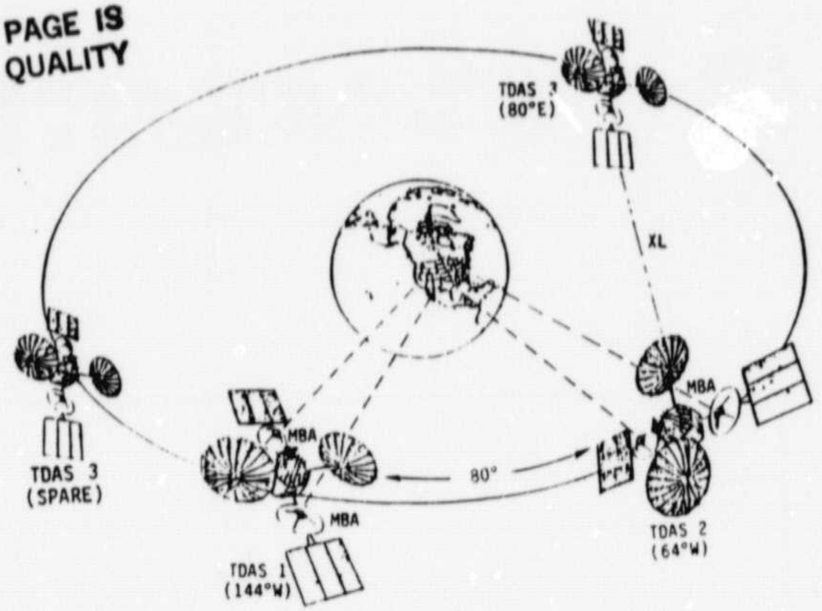
4.4 DATA FOR CONSTELLATION ASSESSMENT

4.4.1 Stationkeeping Requirements

We noted at the outset of Chapter 4 that a few degrees of orbital inclination markedly decreases North-South stationkeeping requirements. The following two figures quantify this observation.

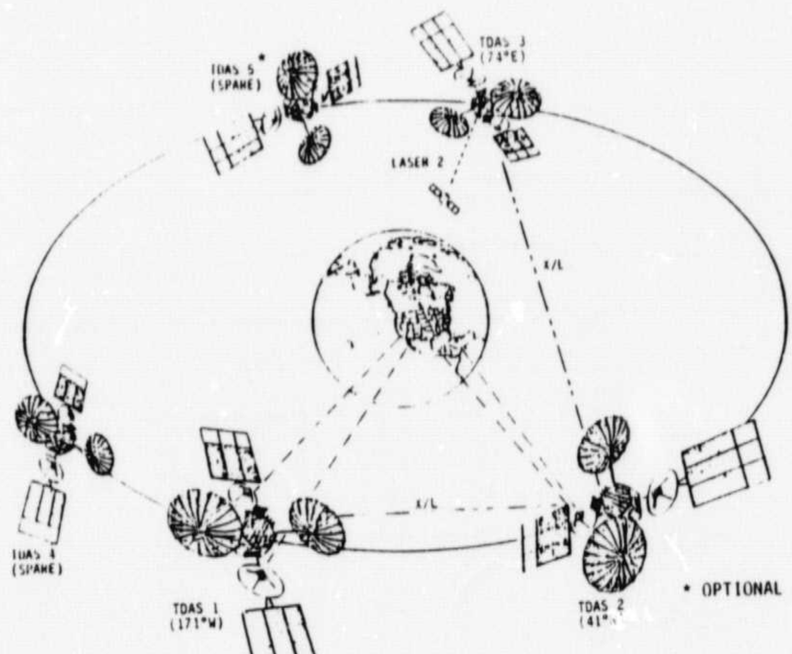
Maximum time interval between maneuvers is indicated in Figure 4-9 for inclinations up to 5°. The abcissa is launch date, which effects the

FIGURE 4-7: TDAS CONSTELLATION 3A (ENHANCEMENTS: SMA, WSA, MBA, LSA, XL)



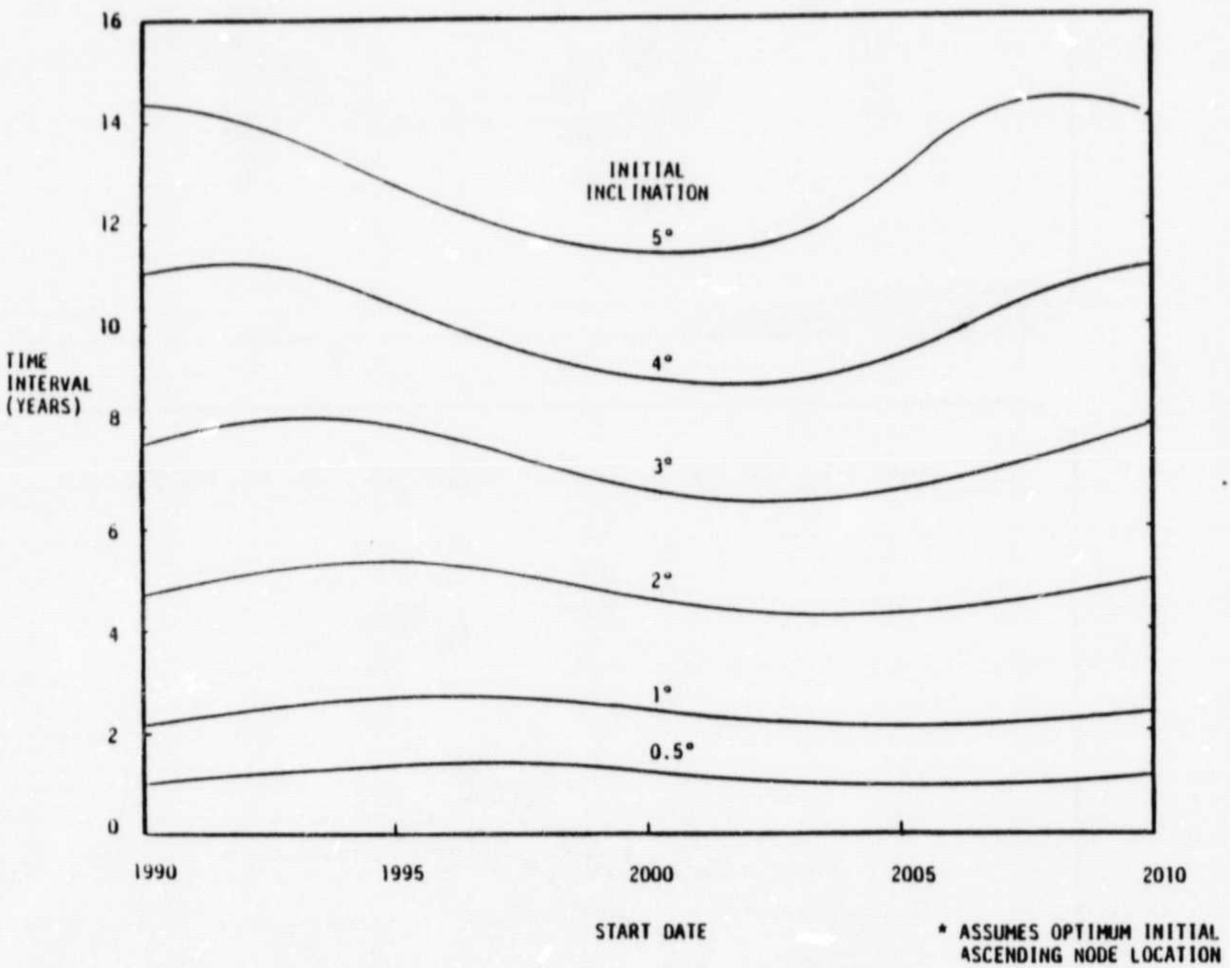
STANFORD TELECOMMUNICATIONS INC.

FIGURE 4-8: TDAS CONSTELLATION 3B (ENHANCEMENTS: SSM, WSA, MBA, LSA, XL)



STANFORD TELECOMMUNICATIONS INC.

FIGURE 4-9: MAXIMUM TIME INTERVAL BETWEEN MANEUVERS FOR NORTH-SOUTH STATIONKEEPING OF 24-HOUR SATELLITES



STANFORD TELECOMMUNICATIONS INC.

results slightly because of an 18-year precession cycle of the earth's axis. If the initial inclination exceeds 4.5°, the satellite can have a ten-year lifetime without need of N-S stationkeeping. By contrast, inclinations of a few tenths of a degree can be maintained only a few months between maneuvers. The actual number of maneuvers and the amount of propellant consumed by a 5000 lb spacecraft over ten years are seen in Figure 4-10. A TDAS launched in 1992 would use some 750 lbs of fuel in three maneuvers to maintain 1° inclination. No maneuvers are required if 4.5° is acceptable.

4.4.2 Coverage

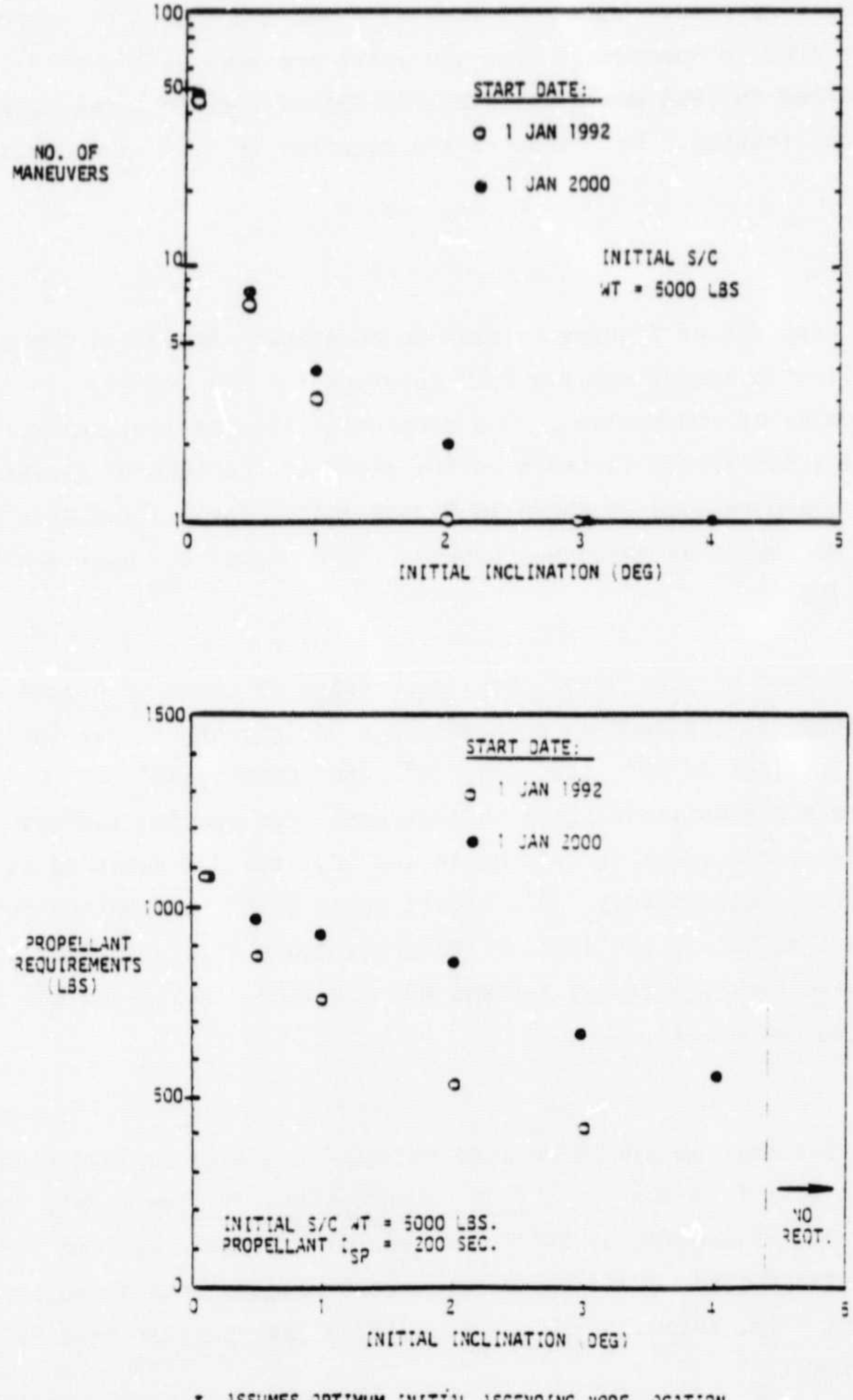
The next set of figures relates to coverage. Because a two satellite constellation cannot achieve full coverage for all orbits, its design entails a number of compromises. One compromise relates to longitudinal spacing of the satellites in orbit vs the width of the zone of exclusion (ZOE); these are related as shown in Figure 4-11. For a fixed user altitude, the ZOE decreases as spacing increases. The higher the user orbit, the smaller the ZOE.

The impact of the ZOE on average coverage is shown in Figure 4-12. Average coverage vs altitude is plotted for a variety of orbital inclinations and for spacings of 80°, 110° and 130°. For spacing 80° (as in Option 1B), there are substantial gaps in coverage. For spacing 110° and 130° (the latter corresponds to Options 1A and 1C), the ZOE vanishes at 2300 and 1200 km, respectively. All orbits below 28.5° inclination suffer equal blockage, but as inclination increases above 28.5°, so does coverage. Average coverage always exceeds 80% for 110° spacing and 85% for 130° ($\geq$ 200 nmi orbit).

This information can be related to available data on TDAS mission models. Using data from Vol. III, TDAS Commuications Mission Model, the number of missions vs average coverage has been plotted for the same three spacings. The widest coverage is shown to be most advantageous by this criterion. In Figure 4-13, 24 out of 29 missions (83%) have greater than 90% coverage for spacing.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 4-10: NORTH-SOUTH STATIONKEEPING REQUIREMENTS FOR 24-HOUR SATELLITES VS INITIAL INCLINATION*

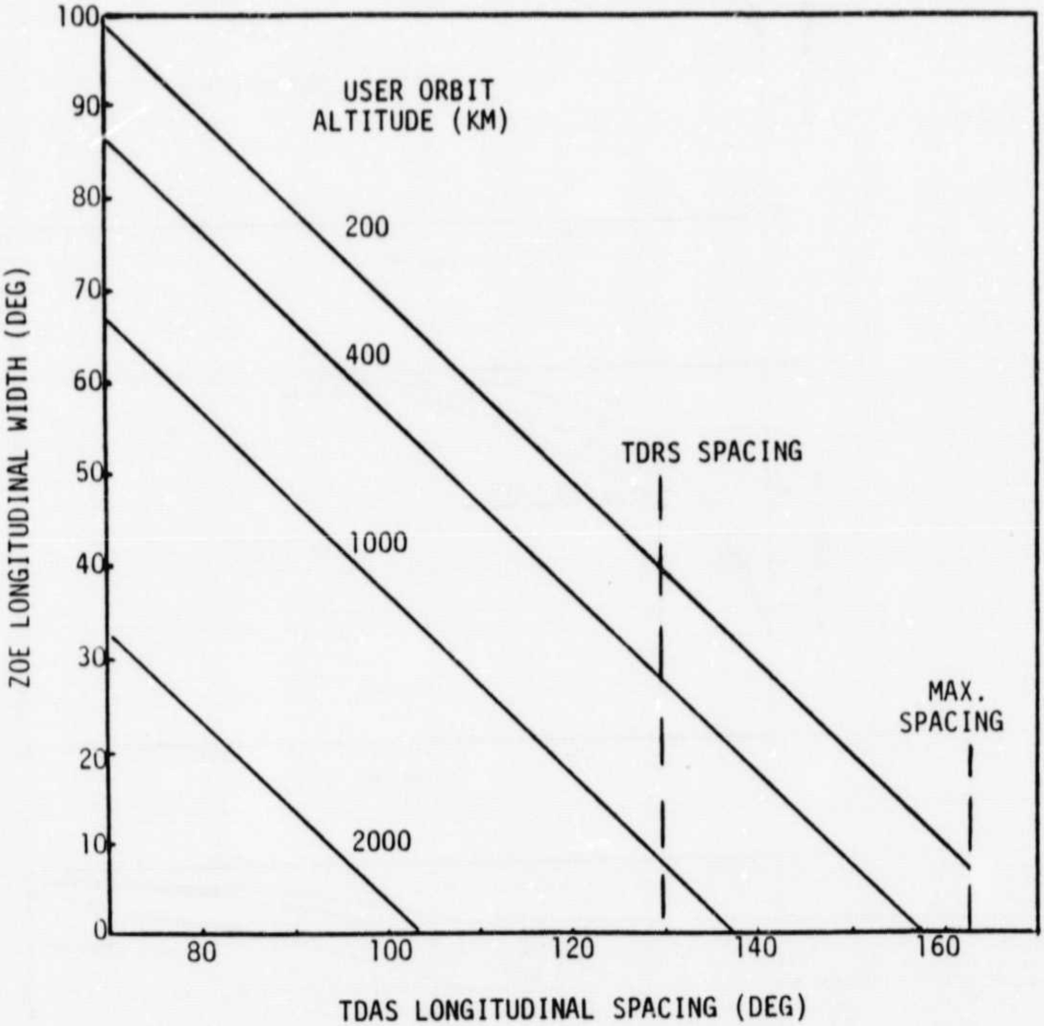


* ASSUMES OPTIMUM INITIAL ASCENDING NODE LOCATION

STANFORD TELECOMMUNICATIONS INC.

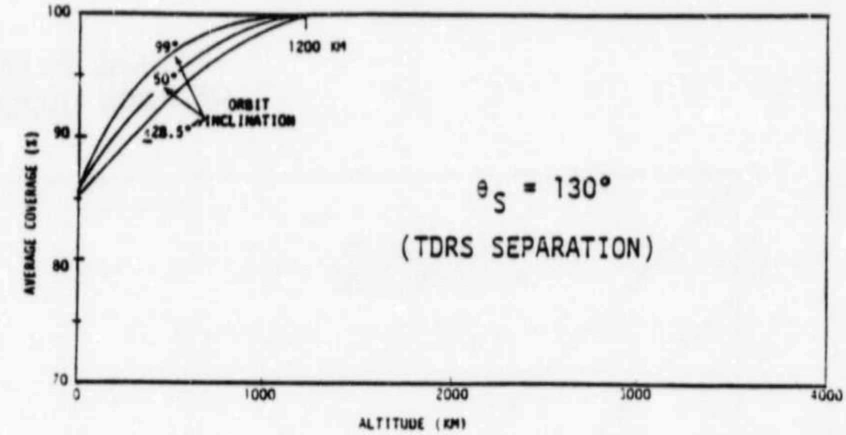
FIGURE 4-11: MAXIMUM WIDTH OF TDAS ZONE OF EXCLUSION (ZOE) VS TWO SATELLITE SPACING

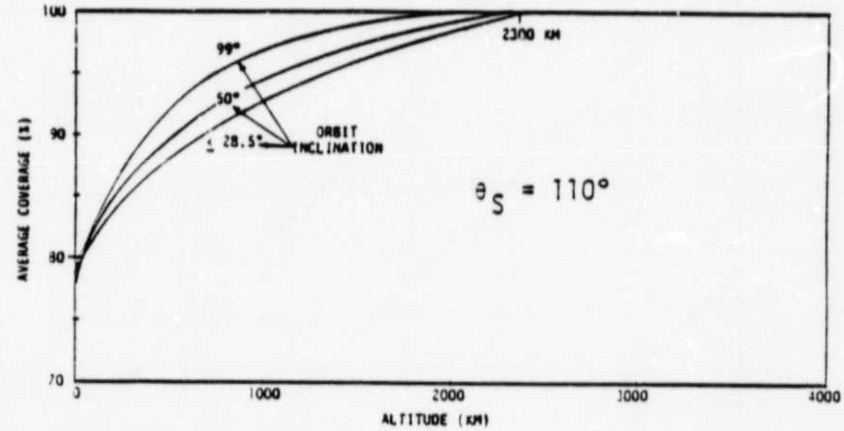
ORIGINAL PAGE IS
OF POOR QUALITY



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 4-12: GEOMETRIC COVERAGE VS. USER ORBIT ALTITUDE, INCLINATION, AND LONGITUDINAL SEPARATION (θ_S) FOR A TWO-SATELLITE TDAS CONSTELLATION





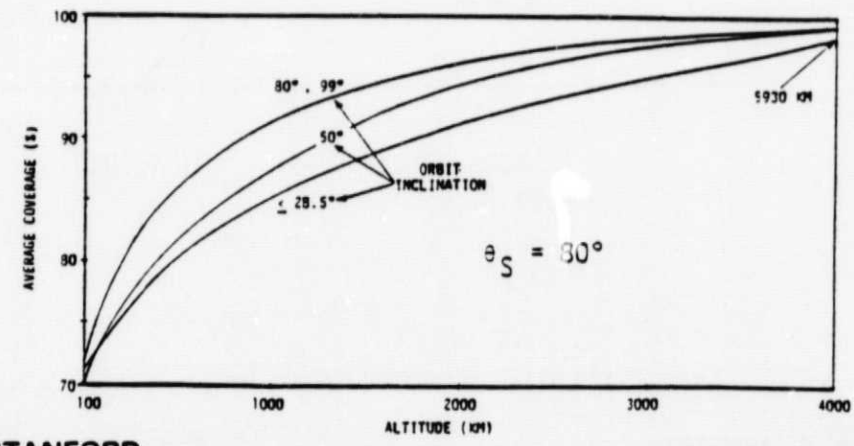
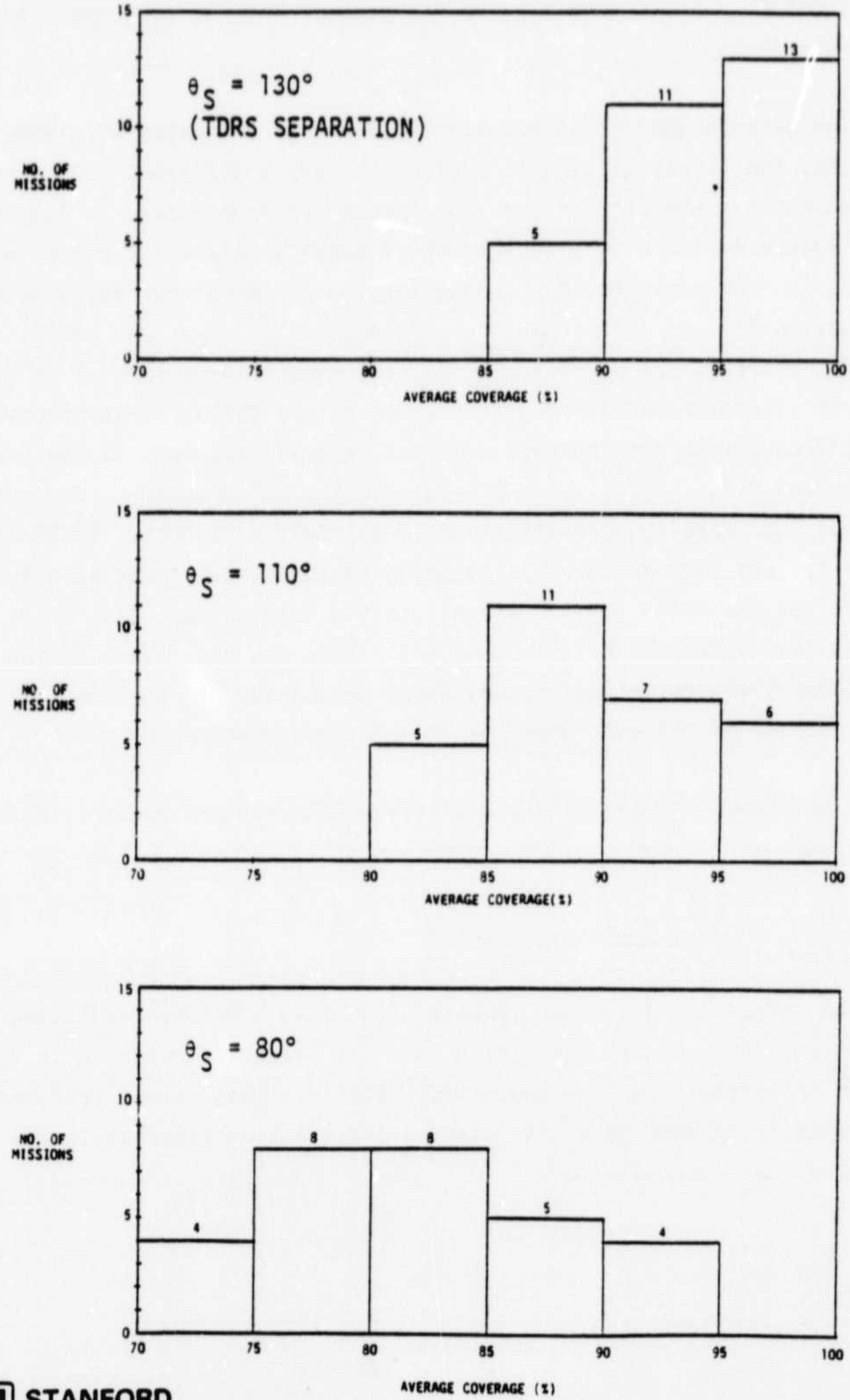


FIGURE 4-13: GEOMETRIC COVERAGE FOR SCENARIO A1 MISSIONS VS TDAS SATELLITE LONGITUDINAL SEPARATION (θ_S)



STANFORD TELECOMMUNICATIONS INC.

130°. The histograms for 110° and 80° show how the number of missions in the coverage percentiles drop off as the TDAS spacecraft are placed closer together. At 80°, no mission has greater than 95% coverage, and four have only 70-75%.

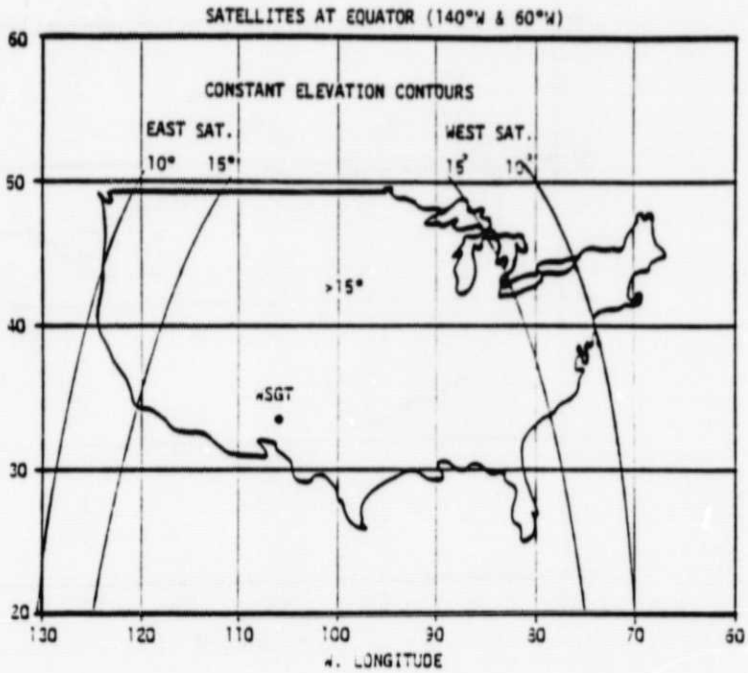
The data on user orbit and mission coverage indicates with some certainty that the larger spacing is preferred. But a different viewpoint emerges when the visibility of the TDAS spacecraft from ground is considered. Figures 4-14 and 4-15 show lines of constant elevation coverage on the earth from two-satellite constellations centered over White Sands and having 80° and 130° separation, respectively. Two TDAS satellites spaced 80° apart on the equator will be seen from a large portion of CONUS above 10° elevation and jointly they cover all of CONUS. Dropping the TDAS's to 5°S cuts into the coverage somewhat, and at least one of the porposed ground sites (GSFC) would lie outside the 10° boundary a few hours per day. For 130° spacing, the situation is markedly different. Equatorial satellites are seen at about 12° from White Sands, but those at 5°S are within 10° of the White Sands horizon. In the latter case, coverge at Colorado Springs is practically nonexistent. Even so, the latter option is usable in Constellations 1A (which uses TDRSS networking) or 1C (the TDAS's are crosslinked and each downlink to selected ground stations).

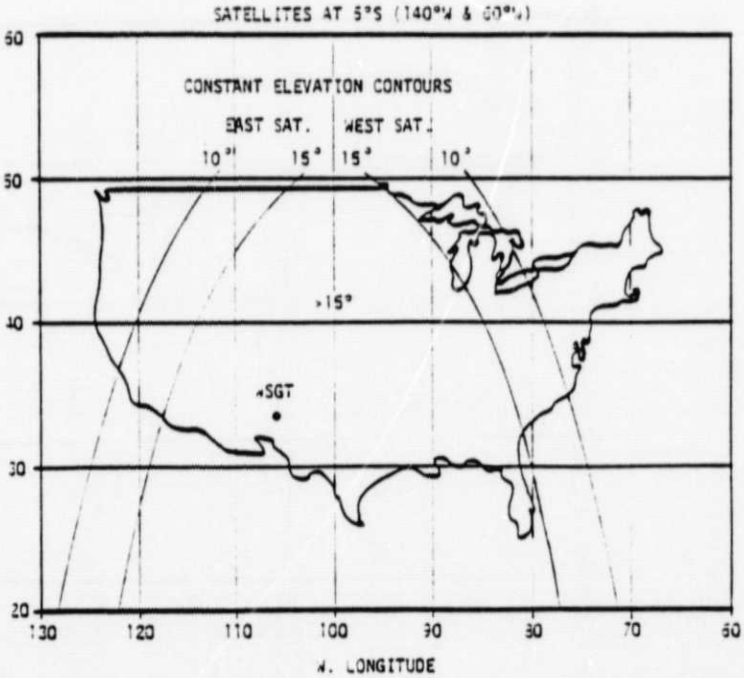
Figure 4-16 summarizes the visibility data for the constellation alternatives.

4.4.3 USAT Tracking Accuracy

The constellations under consideration have also been evaluated for their performance in user navigation, and the reader is referred to Volume VI of this report for the supporting details. What is explored here is the tradeoff between satellite spacing and tracking accuracy in the selection of a TDAS constellation.

FIGURE 4-14: TDAS VISIBILITY FROM CONUS (80° LONGITUDINAL SEPARATION)

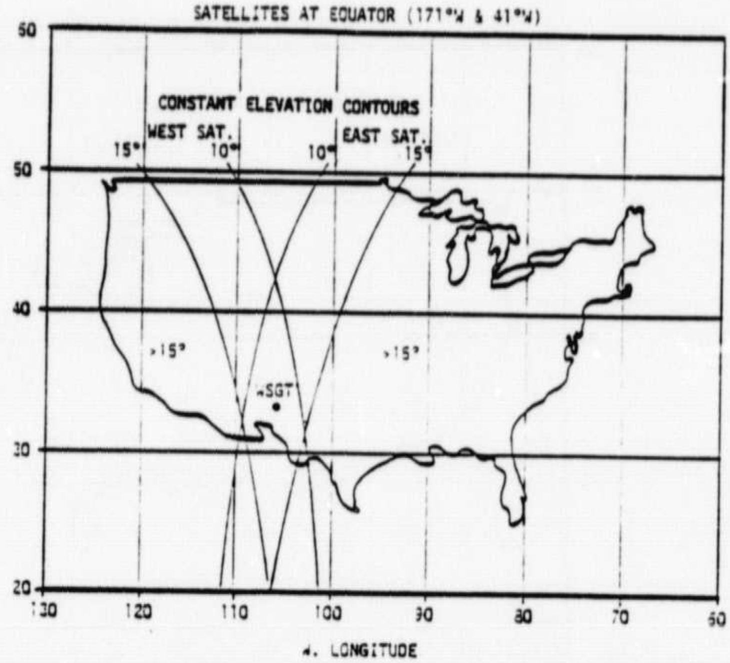


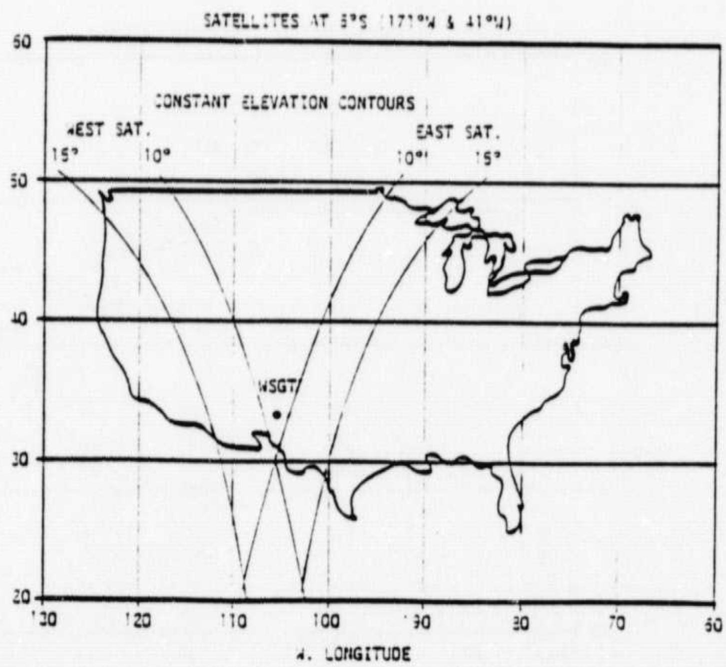


STANFORD TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 4-15: TDAS VISIBILITY FROM CONUS (130° LONGITUDINAL SEPARATION)





STANFORD
TELECOMMUNICATIONS INC.

FIGURE 4-16: VISIBILITY SUMMARY FOR TDAS CONSTELLATION ALTERNATIVES

CONSTELLATION ALTERNATIVE	ACTIVE S/C		USER COVERAGE* (%)	ACCESS TO/FROM CONUS TERMINALS	
	FRONT SIDE	BACK SIDE		ROUTE	REDUNDANCY
1_A	2^{+}	0	85-100	VIA WSGT + DOMSATS	NONE
1_B	2^{++}	0	70-95	DIRECT	FULL
1_C	2^{+}	0	85-100	DIRECT	PARTIAL
2^{+++}	1	1	98-100	DIRECT	NONE
3	2^{++}	1	100	DIRECT	PARTIAL

* MINIMUM ALTITUDE - 200 KM; ANY INCLINATION

\+ 130° SPACING

++ 80° SPACING

+++ 162° SPACING

Two TDAS placed close together would have a large ZOE which reduces tracking opportunities (critical in high drag orbits). Unfavorable geometry for doppler tracking exists in high inclination orbits whenever the orbit normal points toward the TDAS satellites. Less benefit from range tracking is realized because of the nearby parallel directions to the two satellites.

As the TDAS spacing increases, both ZOE and tracking accuracy tend to improve. Beyond 90° the ZOE continues to decrease, but a point is reached where tracking accuracy begins to degrade. At opposition (e.g., 168° spacing), doppler tracking of normally oriented polar orbits again degrades. Thus the two satellite design must strike a balance between achievable coverage and accuracy of user tracking.

The three-satellite constellation has been evaluated for tracking also. Constellation 3 has about a 2:1 advantage over Constellation 1A for low altitude users. This advantage decreases as orbit altitude increases (> 400 —500 km).

SECTION 5

TDAS SPACECRAFT OPTIONS

Astute selection of a constellation, a networking scheme and a ground segment architecture will open the way for TDAS to satisfy its mission and realize its goals. One might say that these define the channels through which all TDAS data will flow. The crux, then, becomes the nodes, in this case the TDAS spacecraft, which will receive, process and distribute that data. Beginning in this chapter, we undertake the development of that final major element of TDAS. The task carries us through Chapter 6, where the crosslinks between TDAS satellites are taken up.

A set of options for the manner of derivation of the TDAS spacecraft is introduced first. These range from the use of proven, available assets — TDRS's — to the full development of a new dedicated bus. Once having settled this, we undertake to see how the various subsystem level enhancements discussed in Chapter 3 can be accommodated.

5.1 SPACECRAFT OPTIONS

Three options, arranged in order of increasing risk and decreasing TDRS heritage, are posed. In the first of these, TDRSS lifetime is extended for another 10 years, TDAS requirements being met by increasing the number of active spacecraft. A system composed of modified TDRS's is then considered. Power and weight margin are recouped by deleting the Advanced Westar package of TDRS prior to modification. The third option breaks continuity with TDRSS in developing an entirely new TDAS-dedicated bus.

5.1.1 Expanded TDRSS

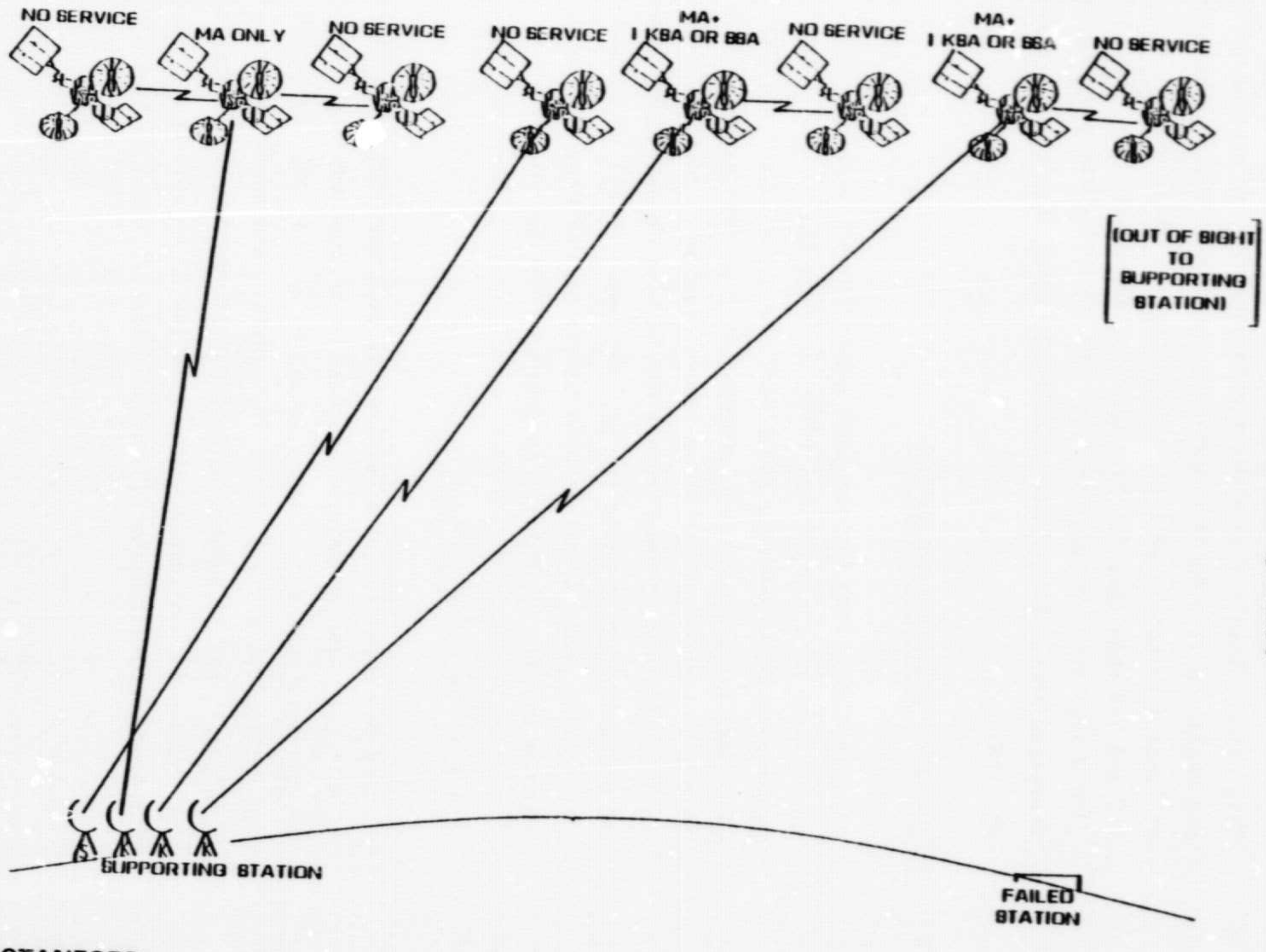
The lifetime of TDRSS as it is currently defined could be extended for another 10 years by a continued spacecraft replenishment program supported by extension of the companion services: spacecraft support, on-orbit testing, data distribution, and O&M. Mere replacement will perpetuate TDRSS without realization of the new TDAS mission. But many aspects of the TDAS enhancements could be met by increasing the number of active, on-orbit spare, and ground spare spacecraft. This expanded mode of operation induces any number of operational changes and becomes almost a new system itself. TDRSS expansion has been studied in detail in a subcontractor task, and the results are reported as Vol. X of this study. We summarize below the key results of that study.

- Twelve scenarios for TDRSS expansion were conceived in which the first 10 years are serviced by TDRSS, the next 10 by launch of replacements for the original TDRS's plus addition TDRS's. The number of active S/C for the second ten years varies from 4 to 6; including spares the number is 5 to 8. The mission models developed for these indicate that from 13 to 16 spacecraft will be build and launched during the system lifetime.

- An additional ground terminal, functionally identical to the White Sands terminal, will be installed in the Washington, D.C. area to support the space segment. A backup POCC would be constructed nearby. New backup measures to support a failed ground site are needed. In these backup scenarios, some of the spacecraft will provide no user service, and some only MA plus limited or no SA Service, because their SA antennas are used for TT&C cross-support of other satellites. Some options would entail spacecraft modification. Figure 5-1 shows an example backup scenario.

- Data distribution is handled via domsat relay to the five ground terminals plus Hawaii. The maximum data rate is 300 Mbps per user.

FIGURE 5-1: EIGHT SPACECRAFT CONSTELLATION: POSSIBLE FAILED STATION SUPPORT SCENARIO



STANFORD
TELECOMMUNICATIONS INC.

5.1.2 Enhanced TDRS

This concept involves deleting the Advanced Westar package from the TDRS, and replacing it with TDAS-dedicated hardware. This permits continuation of TDRSS services as well as the addition of new TDAS services. Figures 5-2 and 5-3 show that net maximum deletion of 1700 lbs is possible, leaving 1100 W available for new services. If the STS payload weight envelope is increased above the current 5000 lbs, greater capacity for modification will exist.

5.1.3 New Bus Architecture

Maximum flexibility for the TDAS spacecraft would be attained by the development of a new bus specifically dedicated to TDAS. Not only could new services be added and TDRSS services perpetuated; the implementation of the TDRSS services could be improved in a manner transparent to the user, (e.g., by use of a lower noise figure receiver), possibly even enhanced in a way that would constitute a new service (e.g., higher bandwidth MA) to users willing to equip for it. The price of all this flexibility is a development program that is both costly and lengthy, and it is this that must be weighed against the advantages a new bus offers.

5.1.4 Selection of Option

Figure 5-4 summarizes the features of each approach to obtaining the TDAS satellites. These observations lead us to conclude that the enhanced TDRS is the best approach. Simple expansion of the TDRSS system will not lead to realization of many of the TDAS goals. And starting anew with the spacecraft design appears to be overkill when the TDRSS compatibility groundrule is considered. In the following discussion, three enhancements to the TDRS are considered as candidates for the TDAS spacecraft.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 5-2: MAXIMUM SATELLITE WEIGHT AVAILABILITY BY ADVANCED WESTAR DELETION

		TDRS (LBS)	DELETIONS FOR TDAS	
COMMUNICATIONS ELECTRONICS		770		
			AW PROCESSOR	
			AW TRANSPONDER	
			MISCELLANEOUS	
				145
COMMUNICATIONS ANTENNAS		200	AW C- AND K-BAND	70
PROPULSION		1500		
EQUIPMENT	200		SMALLER TANKS	100
PROPELLANT/PRESSURANT	1300		LESS PROPELLANT	1100
OTHER SUBSYSTEMS		2350	LOWER UPPER STAGE PERFORM-ANCE	300
RESERVE		250		
TOTALS		5000		1714
AVAILABLE SPACECRAFT WEIGHT (SHUTTLE/IUS)		5000		

WEIGHT AVAILABLE FOR NEW SERVICES - APPROX. 1700 LBS.

STANFORD TELECOMMUNICATIONS INC.

FIGURE 5-3: MAXIMUM ELECTRICAL POWER AVAILABILITY BY ADVANCED WESTAR DELETION

POWER(W)	
98.8 -	C-BAND EQUIPMENT DELETION
122.1 -	C-BAND EQUIPMENT HEATER DELETION
206.5 -	TDRS MARGIN
427.4	

POWER AVAILABLE FOR NEW SERVICES - APPROX. 425 W

STANFORD TELECOMMUNICATIONS INC.

FIGURE 5-4: FEATURES OF TDAS SPACECRAFT ACQUISITION STRATEGIES

	EXPANDED TDRS	ENHANCED TDRS	NEW BUS
TDRSS HERITAGE	HIGH	MODERATE	LOW
FLEXIBILITY	LOW	MODERATE	HIGH
TDAS GOALS ACHIEVED	NO MULTIPOINT DISTRIBUTION NO ULTRA-HIGH RATE ACCESS	ALL	ALL
TOTAL COST	HIGH	MODERATE	HIGH
TECHNICAL RISK	LOW	MODERATE	HIGH
TRANSITION PROBLEM	TWO GROUND STATIONS	DIFFICULT BUT FEASIBLE	?
STS COMPATIBILITY	COMPATIBLE NOW	MAY NEED INCREASED WEIGHT LIMIT	?

STANFORD TELECOMMUNICATIONS INC.

5.2 TDRS ENHANCEMENTS

Figure 5-5 shows the basic TDRS satellite. It carries two unfurlable single access dishes (4.9 m) for S- and K- band use. The multiple access aray is on the spacecraft body along with a 1 m dish that was to provide Advanced Westar service. The 2 m space-to-ground link (SGL) antenna sits off on a boom in the direction of the collapsable solar panels.

Each of the enhancements to be discussed is derived from this basic structure by the deletion of certain equipments and the addition of others. Figure 5-5 reminds us that the AW deletions yield 1700 lbs and more than 1100 W for TDAS functions.

5.2.1 Enhancement I

The first enhancement to TDRS consists of installing the improved SMA module and the expanded SA service at W-band. Figure 5-6 shows how the resulting configuration looks.

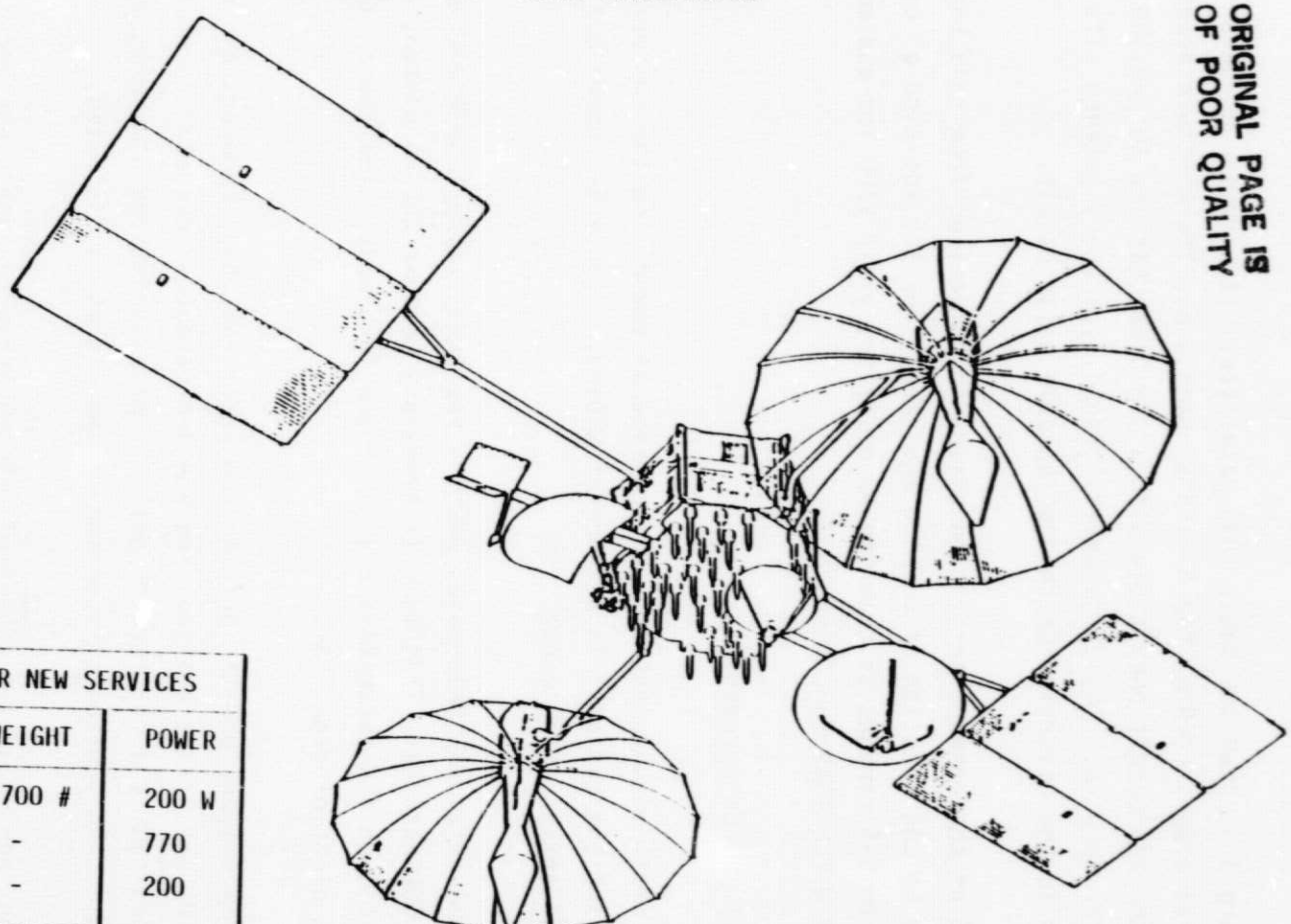
The MA array has been moved off the spacecraft body into a position opposite the SGL antenna. This move is necessary because the 60 element array will not fit on the earth-facing side of the TDRS body. The phased array sits on a plate of area $2\,m^2$.

The AW antenna and the original MA array have been removed, and on the body of the spacecraft are the five WSA 1-m parabolic dishes. By placing the dishes near the spacecraft center of mass, undesired torqueing of the satellite due to mechanical steering of the dishes is minimized.

Weight and power breakdowns of the two enhanced subsystems are given in Chapter 3 of this report. The SMA system required 650 lbs and 420 W, the WSA 500 lbs and 210 W, for a total of 1150 lbs, 630 W. Because the TDRS can supply the required power, no modification is made to the solar panels. The deleted TDRS SMA array has a burden of 230 lbs and 140 W, leaving a net increment of 920 lbs and 490 W for Enhancement I.

ORIGINAL PAGE IS OF POOR QUALITY

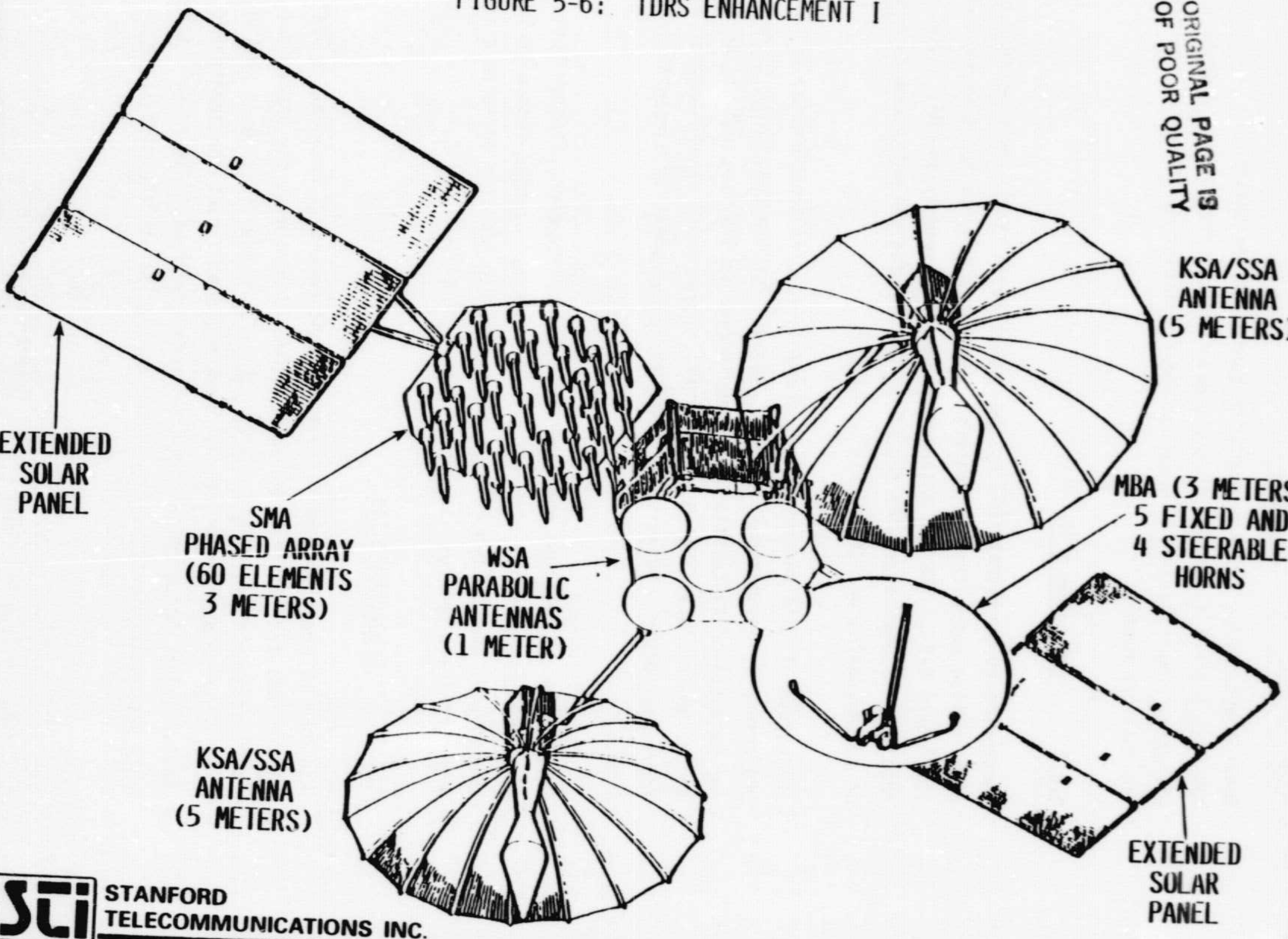
FIGURE 5-5: TDRS SATELLITE



CAPABILITY FOR NEW SERVICES		
ITEM	WEIGHT	POWER
AW DELETIONS	1700 #	200 W
EPS ADDITIONS	-	770
TDRS MARGIN	-	200
TOTAL	1700 #	1170 W

STANFORD TELECOMMUNICATIONS INC.

FIGURE 5-6: TDRS ENHANCEMENT I



STI STANFORD TELECOMMUNICATIONS INC.

Enhancement I goes hand-in-hand with constellation option 1A. The retained TDRS SGL antenna is used for single point data distribution to White Sands. All other constellations are set up for multipoint distribution and cannot use this enhancement.

5.2.2 Enhancement II

Continuing to increment TDRS by the installation of the multipoint data distribution and ultra-high rate single access service leads to Enhancement II (Figure 5-7). The SGL antenna has been replaced by an MBA, and a laser receiver has been added for the LSA. The SMA and WSA enhancements described in the preceding paragraphs are unchanged.

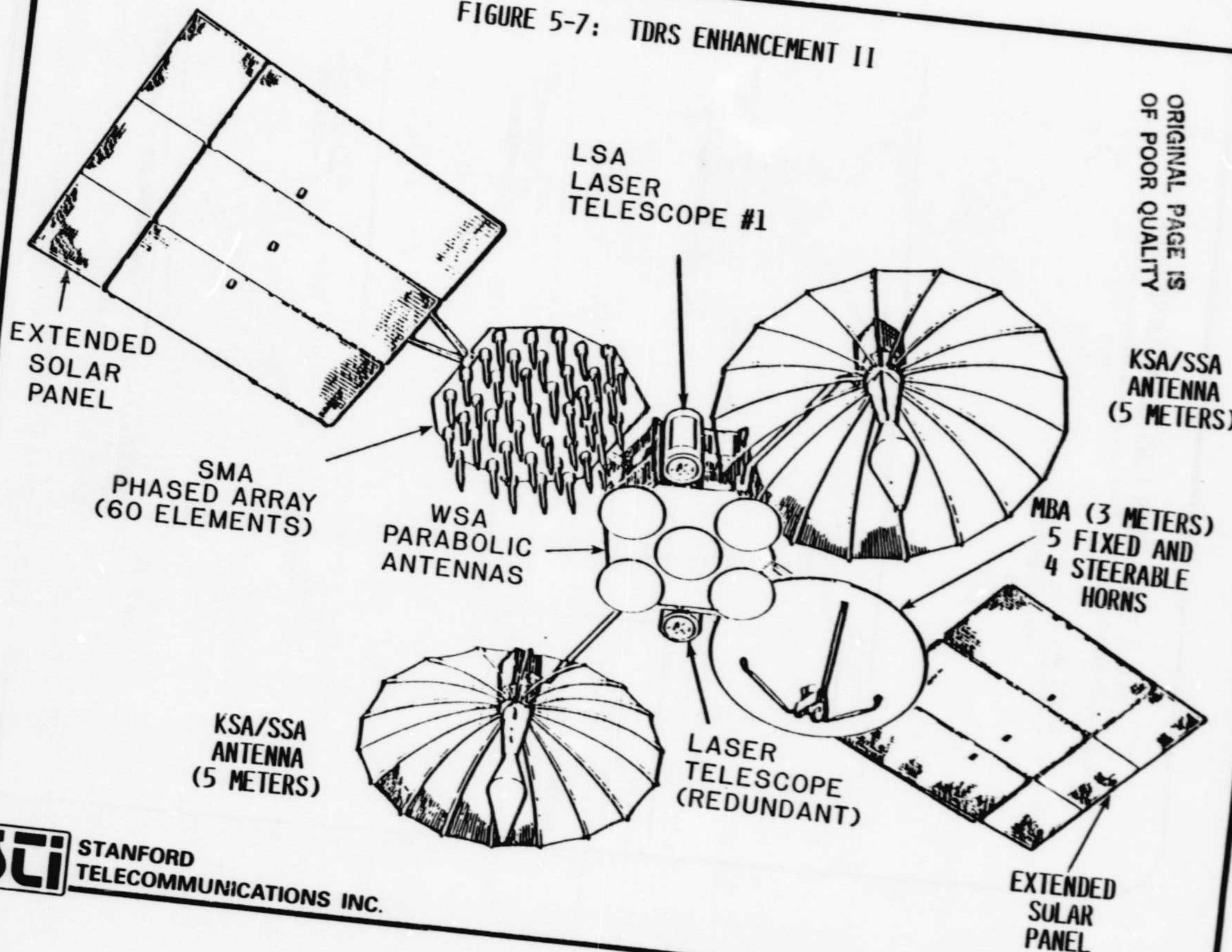
The burden of this enhancement is found using data from Chapter 3. The MBA burden is estimated at 220 lbs, 460 W. For the LSA, taken to be Nd:YAG for purposes of calculation, the requirement is 170 lbs, 135 W. An additional 90 lbs is allocated to enlarged, hinged solar panels that provide additional power. Relative to TDRS, the Enhancement II burden is 1400 lbs, 1085 W.

Enhancement II provides the services allocated to constellation Option 1B. Via MBA, communication with all ground sites is possible from both TDAS spacecraft, thereby generating enough downlink capacity to support the LSA, and sufficient connectivity to obviate a crosslink.

5.2.3 Enhancement III

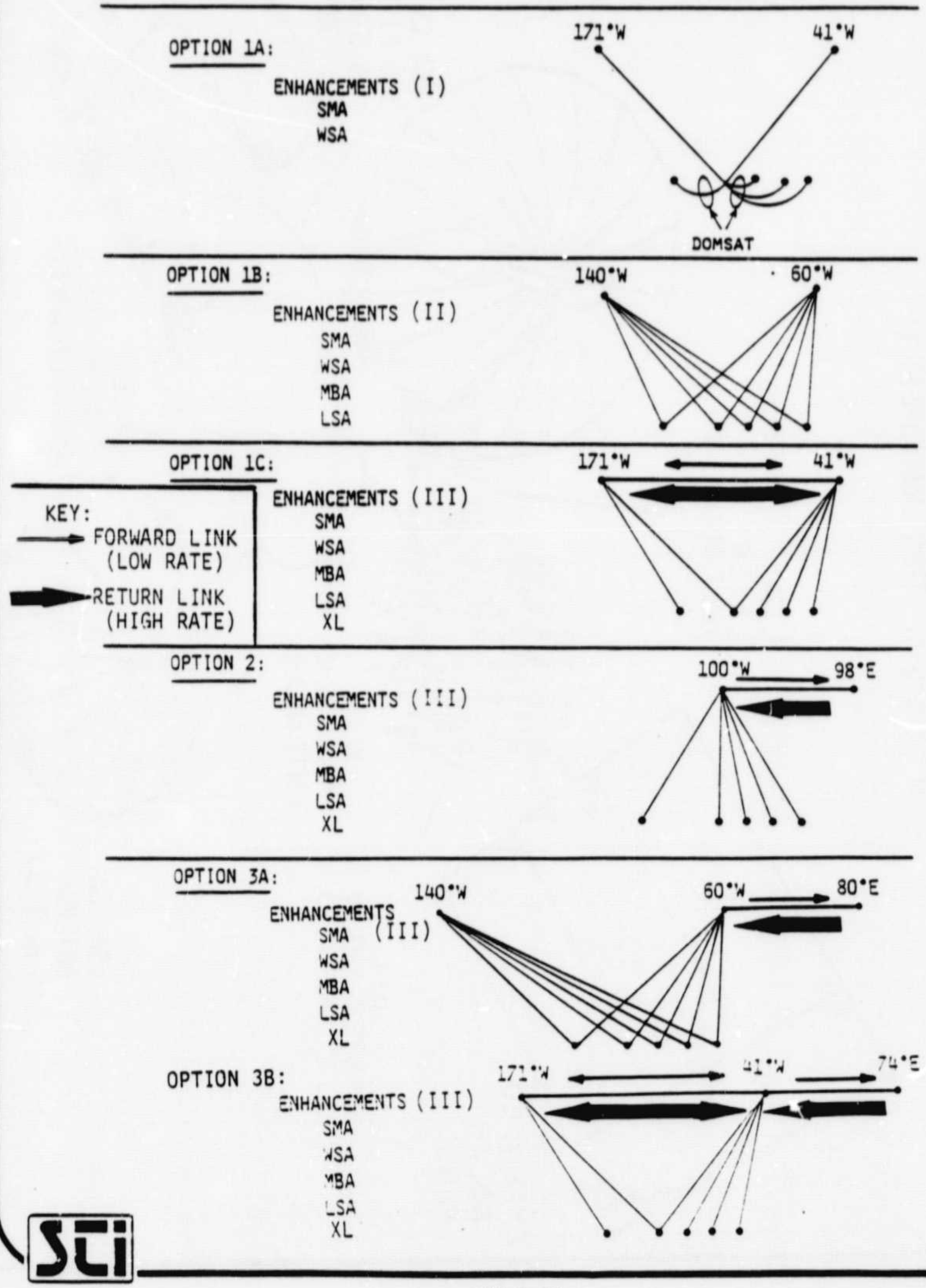
Addition of the crosslink facility to Enhancement II creates the last enhancement. This satellite is the one that would work with the other four constellation options: 1C, 2, 3A and 3B. There are differences in the crosslink function among the options, however, that impact the spacecraft architecture, forcing us to consider two separate cases. Figure 4-1 is reproduced with minor amendments as Figure 5-8 to facilitate the discussion.

FIGURE 5-7: TDRS ENHANCEMENT II



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 5-8: TDAS CONSTELLATION/NETWORK OPTIONS



Constellation options 2 and 3A share the property that the crosslink usage is highly asymmetric. Low rate forward link data travels in one direction, high rate return traffic in the other. But in options 1C and 3B, the flow is symmetric between the frontside satellites. In 3B there are two crosslinks, one symmetric and one asymmetric; this configuration has the peculiarity that some forward and return link data traverses both crosslinks to reach its destination.

In the asymmetric cases (2 and 3A) each satellite is equipped to transmit or receive high rate return link data, but not to do both simultaneously. The same is true of the low rate forward links. As a result, there is a choice between using a single crosslink bilaterally at disparate rates or employing two unilateral links, each one sized for its expected traffic load. In the symmetric cases (1C and 3B) there can be simultaneous, bilateral flow of high and low rate traffic. Again, there could be separate high and low rate links, or a single link that multiplexes the high and low rate traffic going along a particular route. With either choice there is a simultaneous two-way communication, which probably requires two-frequency operation and a great deal more concern about isolation. And in 3B, the satellite must accommodate simultaneous two-way operation of two crosslinks. Two fully independent crosslink subsystems are thus required, along with the ability to effect the requisite crossbanding.

It is interesting to note that the asymmetric case, which handles the least crosslink throughput per satellite, may not be the simplest (or lightest or least power consuming) to implement. One possibility is to use laser for the return link traffic and a small 60 GHz link for the forward link. But it could turn out that the burden associated with the dual links exceeds that of a single link configuration.

To size all the emergent possibilities would be excessive for the purpose at hand. The high speed crosslink can be at 60 GHz or laser (several types), and the laser system can be regenerative or transponding. We will look at some of the simpler alternatives and make a few extrapolations to scope Enhancement III.

Figures 5-9 and 5-10 show two versions of the basic configuration. In the former, all crosslinking is at 60 GHz; the latter uses laser for both the high speed link and the forward service. The 60 GHz crosslink is implemented by two 2m parabolic dishes balanced on opposed deployablebooms. A beam waveguide (not shown) might replace the conventional waveguide to minimize feed losses. In this configuration, the most general requirements posed by Option 3B can be met. For other constellations, the second 60 GHz antenna serves for redundancy and/or extension of coverage.

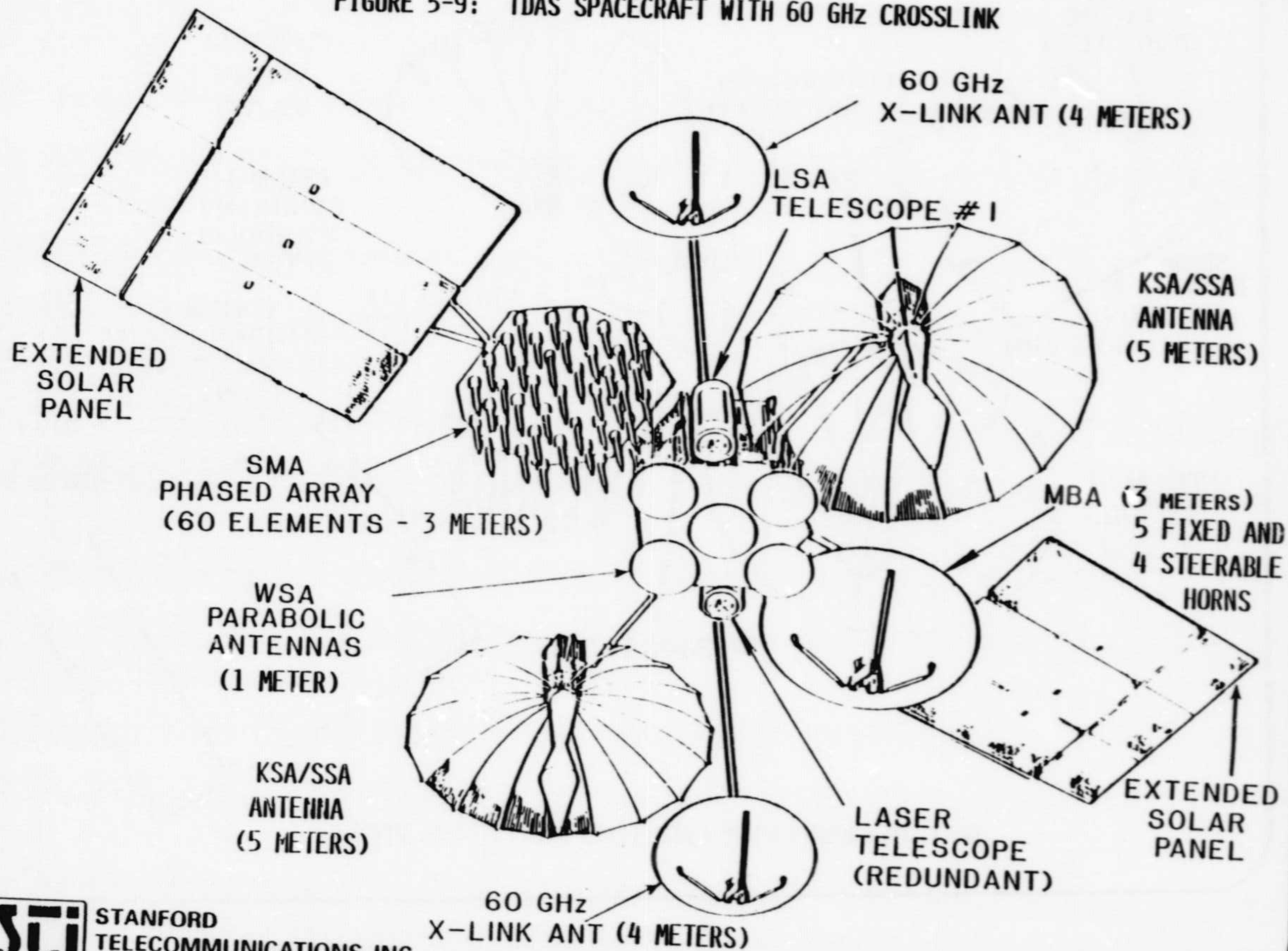
In the laser version there are three lasers mounted on the spacecraft body. The redundancy or backup functions of these vary with the laser type(s). Of course, no new 60 GHz dishes are added. The total for 60 GHz is 1860 lbs, 1285 W; for the laser option it is 1620 lbs, 1325 W.

Total weight and power of the enhancements are summarized in Figure 5-11 below.

FIGURE 5-11: TOTAL WEIGHT AND POWER OF THE ENHANCEMENTS

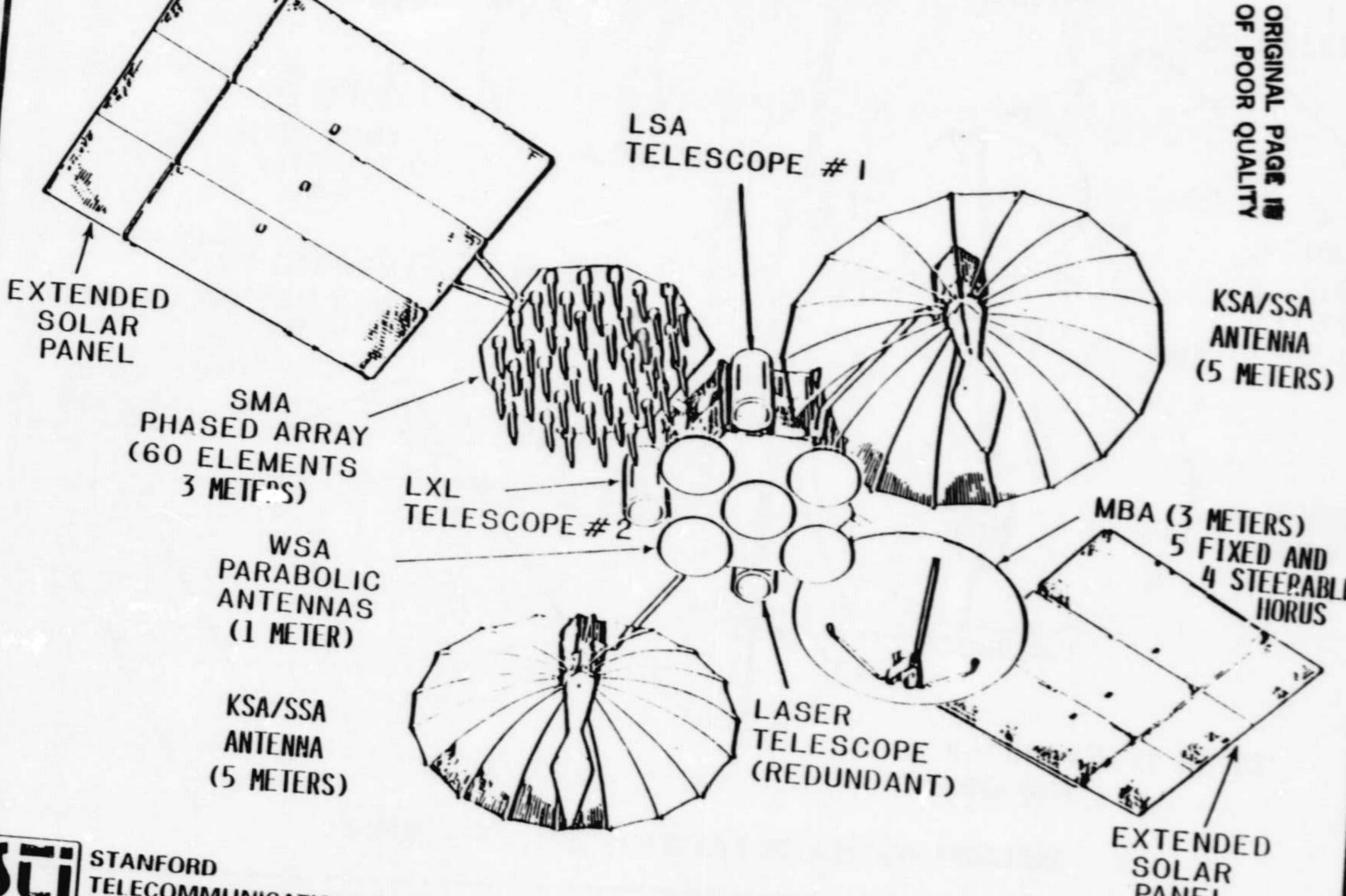
ENHANCEMENT	WEIGHT (LBS)	POWER (W)
I	1166	579
II	1626	1174
III (60 GHz)	2106	1374
III (LASER)	1866	1424

FIGURE 5-9: TDAS SPACECRAFT WITH 60 GHz CROSSLINK



STANFORD
TELECOMMUNICATIONS INC.

FIGURE 5-10: TDAS SPACECRAFT WITH LASER CROSSLINK



STANFORD
TELECOMMUNICATIONS INC.

SECTION 6

CROSSLINK IMPLEMENTATION

The choice of crosslink implementation, especially the return crosslink, has a telling impact on TDAS. Principle drivers are maximum throughput (1.8 Gbps, see Figure 6-1) and projections of 1988 technology. In coming to an assessment of the crosslink, possibilities at both RF and laser frequencies have been investigated. Onboard processing ranging from FDMA transponding to full regenerative repeating is considered. In the laser options, tradeoffs of heterodyne and direct detection receivers show the relative merits of each.

The section begins with a brief discussion of the forward crosslink. Subsequent material dealing with the return link is divided into technology options and architecture options. The technology discussion is restricted to listing options; detailed tradeoffs are found in Volume VII of this report. Architectures are initially given generically according to signal processing approach, and are subsequently related to specific lasers. Closing the section is the presentation of the baseline candidates.

6.1 FORWARD CROSSLINK

Capacity requirements for the forward crosslink are roughly three orders of magnitude less than those on the return. This disparity frees the forward link of substantial technical risk. It is the recommendation of this study that no tradeoff effort is required to sort out various options for the forward link. Technology being developed at 60 GHz for user application will more than suffice for crosslink purposes. The forward link could be a separate, small 60 GHz link or could be integrated into an all-60 GHz crosslink. Or, a coherent laser link will easily provide ample capacity if it is sized to carry the worst-case return crosslink loading. It becomes mostly a matter of convenience in spacecraft design as to whether the forward crosslink is separate from or integrated with a return link.

FIGURE 6-1: TDAS SERVICES (PER SATELLITE) FOR THE BASELINE CONFIGURATION (MAXIMUM THROUGHPUT 1.8 GBPS)

	DATA RATES (bps)		NUMBER OF CHANNELS	MAXIMUM THROUGHPUT (bps)
	MIN	MAX		
RETURN LINK				
KSA	1 k	300 M	2 } *	600 M
SSA	1 k	3 M	2 }	
WSA	50 k	50 M	5	250 M
LSA		1000 M	1	1000 M
SMA	100	50 k	20	1 M
TOTAL			28	1851 M
FORWARD LINK				
KSA	1 k	25 M	2 } *	50 M
SSA	100	300 k	2 }	
WSA			5	
LSA			1	
SMA	100	10 k	2	
TOTAL			10	

* Maximum of two total KSA + SSA at one time.

If a 60 GHz return link is chosen, the antenna sizes will permit generation of adequate forward link EIRP by a single IMPATT amplifier unit. No power combining will be needed. In the event that the return crosslink is via laser, the forward link at 60 GHz can use even smaller antennas with an IMPATT source. The link budget in Figure 6-2 shows that 1 W and a 1 ft dish will suffice to handle two 300 Kbps forward links (the maximum rate for SSA service). A much stronger link would be required to support even one KSA forward link at its 25 Mbps maximum rate.

A forward link at 60 GHz is completely coherent and avoids any problems associated with maintaining doppler and PN coding for navigation purposes.

6.2 RETURN CROSSLINK

6.2.1 Frequency Alternatives

The return link data throughput requirement for the crosslink precludes RF at SHF or below. Achievement of EIRP and G/T sufficient to close the link would be at the price of severe antenna size and/or prime power requirements. RF technology well-suited to crosslink applications is under development at 60 and 95 GHz. Of these, work at 60 GHz is the more advanced, and there seems to be no revolutionary benefit attendant to skipping the evolutionary step of accumulating 60 GHz experience prior to going to 95 GHz. It is believed that technology development for the 60 GHz user service will have much in common with crosslink requirements, and thus our RF alternative is 60 GHz.

The remaining alternatives are optical crosslinks. Three laser technologies have high near-term potential for space communications: frequency doubled Nd:YAG (532 nm), CO_2 (10.6 μm), and various dopings of GaAs (most prominently, GaAlAs, 832 nm). The system implications of a choice of one of these vary widely with the choice. We will not tabulate the differences here, but let them arise in context as other issues are considered. Volume VII of this report contains a section in which crosslink technology is discussed in detail.

FIGURE 6-2: 60 GHZ FORWARD CROSSLINK BUDGET

TRANSMITTER POWER (1 W)	0.0 DBW
TRANSMIT GAIN (1 M)	53.0 DB
PATH LOSS (162° SEPARATION, SYNCHRONOUS)	-226.3 DB
RECEIVE GAIN (1 M)	53.0 DB
RECEIVED POWER (C)	-120.3 DBW
RECEIVER TEMPERATURE (1000°K)	30.0 DB°K
BOLTZMAN'S CONSTANT	-228.6 DBJ/°K
NOISE POWER DENSITY (N_0)	-198.6 W/Hz
C/N_0	78.3 DBHz
RF BANDWITH^{-1} (1.2 MHz)	- 60.8 DBHz
EB/N_0 AVAILABLE	17.5 DB
EB/N_0 REQUIRED	10.0 DB
MARGIN	7.5 DB

STANFORD TELECOMMUNICATIONS INC.

6.2.2 Onboard Processing Alternatives

Onboard processing in satellite relay systems can run the gamut from simple transponding to full regeneration (which may include decoding, editing, reformatting and switching prior to retransmission). Consider that in TDAS the information upon which the return (user-to-ground direction) crosslink signal is based comprises user signals of various data rates, power levels, modulations/formats and frequencies (S-, K-, W-bands and optics). Either processing extreme can in principle service the communications functions. For example, the signals can be individually downconverted to nonoverlapping frequency bands at an IF, frequency division multiplexed, power leveled and/or clipped (optional), and transponded to another TDAS via RF or optical carrier. Alternatively, each user signal can be demodulated (and if necessary decoded), buffered, and remodulated into a framed TDMA stream for crosslinking, again via either RF or laser. For multiple access user signals, the transponding approach accommodates, but does not require, beamforming at the blind side TDAS. The demodulation alternative, of course, necessitates prior beamforming. Figure 6-3 illustrates the processor choices.

The two processing alternatives are less readily interchangeable with respect to navigation data. PN codes, superimposed on some user data signals for ranging and synchronization, must be despread prior to demodulation (also prior to the multiple access beam calibration, if any), and would therefore be lost to the ground station unless reconstituted (impractical for a TDMA link) or measured and inserted into the digital data stream. User doppler, to be sensed at the ground station for range rate computation, is lost in the demod/remod process unless special precautions are taken to measure it, for example, by reading the phase tracking loop VCO, and similarly digitizing and transmitting the result. The transponding option has the problem of inserting guard bands for uncompensated doppler into the FDMA signal, creating a small bandwidth expansion requirement.

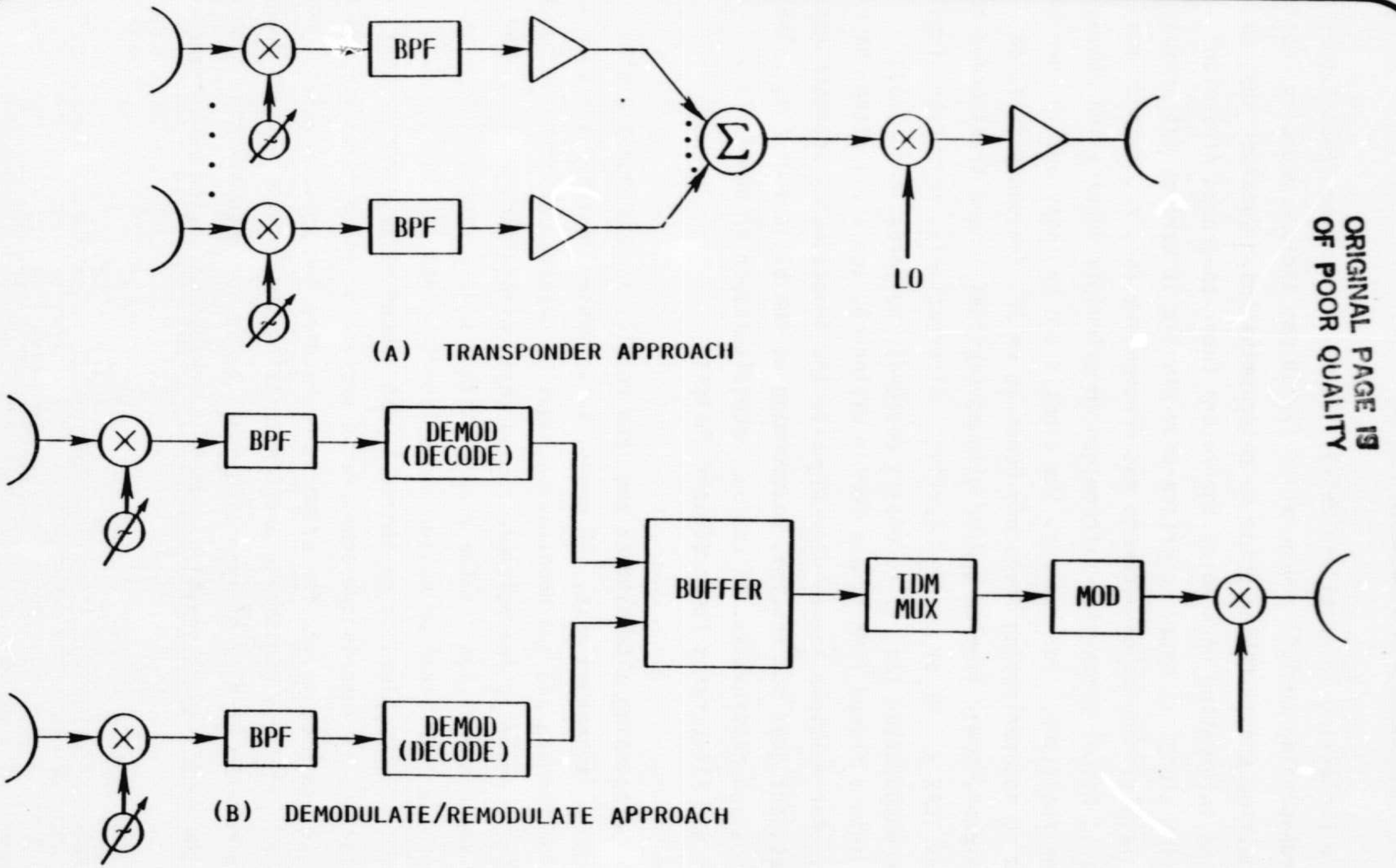


FIGURE 6-3: ONBOARD PROCESSOR APPROACHES FOR THE CROSSLINK RANGE FROM PURE TRANSPONDING TO FULL DEMOD/DECODE/ENCODE/REMOD. THE TWO EXTREMES ARE INDICATED HERE IN FIGURES (A) AND (B), RESPECTIVELY.

The choice between transponding and onboard demodulating will be driven primarily by technological readiness, but it seems appropriate here to note that onboard demodulation as an end in itself has, for TDAS, less of the appeal that it might have for military strategic/tacctical data nets or commercial switching operations. The advantages of onboard demodulation for interference rejection and beam switching do not address crucial TDAS issues.

Demodulation does eliminate the need to increase link margins so that retransmitted noise is not a problem. On the whole, we conclude that onboard demodulation is a potential burden that, if accepted, is done so because of a more-than-compensating advantage accrued elsewhere, or because the status of enabling technology demands it.

Onboard processing for the forward link (ground-to-user) is less an issue. By analogy to TDRSS, there is no need to demodulate the ground-to-space link at the front side TDAS, since the various channels are assigned via FDMA and can be demultiplexed for SA, MA, or crosslink transmission. A blind side TDAS receives the forward crosslink and treats it just as the front side TDAS treated the ground-to-space link. Thus, the processing can be restricted to filtering and frequency conversion in an independent forward link.

6.2.3 Receiver Alternatives (Laser Links)

There are two basic receiver techniques for laser communications, heterodyne and direct detection — sometimes referred to as "coherent" and "noncoherent", respectively, a confusing choise of terminology that we abandon. These are depicted in Figures 6-4 and 6-5.

6.2.3.1 Heterodyne Detection. Heterodyne detection is the optical analog of a radio receiver. Incident light is focussed to a diffraction-limited spot or collimated to a parallel beam and passed through an optical bandpass filter. Downconversion is performed by adding to this received field a field generated by a local oscillator (another laser), and allowing this sum to impinge upon a photodetector surface such as a photomultiplier

ORIGINAL PAGE IS
OF POOR QUALITY

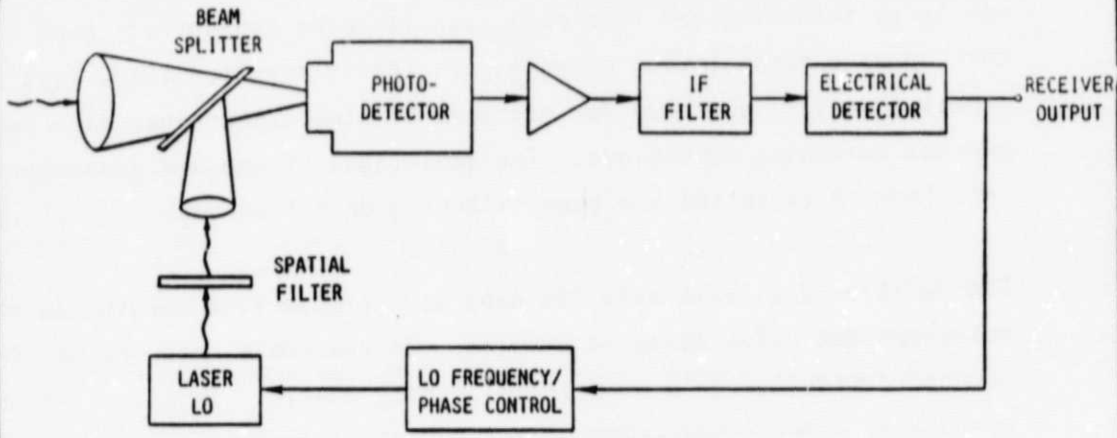


FIGURE 6-4: A HETERODYNE RECEIVER USES A PHOTOSENSITIVE DETECTOR TO MIX A SINGLE SPATIAL MODE OF A LOCAL OSCILLATOR WITH THE RECEIVED FIELD. THE TWO SIGNALS ARE COMBINED BY A HALF-SILVERED MIRROR PRIOR TO DETECTION, AND THE DETECTOR OUTPUT IS AT AN ELECTRICAL IF. THE MODULATION OF THIS IF IS DETECTED, AND THE RESULTING SIGNAL IS OUTPUT TO THE NEXT STAGE. THE DETECTOR OUTPUT IS ALSO FED BACK TO A PHASE-LOCK LOOP TO MAINTAIN A CONSTANT IF IN THE PRESENCE OF INPUT CARRIER DRIFT.

STANFORD
TELECOMMUNICATIONS INC.

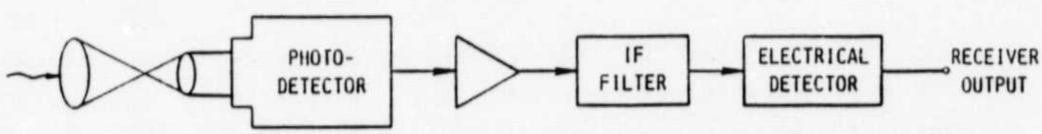


FIGURE 6-5: THE FRONT-END OPTICS OF A DIRECT DETECTION RECEIVER PRODUCE EITHER A DIFFRACTION-LIMITED SPOT OR A COLLIMATED BEAM THAT IS INCIDENT ON A PHOTODETECTOR SURFACE. THE DETECTOR MAY REQUIRE A FOLLOWING AMPLIFIER. AFTER IF FILTERING, AN ELECTRICAL DETECTOR RETRIEVES THE INFORMATION IN THE SIGNAL. THIS MAY BE A SUBCARRIER THAT IS DETECTED OR IT MAY BE A DIGITAL SIGNAL THAT IS DEMODULATED IMMEDIATELY. NOTE THAT THERE IS NO LO, AND THAT PHASE OR FREQUENCY LOCK TO THE CARRIER IS NOT REQUIRED AS LONG AS THE INPUT CARRIER REMAINS WITHIN THE PHOTODETECTOR BANDWIDTH.

STANFORD
TELECOMMUNICATIONS INC.

tube or an avalanche photodiode. The summation, shown in Figure 6-4 by incidence of both signals on half-silvered beam splitter, can be accomplilshed in a variety of ways. Since photodetectors respond to intensity, the electrical output of the photodetector contains a term at the difference frequency of the input carrier and the LO which is proportional to the input amplitude and retains its phase. In the special case that the LO tracks the input exactly in frequency, we have a homodyne receiver with a baseband output.

It is because of the temporal phase stabilities of the transmit and receive lasers that this receiver is designated "coherent". The receiver is not complete, however, for typical coherent communications functions until equipped with frequency- or phase-lock loops, just as is the case for RF links. And a heterodyne receiver can be used equally well for digital communications in which noncoherent or differentially coherent reception is appropriate. Furthermore, heterodyne receiver can be used when temporal coherence exists but the spatial coherence of the incident wave has been disrupted by the channel (e.g., the turbulent atmosphere). To minimize confusion, we designate the receiver by its generic type, not by the degree of coherence of signals it generates or processes.

In addition to the signal term, the output contains a noise signal known as shot noise or quantum noise. This term is present even if the input is noiseless and the system is otherwise ideal up to this point. Its origin is in photon detection and the subsequent photoelectron generation process; it is fundamentally a manifestation of the quantum mechanical uncertainty principle which denies the simultaneous, exact measurement of two canonically conjugate variables such as amplitude and phase. The amplitudes of the signal and noise terms are proportional to the LO amplitude, and with a strong enough LO the quantum noise can be made to dominate any dark current or thermal noise generated in the detector circuitry. Operation as close to this ideal quantum- or shot-noise limited condition is, of course, desirable.

6.2.3.2 Direct Detection. A direct detection receiver is somewhat simpler. The front end optics focuses of collimates the filtered incident radiation directly onto one or more photodetectors. Depending on the form of the signal to be detected, some beam splitting and polarization filtering may preceed the detector. The detector output is a shot noise process in which each detected photon has generated a pulse of fixed energy. Detecting energy of this waveform in time of frequency slots is equivalent to counting photon arrivals, which can be used as detection statistics in digital communications. Analog IF waveforms (subcarriers) can be detected as well, and subsequent electrical processing can demodulate analog or digital data so contained. Direct detection requires no local oscillator and no diffraction-limited optics.

Photon counting is an "energy-only" process which discards phase information and hence is not subject to any quantum-mechanical restriction on accuracy. Because carrier phase is not used, direct detection is dubbed noncoherent. Nonetheless, a simple example shows that fully coherent communications can be carried out by this means. Assume that a phase-modulated electrical subcarrier is intensity modulated onto a laser beam. Direct detection reception restores the intensity modulated component plus dc in the detector signal output envelope at IF. Electrical phase demodulation follows, coherently recovering the original data signal. This option is given further consideration in Section 6.3.4.

It is desirable that photodetectors used with direct detection receivers have internal gain in the photon-to-photoelectron conversion process, since there is no signal amplification by an LO - such as that found in a heterodyne receiver - to overwhelm thermal and dark current noise. Operating a direct detection receiver near the quantum limit is in general a difficult task.

Not all lasers are equally suitable for heterodyne and direct detection. In brief, the CO_2 laser is suited to heterodyne detection, the Nd:YAG to direct. Receivers of both types have been demonstrated for GaAlAs.

6.3 COMMUNICATION/NAVIGATION CONFIGRUATION ALTERNATIVES

Most of this seciton will concentrate on the laser alternatives, there being a greater variety of these. But first the RF configuration question is addressed.

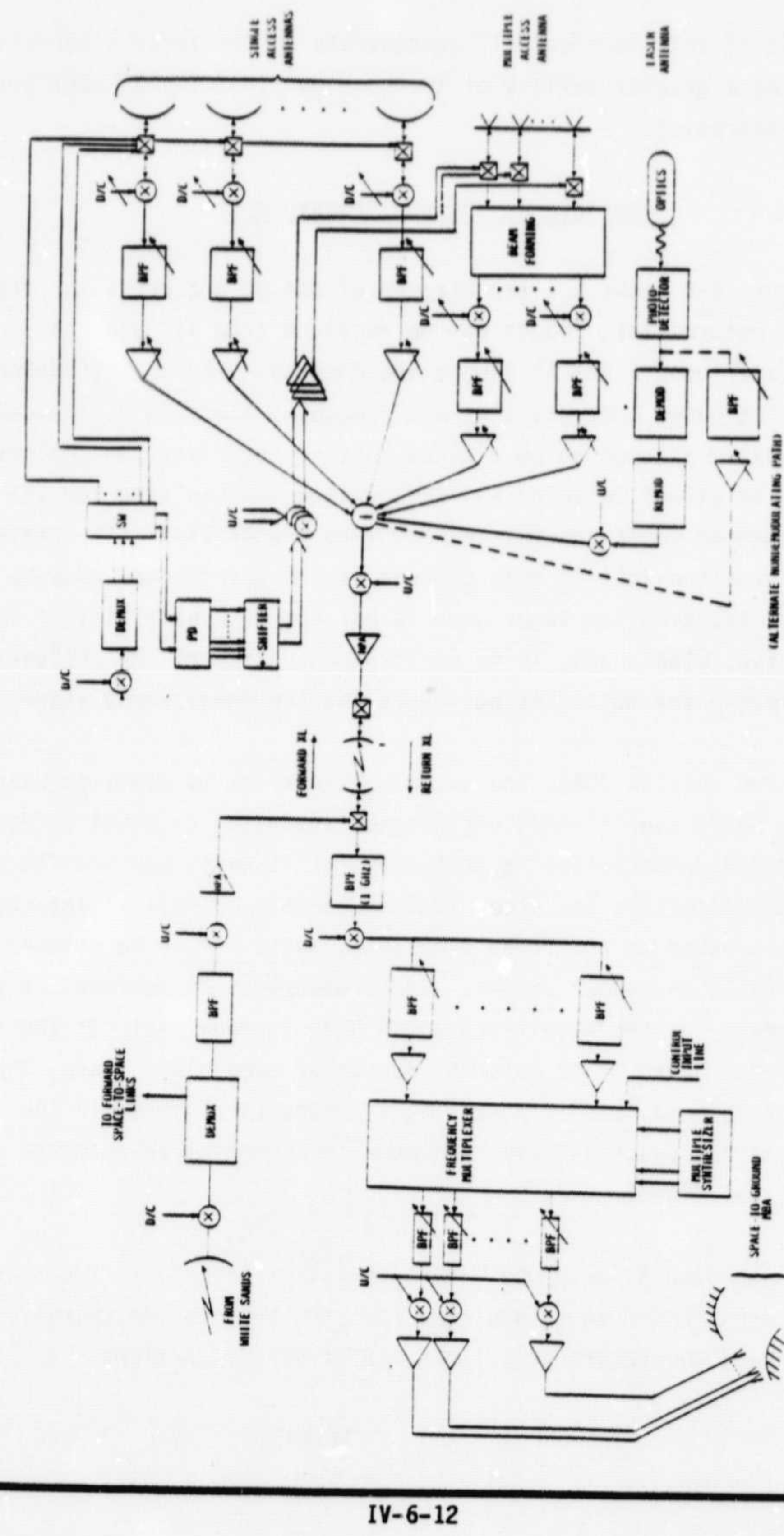
6.3.1 Approach A: 60 GHz Transponder

Figure 6-6 shows a block diagram of the 60 GHz crosslink transponder. On the return link, inputs may be received from all user services, including a laser user. The RF inputs are downconverted to a wideband IF where, following power control, they are frequency division multiplexed. For the LSA signal – assumed to be digital data — there are two choices. The signal may be direct detected and demodulated, remodulated for the crosslink, upconverted to IF and multiplexed into the RF link data stream. Tracking information lost in this process is not detrimental because it is assumed that tracking the laser user is not the responsibility of TDAS. The alternative, also shown, is to amplify and upconvert the photodetector output directly for multiplexing, bypassing the demod/remod stage.

At the receive TDAS, the incoming crosslink is demultiplexed at IF, following which user signals are grouped according to downlink destination. No onboard demodulation is performed (if it were, our architecture would have demodulators in the other TDAS spacecraft as well). The LSA signal, if transponded to the front side TDAS, would simply be demuxed and routed as would any other signal. If it underwent demod/remod at the first TDAS, symmetry of the satellites would have it done again at the second. But because there is no apparent reason to demodulate again, the preference is to transpond, possibly leaving a demodulator unused in the front side TDAS. These observations favor the pure transponding approach to crosslinking the LSA signal.

In approach A, only one W-band crosslink antenna is required per crosslink on each TDAS. It is diplexed for simultaneous T/R operation because the forward and return crosslinks are at offset carriers.

FIGURE 6-6: APPROACH A: 60 GHz CROSSLINK



STANFORD TELECOMMUNICATIONS INC.

6.3.2 Approach B: Laser Demod/Remod

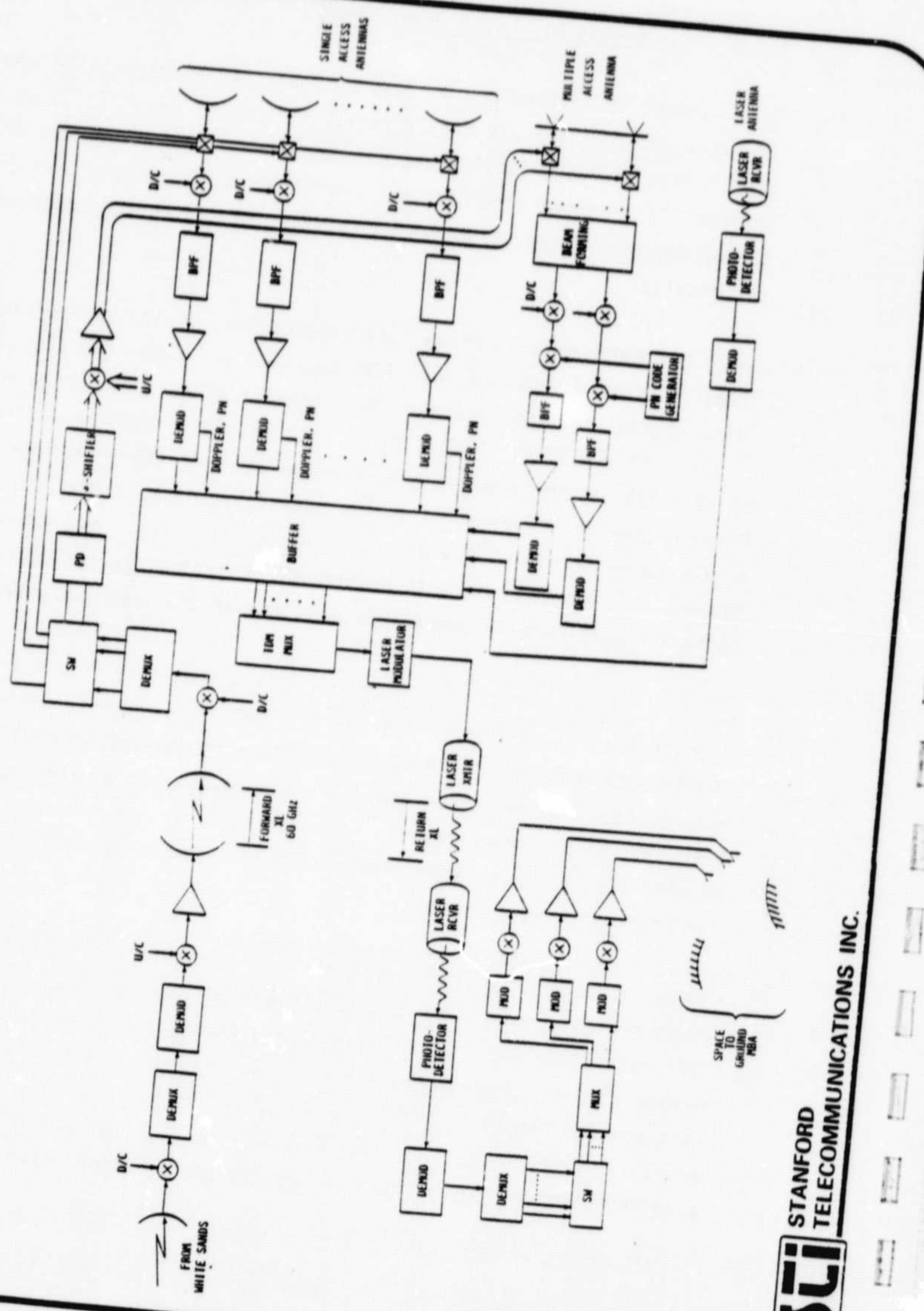
Laser crosslink options are defined by their signal processing approaches, and only subsequently are they directly related to specific laser technologies. This approach facilitates distinguishing between conceptually and technically inspired alternatives, and allows us to draw on the crosslink technology discussion of Volume VII without having to reproduce entirely its results.

There are fundamentally three laser approaches. Briefly, Approach B utilizes full demod/remod at both TDAS satellites. Thus, the crosslink is fully digital and uses a direct detection receiver. Two closely related versions of B will be shown: B_1 is a laser-only crosslink system, whereas B_2 is a hybrid that employs both a laser and a 60 GHz crosslink. Approaches C and D have no demodulation at the satellites; they differ in that C has a heterodyne receiver, D a direct detection receiver. Yet another possible option, full demod/remod with heterodyne detection, is not discussed because it is not particularly compatible with any of the applicable technologies.

6.3.2.1 Approach B_1. Approach B_1 is illustrated in Figure 6-7. All user signals are demodulated at the initial TDAS. In order to accomplish this, carrier phase lock and bit synchronization in the presence of user doppler must be attained for all signals; PN despreading of spread signals must likewise precede demodulation. Accommodation of the multiple access signals necessitates that the beam forming and PN despreading (a distinct PN code for each user) be performed.

The demodulators must have variable rate capability to handle the full range of TDRSS data rates plus whatever new rates are introduced as new TDAS services. Every alteration of the demodulator configuration is commanded via the forward crosslink from the ground, and the return telemetry must confirm the result. In the demodulation process, user doppler is measured on any signals for which doppler navigation is required; the doppler information is digitized so that it can be crosslinked and downlinked

FIGURE 6-7: APPRAUCH B1: LASER DEMOD/REMOD CROSSLINK



to the ground station. Similarly, PN data that has been superimposed for ranging purposes will have its offset from a known reference measured in the delay-lock loop, and the measurement also becomes part of the crosslink data stream. A more detailed understanding of these operations can be had by studying block diagrams of the White Sands receiving terminal, whose functions this TDAS essentially replicates in space.

There is an issue as to whether decoding of encoded data should be done onboard. From the point of view of relieving TDAS burden it is preferable to postpone decoding until the ground station, but this may not be possible if the net crosslink data rate (in encoded bits/s as opposed to information bits/s) will thereby require bandwidth in excess of what the implementation technology can provide.

The demodulated bits are buffered and TDMA framed along with control data that identifies frame content for crosslink transmission. There is a trade-off between frame length and efficiency to be worked in this approach – a long frame has delay but low overhead; a short frame provides more timely delivery at the possible expense of overhead and net data rate. The digital TDMA stream modulates the optical carrier.

At the receive TDAS, the laser crosslink signal is detected and demodulated. We have made the assumption, supported by the technology data, that the crosslink digital modulation is amenable to direct detection. We demodulate because the modulation formats best suited to the optical crosslink are not efficient for the RF downlink, thus precluding a transponding option at this point. Unfortunately, the equipment designed to demodulate the user signals is not usable in the crosslink demodulation function, and thus a separate laser demodulator is required (this could be the same demodulator that demodulates the front-side laser user, but only <u>if</u> that user and the crosslink employ identical lasers, formats, etc. and <u>if</u> the conflicts of time sharing could be resolved).

The user RF demodulation equipment — which by our original premise is present — either remains unused (if front side users are not demodulated) or it demodulates those users. If the front side users are not demodulated, there would result two distinct downlink signal formats to the ground stations, barring the unlikely possibility that each user signal arriving at the front side TDAS via crosslink is regenerated in its original modulation, data rate, format, doppler shift, PN code, etc. for downlinking. Demodulation of the front side users is certainly not required for link closure purposes. But the equipment is in place, and to use it would permit a unified downlink format, along with some options to more efficiently use the link to the ground station by multiplexing front side and crosslinked user data in a ground-controllable format. These options are illustrated in Figure 6-8.

To conclude discussion of Approach B_1, we note that there would be a low capacity forward crosslink at 60 GHz. No RF return crosslink function is proposed, although equipment in each TDAS would be in place to provide it.

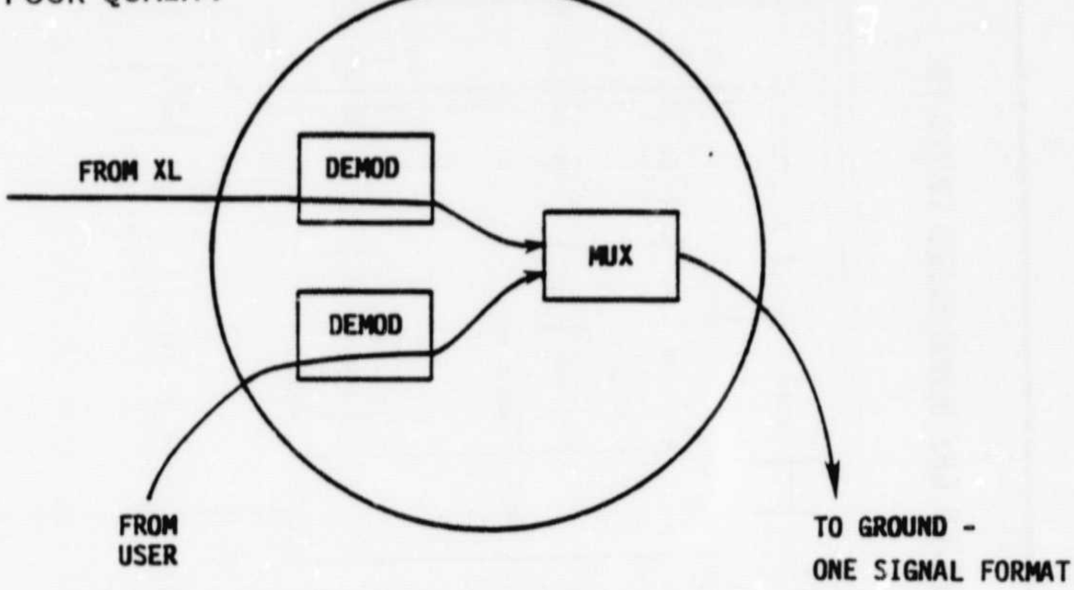
6.3.2.2 Approach B_2. Approach B_2 (Figure 6-9) is a modification of B_1 that retains the essential approach. The RF crosslink is used bilaterally here. The forward function is unchanged; the return link is used to carry the multiple access data. Thus, even though beamforming may still be carried out at the blind side TDAS, PN despreading, doppler tracking and demodulation onboard are obviated. Though this lessening of TDAS burden is the major improvement, there is also a decrease in the optical return link throughput that may be interpreted as an increase in margin.

The laser technologies appropriate to Approaches B_1 and B_2 are Nd:YAG and GaAlAs.

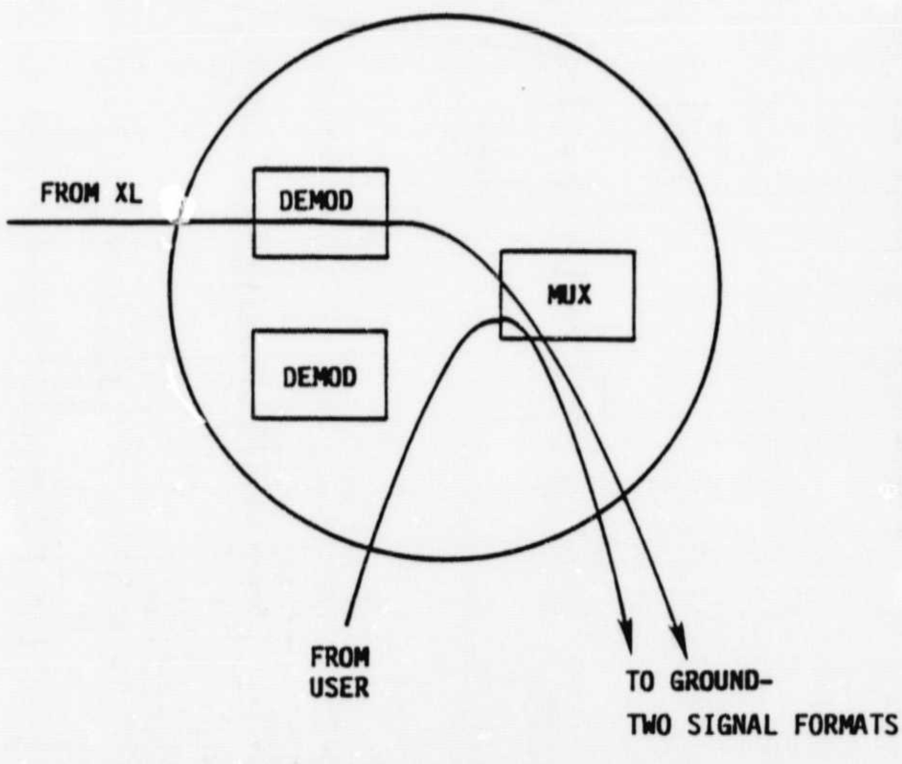
6.3.2.3 Functional Design Considerations for Approach B. The preceding subsections focused attention on the key spacecraft functions associated with implementing a laser demod/remod crosslink alternative. The objective now is to present a detailed TDAS spacecraft configuration that supports these crosslink capabilities as well as all the intended TDAS user services.

FIGURE 6-8: OPTIONS FOR FRONT-SIDE USERS WITH DEMOD/REMOD CROSSLINKS

ORIGINAL PAGE IS
OF POOR QUALITY



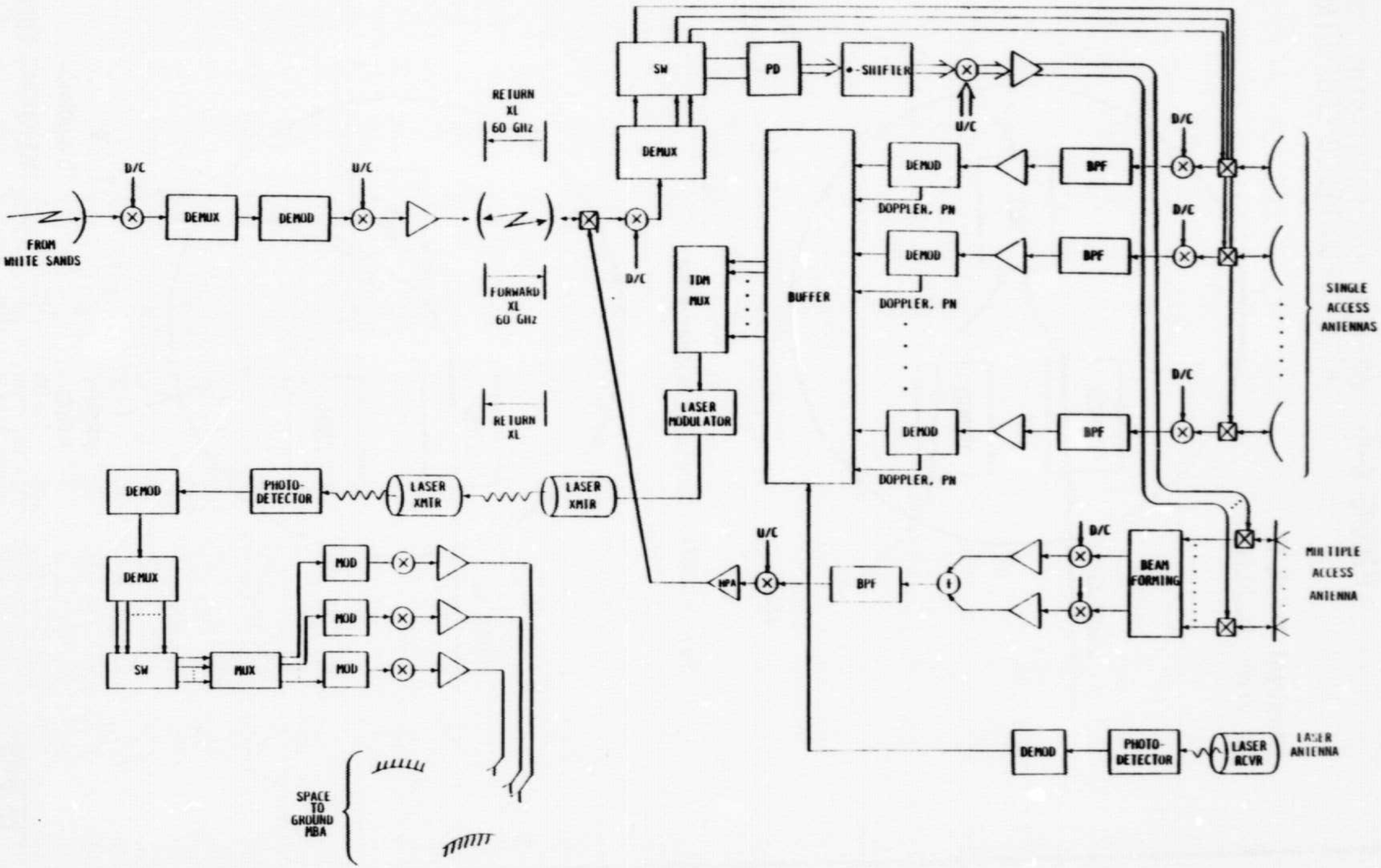
(a) FRONT-SIDE USERS DEMODULATED



(b) FRONT-SIDE USERS NOT DEMODULATED

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 6-9: APPROACH B2: HYBRID LASER/60 GHz DEMOD/REMOD CROSSLINK



STANFORD
TELECOMMUNICATIONS INC.

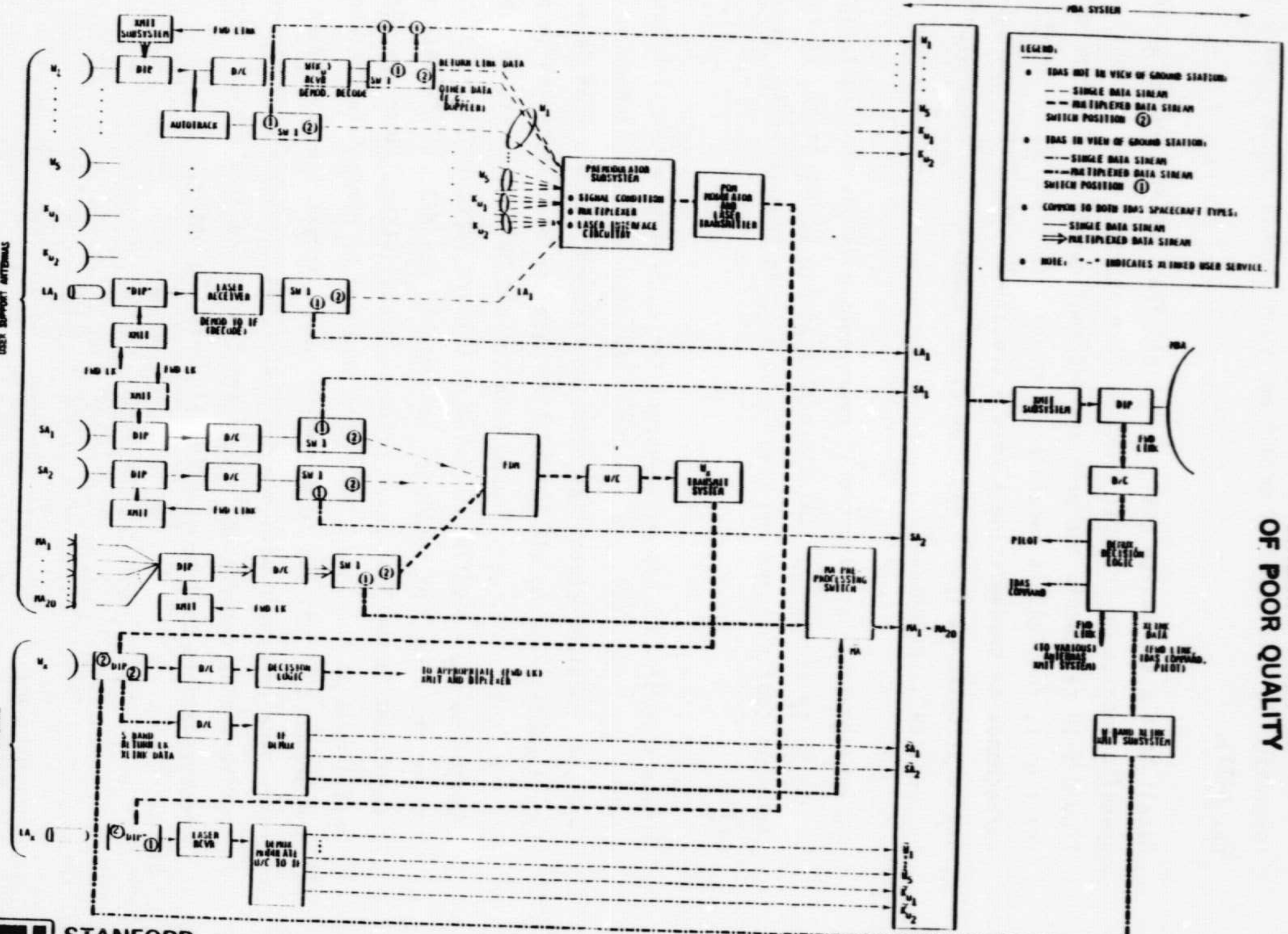
This material is included because of the considerable impact on the spacecraft architecture of demod/remod processing. The reader not immediately interested in this level of detail may turn directly to Section 6.3.3 (p. 6-27).

Recall that a key design goal is that all TDAS S/C are identical and that specific receive or transmit functions are appropriately switched in. Figure 6-10 represents the proposed S/C configuration; with the switch in Position 1, the TDAS is receiving a return crosslink, while Position 2 corresponds to transmitting a return crosslink. These two configurations are referred to as Type 1 and Type 2, corresonding to "front side" and "blind side", respectively.

The configuration of Figure 6-10 represents a slight modification to Approach B2 by adding all SSA return data to the 60 GHz link. It is clear that this configuration can readily be adapted to support Approach B1 as well.

Either type of TDAS S/C must support the following return link user services: WSA, KSA, SSA, LSA and SMA. The user support antennas in Figure 6-10 both receive return link data and transmit forward link data. In the Type 1 configuration, all return link data can be transponded to ground. For the Type 2 S/C, only S-band data (SA and MA), which are relayed via the coherent 60 GHz crosslink, require no onboard demodulation or decoding. Because the crosslink modulator is digital, the WSA and KSA data must be demodulated in the Type 2 S/C prior to crosslinking. When the WSA or KSA data arrive at the Type 1 S/C, they need not be demodulated before relay to the ground station, but to provide a common format for all W-band and K_u-band space-to-ground data would dictate that the spacecraft incorporate receivers that demodulate in both the Type 1 and Type 2 configurations. These receivers will be described in detail shortly.

FIGURE 6-10: TDAS SPACECRAFT CONFIGURATION



STANFORD TELECOMMUNICATIONS INC.

ORIGINAL PAGE IS OF POOR QUALITY

The following items will now be treated individually:

- Type 2 S/C Configuration (Figure 6-10)
- Type 1 S/C Configuration (Figure 6-10)
- K_u(W)-Band Onboard Receiver (Figure 6-11)
- Data Demodulator for the K_u(W)-Band Receiver (Figure 6-12).

Type 2 S/C Configuration

The spacecraft configuration of concern here is that of Figure 6-10 with the switch SW1 is set to Position 2. SMA and SSA return links are received by their respective antenna subsystems, downconverted and frequency multiplexed. This multiplexed data stream is then upconverted and crosslinked by the W_x antenna via the 60 GHz crosslink channel. All return K_u-band (two KSA channels) and W-band (5 WSA channels) links are received by their respective antenna subsystems, and are subsequently downconverted, demodulated and decoded. Autotrack information for each channel is extracted at the diplexer prior to the downconversion process. All decoded user data and autotrack information are passed to the Premodulation Subsystem prior to laser crosslinking. If a single access laser user is being supported, its demodulated and decoded data also form part of the input to the premodulation system.

The Premodulation Subsystem includes the following:

- Signal Conditioner
- Multiplexer
- Laser Interface Circuitry.

The multiplexed data out of this subsystem are modulated and crosslinked by the laser transmit subsystem via the laser crosslink.

All forward link communications are received by the W-Band (60 GHz) crosslink. These received data are downconverted, demultiplexed and switched to the appropriate forward link user antenna transmit subsystem.

Type 1 S/C Configuration

The Type 1 S/C configuration constitutes Figure 6-9 with the switch SW1 set to Position 1. In this configuration, user return link data are received both from the "user support" antennas and, indirectly, via the W-Band (W_x) and laser (LA_x) crosslink antennas. All this return link communications is ultimately destined for the space-to-ground link.

Return link data received via the laser crosslink consist of K_u-Band and W-Band user data and are detected by the laser receiver. These detected data are demultiplexed, upconverted from baseband to IF and subsequently passed to the IF switch.

The return data arriving at the 60 GHz crosslink antenna (W_x) comprise both SSA and SMA user return link data. After downconversion and demultiplexing, the SSA portion is directed to the IF switch; the SMA data are first processed by the SMA preprocessing switch, whose output is then passed to the IF switch. This preprocessing switch reduces the complexity of the IF switch. Since the maximum number of MA users supported by TDAS at one time is ten, it may be that not all ten user channels from each TDAS S/C are active simultaneously. The SMA preprocessing switch selects only those active channels for the IF switch.

Return link data from W-Band and K_u-Band users that enter via the respective user support antenna rather than the crosslink antenna are downconverted to IF, demodulated and decoded by the onboard receivers. The receiver outputs are subsequently passed to the IF switch.

In constrast, S-band return link data are neither demodulated nor decoded onboard. The SSA data are downconverted and sent directly to the IF switch, whereas the MA channels have intervening processing by the MA preprocessing switch.

Forward Link S/C Configuration

Forward link data received from the ground stations are of these forms:

- TDAS Command
- Pilot
- Forward User Data.

After reception at the MBA receiver, the data are downconverted and demultiplexed. Subsequent routing ensures that data for blind side users are sent to the crosslink subsystem, and data for users directly supported by the front side TDAS are sent to the appropriate user antenna subsystems.

K_u (W) Band Receiver

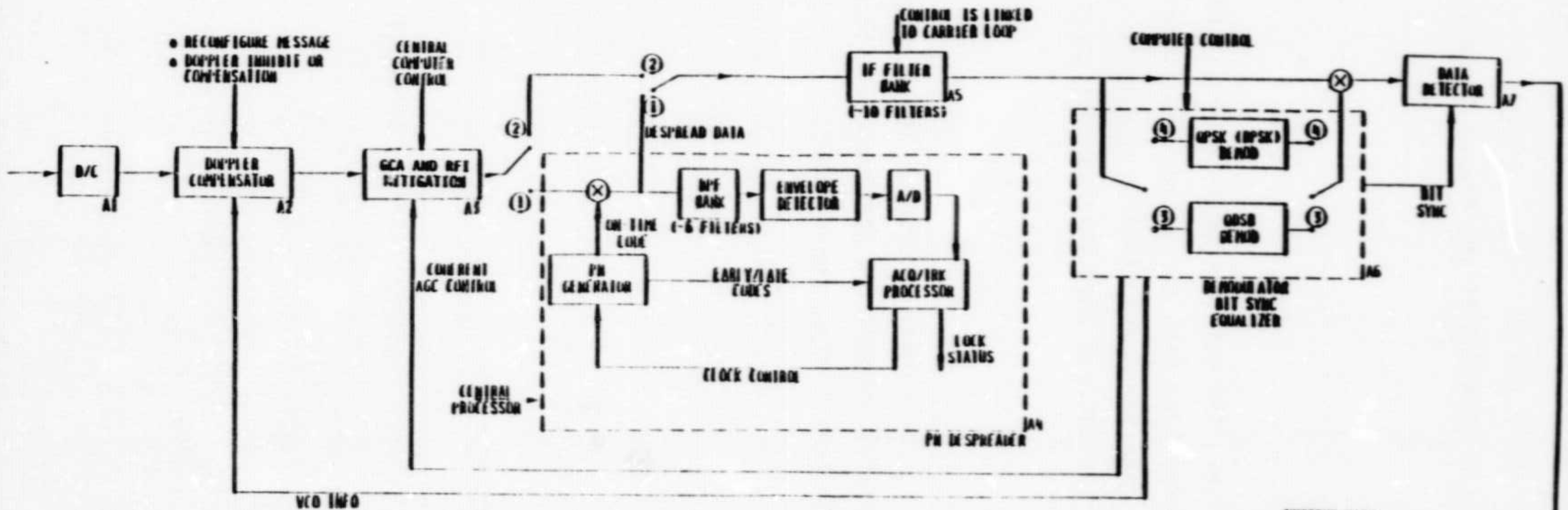
Figure 6-11 details the onboard K_u- or W-band receiver. The receiver (which is identical in both type spacecraft) demodulates and decodes. It must handle all user signal formats currently supported by TDRSS:

- PN coding
- NRZ, Bi-ϕ signalling
- BPSK, QPSK (balanced, unbalanced), QDSB
- Special Shuttle unique requirements
- Uncoded, Coded (Convolutionally encoded/Viterbi decoded)
- $1 \text{ kbps} < \text{Data Rate} < \begin{cases} 300 \text{ Mbps } (K_u) \\ 50 \text{ Mbps } (W) \end{cases}$

Other potential capabilities may include RFI mitigation and deinterleaving.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 6-11: Ku (W) BAND RECEIVER



INPUT

- BPSK, QPSK (BALANCED OR UNBALANCED), QDSB
- UNCODED, CODED R - 1/2, CODED R - 1/3
- NRZ, BIPHASE
- PN CODED (LOW DATA RATES ONLY)
- INTERLEAVING POSSIBLE (?)
- DATA RATE R_D > 1 Kps; < 300 Mbps (Ku)
  > 1 Kps; < 50 Mbps (W)

ADDITIONAL NOTES

- POTENTIAL DIFFERENCES BETWEEN Ku AND W RECEIVERS
  - NO RFI MITIGATION ON W-BAND
  - PERHAPS NO ADAPTIVE EQUALIZERS ON W-BAND (PRESENTLY ADAP. EQUAL ON Ku-BAND FOR DATA RATES > 75 Mbps)
- INTERLEAVING PRESENTLY ONLY AT LOW DATA RATES S-BAND

REQUIREMENTS AND OTHER ISSUES

(A1)
- CONVERTS RF TO 370 MHZ IF

(A2)
- RECEIVES DATA FROM CARRIER LOOP
- RECEIVES COMMANDS FROM CENTRAL COMPUTER

(A3)
- COULD TAKE THE FORM OF SOME COMBINATION OF
  - CONTROLLABLE CLIPPER
  - FAST/SLOW NONCOHERENT AGC
  - COHERENT AGC
- PROVIDES AMPLITUDE INFO TO PN LOOP
- MAY NOT BE NECESSARY FOR W-BAND

(A4)
- DIGITAL PROCESSING FEASIBLE SINCE RELATIVELY LOW DATA RATES
- 6 FILTERS IN BPF BANK (BASED ON CURRENT CONFIGURATION)

(A5)
- NUMBER OF FILTERS BASED ON FOLLOWING DATA RATE RANGES
  - 1 KBPS → 4 KBPS
  - 4 KBPS → 15 KBPS
  - 15 KBPS → 60 KBPS
  - 60 KBPS → 250 KBPS
  - 250 KBPS → 1 MBPS
  - 1 MBPS → 5 MBPS (8 BITS, 16 SAMPLES)
  - 5 MBPS → 50 MBPS (4-8 BITS, 2-6 SAMPLES)
  - 50 MBPS → 150 MBPS (2 ANALOG)

(A6)
- DEMOD INCLUDES
  - CARRIER RECOVERY
  - BIT SYNC
  - EQUALIZER
- QDSB - SHUTTLE K-BAND ONLY

STANFORD TELECOMMUNICATIONS INC.

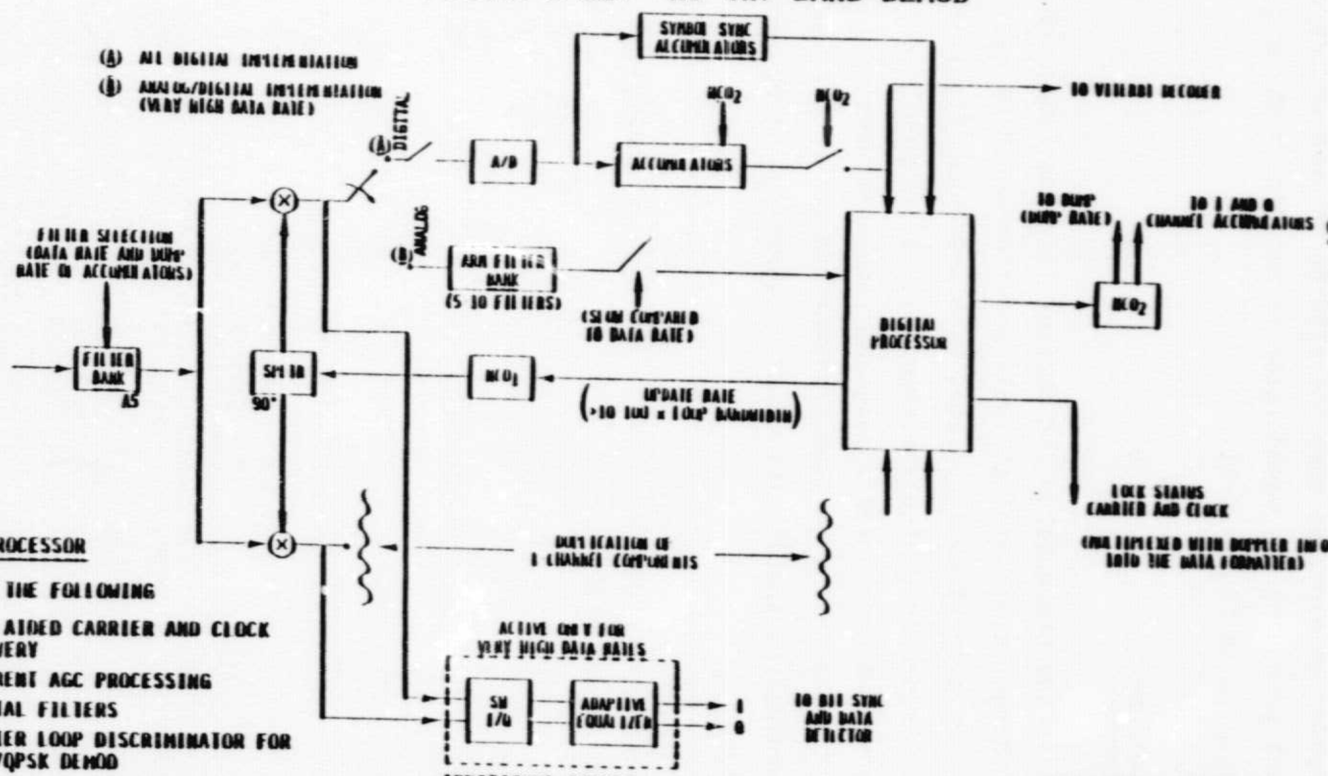
The input IF signal is appropriately updated in frequency by the doppler compensator. Subsequent processing to mitigate RFI effects may encompass some AGC circuitry driven by feedback information from the demodulator. PN coded signals are then despread and the despread signal is input to the IF filter bank — the despreader is bypassed when there is no PN code on the data. The IF filter bank preceding the demodulator is matched to the eight ranges of data rate indicated in Figure 6-11.

K_u(W) Band Demodulator

Figure 6-12 details the demodulator (or carrier tracking loop) imbedded in Figure 6-11. Although an all-digital implementation would be desirable, the potentially high data rates associated with the input signal may make this infeasible. Accordingly, the implementation of Figure 6-12 pairs an all-digital loop with a hybrid analog/digital loop that handles the very high data rates. A prediction of 1988 state-of-the-art technology in A/D converters is required to specify the exact crossover point between these two implementations.

For additional information related to interleaving, RFI mitigation, bandwidths, etc., see Figure 6-12.

FIGURE 6-12: Ku (W) BAND DEMOD



DIGITAL PROCESSOR

- ENTAILS THE FOLLOWING
  - DATA AIDED CARRIER AND CLOCK RECOVERY
  - COHERENT AGC PROCESSING
  - DIGITAL FILTERS
  - CARRIER LOOP DISCRIMINATOR FOR BPSK/QPSK DEMOD
- OPERATIONS
  - CARRIER LOOP ERROR SIGNALS
  - AQ/TRK LOOP FILTER CONTROL AND SWEEPING
  - FALSE LOCK REJECTION
  - LOCK DETECTION AND LOCK STATUS (AFTER LOCK ACQUISITION)
  - APPROPRIATE ARM SELECTION FOR BPSK
  - ACCUMULATOR OPERATION MAY VARY WITH NRZ OR BIPHASE

ADDITIONAL ISSUES

- SELECTION OF ALL DIGITAL (Ⓐ) OR ANALOG/DIGITAL (Ⓑ)
  - AT VERY HIGH DATA RATES MAY NOT BE FEASIBLE TO A/D AND OBTAIN SUFFICIENT NUMBER OF SAMPLES AND BITS
- SAMPLING RATE INTO NCO_1 MAY BE RELATIVELY SLOW

ADDITIONAL NOTES

- ¼ - ½ DB DIFFERENCE BETWEEN 3 BIT AND 2 BIT SOFT DECISION VITERBI DECODER
- BIT SYNC DOES ESSENTIALLY THE SAME OPERATIONS AS THE DIGITAL PROCESSOR EXCEPT (1) NO SWEEPING AND (2) NO FALSE LOCK REJECTION

STANFORD TELECOMMUNICATIONS INC.

6.3.3 Approach C (Laser Transponder/Heterodyne Detection)

The essential characteristic of Approaches C and D is the transponding of user data without prior demodulation. The two differ in the laser receiver mechanism.

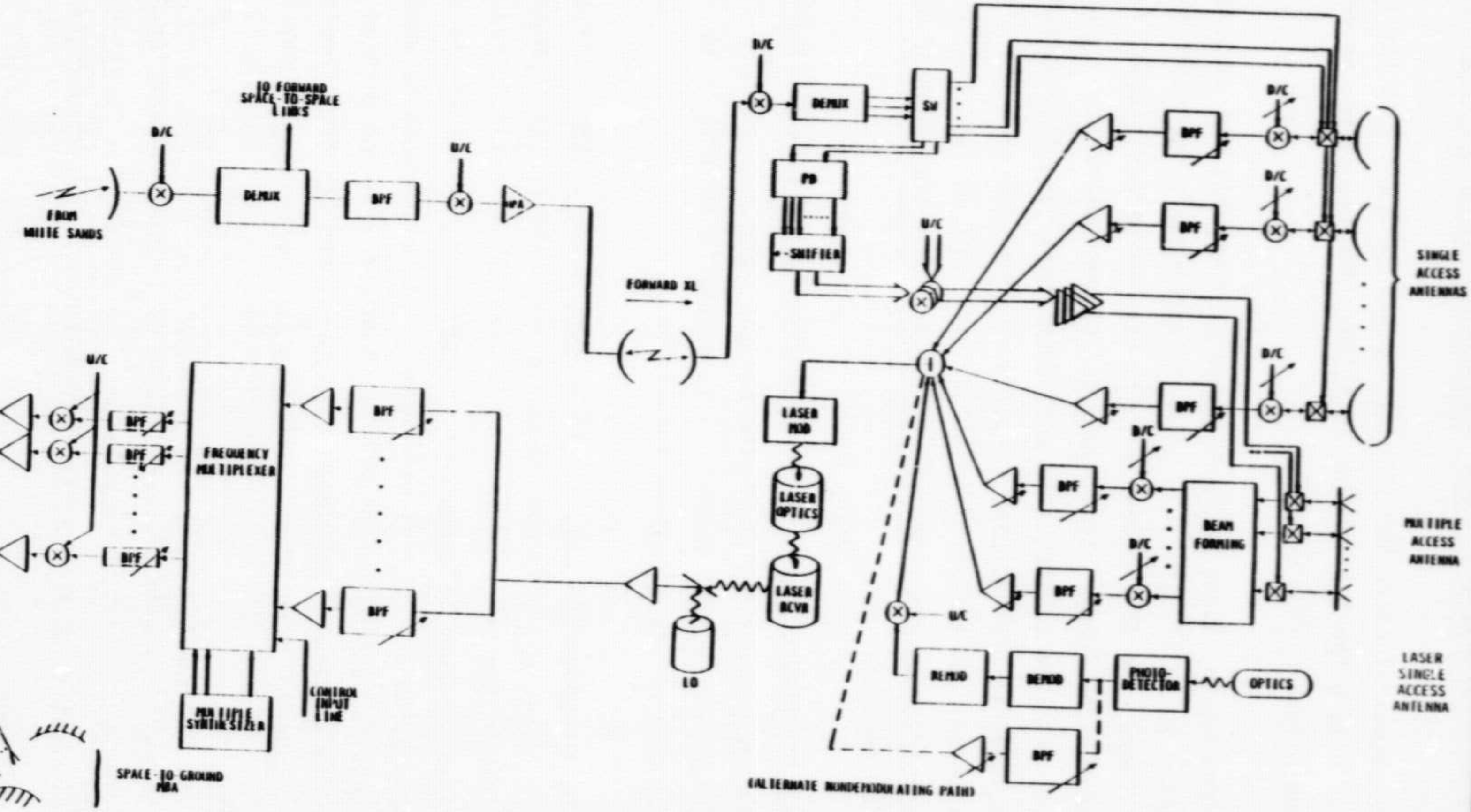
According to Figure 6-13, received user signals are individually downconverted to an IF band. In order to accommodate the most general scheduling of users, the IF frequencies will have to be assignable via ground control through the forward link, just as the demodulator configuration in Approach B is set from ground; this assignment must take into account guard bands to accommodate user doppler. Following downconversion the signals are bandpass filtered, and because this filtering should be tailored to the user signal bandwidth and the anticipated doppler, this operation is also under forward link control.

The IF signals can be power controlled prior to multiplexing, if need be. The requirement for this step has not been studied fully yet. It has no TDRSS counterpart; whether it is needed in general is to some extent a function of the crosslink modulation.

The downconverted signals are summed, which yields a frequency division multiplex, and this sum signal is ready for crosslink modulation. Because a heterodyne receiver is used, a modulation that required amplitude and phase recovery is acceptable. Suppressed carrier AM and phase or frequency modulation are logical candidates. Since there is no apparent need for the bandwidth expansion capability of PM and FM - and perhaps no spare bandwidth available into which to expand - AM, which is simpler to implement is adequate. FM modulator/demodulator technology at GHz bandwidths is also an issue.

In the subsequent discussions, AM will denote modulation in which the field strength is linearly modulated. The alternative is intensity modulation (IM), in which the carrier intensity is directly amplitude modulated. The

FIGURE 6-13: APPROACH C: LASER CROSSLINK WITH HETERODYNE DETECTION



AM subcarrier technique is 6 dB more efficient in SNR than IM for shot-noise limited heterodyne operation, and is, therefore, preferable.

At the receive TDAS, the incoming signal is heterodyned with the LO and detected. (Homodyne detection, which can be up to 3 dB superior in SNR, cannot be used unless each user signal can be individually converted to baseband. The LO frequency is driven by a frequency tracking loop configuration that maintains its frequency at a fixed offset to the carrier. Since the link is between two stationary or nearly geostationary spacecraft, the carrier doppler is much less than would be found in a user-to-TDAS optical link. Optical frequency trackers aer analogous to these used at RF, especially at strong signal levels. For weaker signals more extensive processing is required.

A linear envelope detector operating on the photodetector output recovers the FDM data, which is then separated by filtering into bands for transmission to the various ground stations. The data needed to control the filtering and demultiplexing is the same as that forwarded to the blind side TDAS and would already be present in memory at the receive TDAS. The group of signals designated for a given ground station is remultiplexed as required for that purpose.

A word about the laser user in this approach. Unlike the treatment of the RF user signals, the laser user could be demodulated at the blind side TDAS, but this is not necessary. Instead, the photodetector current can be converted to IF and transmitted in the FDM stream. At the front side TDAS, there is again the choice of demodulating vs transponding. The choice here will likely have strong operational drivers concerning the nature of the laser user technology, signal format, and mission-related factors such as security needs. Although the transponding approach seems preferable for the crosslink, it does not seem critical to worry about this choice now.

The technologies appropriate to Approach C and CO_2 and GaAs, since both can be operated in CW mode and can sustain heterodyne reception.

This approach will now be contrasted to direct detection of the transponded signals, in which link efficiency is sacrificed for a simpler receiver structure.

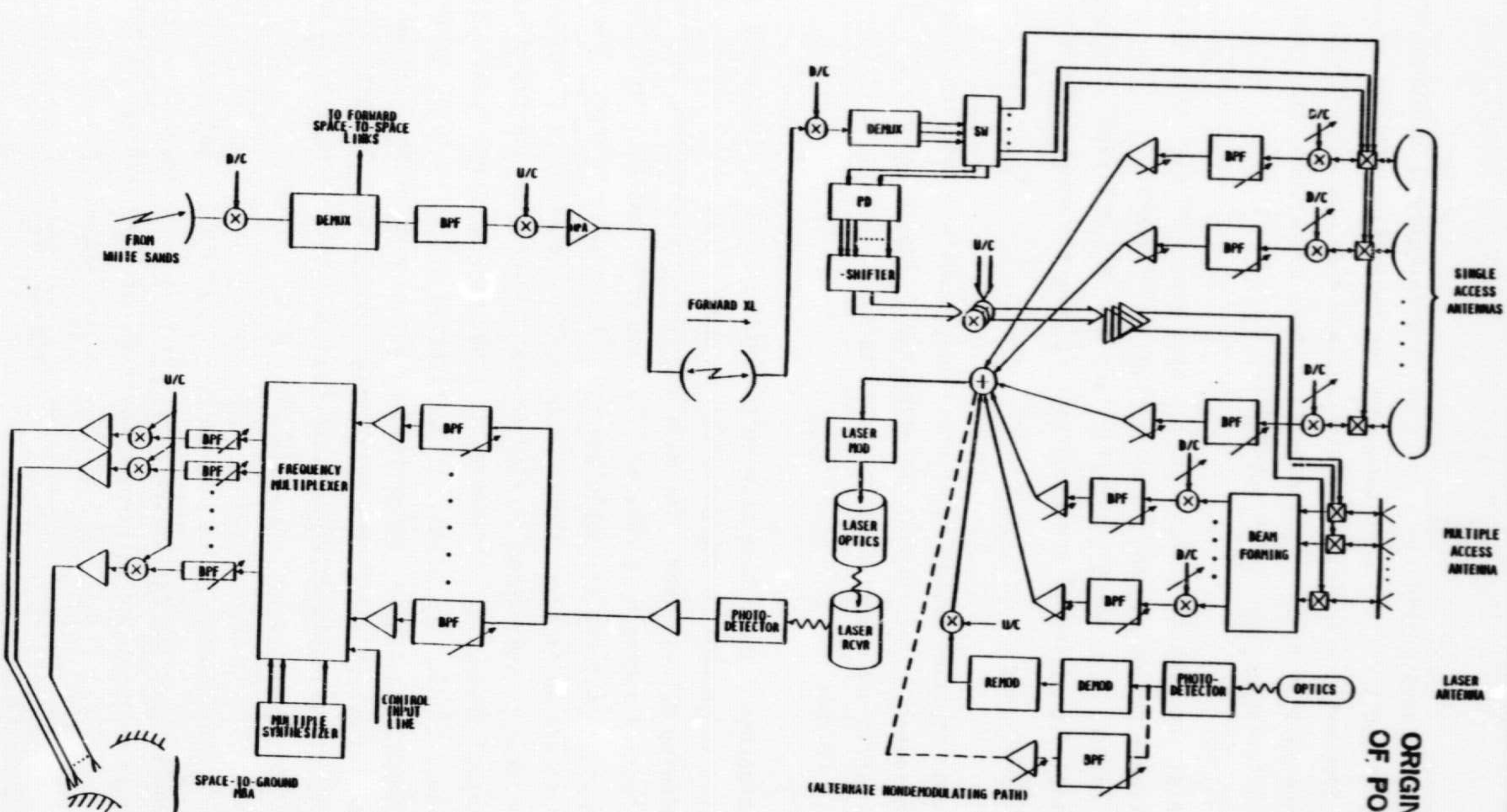
6.3.4 Approach D (Laser Transponder/Direct Detection)

Approach D, shown in Figure 6-14, employs direct detection reception of the crosslink. It is not correct, however, to think of this as a one-for-one receiver replacement in Approach C, because this choice has other system implications which we shall see as we progress.

Processing of user input signals at the blind side TDAS is no different than in the previous approach through the creation of the FDM signal. Because a direct detection receiver will not support carrier phase sensitive modulation, the modulation choices previously considered are inappropriate. Phase recovery is essential for demultiplexing the FDM components regardless of the role of phase in the individual user signals, and thus an analog modulation in which the net amplitude and phase is retained in the carrier amplitude alone is required. For direct detection optics this implies a subcarrier system in which an RF subcarrier (itself modulated by the information signal) intensity modulates the optical carrier.

Such modulation is considerably less efficient than suppressed carrier AM or IM because it contains a carrier component. Also, the modulation index of the net information signal must be controlled so that the modulation does not distort by trying to go negative. This can be accomplished either by clipping the FDM signal prior to amplitude modulation or by modulating the subcarrier with a constant envelope modulation, FM or PM. Clipping a few dB ($\sim$ 3 dB) above signal plus noise level can be expected to introduce neglible distortion in the user signals if they are adequately balanced in power (no small signal suppression). The FM or PM approach has the

FIGURE 6-14: APPROACH D: LASER CROSSLINK WITH DIRECT DETECTION



ORIGINAL PAGE IS
OF POOR QUALITY

STANFORD
TELECOMMUNICATIONS INC.

disadvantages previously cited: extra complexity in mod/demod technology and possibly little spare bandwidth for expansion. The advantage is that it does provide a distortionless constant envelope subcarrier. Since the issue appears to be weighted against phase modulation, the remaining description assumes an AM subcarrier.

The direct detection front end has been described earlier. Its photodetector output current is proportional to intensity, and therefore contains d.c. (removed by filtering) and the IM subcarrier. Subsequent electrical processing of the subcarrier follows the manner of the heterodyne receiver.

Among the laser technologies under consideration, only the GaAs lasers are candidates for Approach D implementation. The CO_2 wavelength is too great for efficient direct detection and the Nd:YAG cannot operate in the necessary CW mode.

Approaches C and D have much in common, as so it is worthwhile at this point to comment on the principle tradeoffs that must be evaluated in choosing between them. The main discriminator arises in that the direct detection approach is considerably less efficient than the heterodyne approach in terms of usable SNR for a fixed power output. There are two contributing factors, the first being the inefficiency of subcarrier IM compared to suppressed carrier AM when referred to quantum noise. The minimum theoretical difference is 9 dB, with measured results likely to exceed 10 dB. The second is the relative effective total noise levels. A heterodyne system can be operated within a dB of the quantum limit, whereas direct detectors, even those with appreciable gain, will still show noise levels well above the quantum limit, perhaps by 10 dB. Thus direct detection suffers by 20 dB or more in total.

In order to make up for this deficit, additional transmitted power must be generated or the optics aperture increased. The technology issues involved in power combining an array of GaAs diodes are discussed in Volume VII.

6.4 ACQUISITION AND TRACKING ISSUES

The method by which crosslink acquisition and tracking is performed is an important issue, one we have ignored until now. What we will do below is sort out the issues that take on importance in various of our alternatives. Because the TDAS spacecraft will be stationary or but slightly inclined, acquisition and tracking are not expected to be formidable problems. Nonetheless, acquisition and tracking assume critical roles alongside communications and navigation in selecting a system concept.

6.4.1 60 GHz Crosslink

A 60 GHz crosslink that can support Gbps data rates will undoubtedly require large apertures, giving rise to small RF beamwidths. A 2 m dish has 0.18° beamwidth, implying pointing accuracy at each end of well under 0.1°. The initiating member of the crosslink should be able to point open loop to the other satellite and encompass it within the error volume without scanning the beam because of the small uncertainties in the TDAS position. The receive satellite would open loop point to the transmitter and slowly scan until the acquisition signal is detected. The autotrack receiver should be capable of generating an error signal without the necessity of having more than one receiver, as would be the case in a monopulse system. Once lock occurs, the receive satellite transmits, and this signal is similarly acquired and tracked at the other TDAS. Once the two-way acquisition is complete, low dynamics tracking should continue virtually uninterrupted.

Little difficulty in this regard is anticipated for the 60 GHz crosslink. The more demanding problem of TDAS/user acquisition and tracking for the WSA service has already been studied and found to be without fundamental problems.

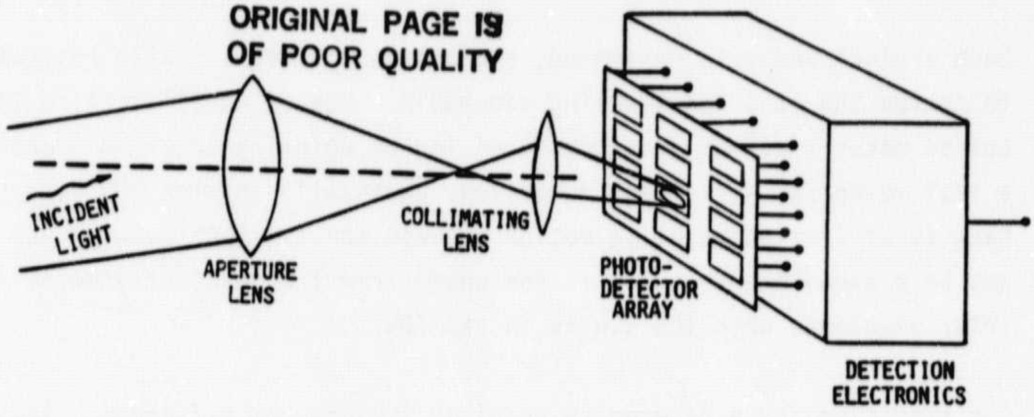
6.4.2 Laser Crosslink

The much narrower beamwidths (μrads) of laser sources necessitate some basic changes in the acquisition approach. A beacon laser, which may or may not be the laser used for communications, initiates the sequence by transmitting a beam that is spoiled or defocused considerably beyond the diffraction limited beamwidth achievable by the transmitting optics. This beam is scanned over the uncertainty region of the other terminal, which detects it and subsequently returns a widened beam to the initiating terminal. Reception of that beam halts the beacon laser scan and narrows its beamwidth. A narrower field of view detector in the beacon receiver detects the more intense beacon, and at this point may go into track mode, or may further iterate the above procedure.

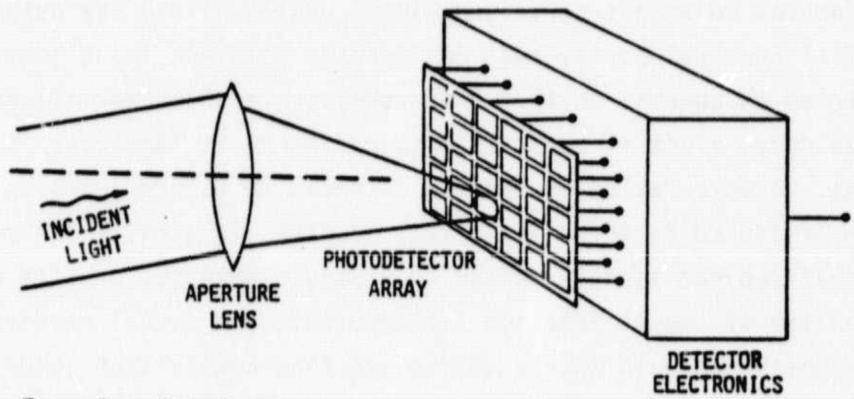
Unlike an RF receiver, the laser acquisition receiver can open its field of view (FOV) by using nondiffraction-limited optics, to permit many spatial modes (i.e., directions of arrival) to be received simultaneously. Figure 6-15 shows two ways this works for a direct detection receiver. The received beam impinges on a converging lens which is used to either focus or collimate the beam. In Figure 6-15(a) the beam is collimated by a second lens located a distance behind the aperture lens equal to the sum of the focal lengths of the two lenses. The collimated beam impinges on an array of photodetectors. In Figure 6-15(b) an array of photodetectors lies in the focal plane of the aperture. For a fixed aperture detector size the receiver that focuses to a diffraction limited spot has the larger field of view.

Each photodetector has its own receiver. For the focusing receiver, the determination of arrival angle can be done by threshold testing the maximum detector output. The collimating technique has less resolution because of the larger spot size, and this prompts the use of monopulse-like techniques to determine arrival angle.

ORIGINAL PAGE IS
OF POOR QUALITY



(a) Collimating Receiver



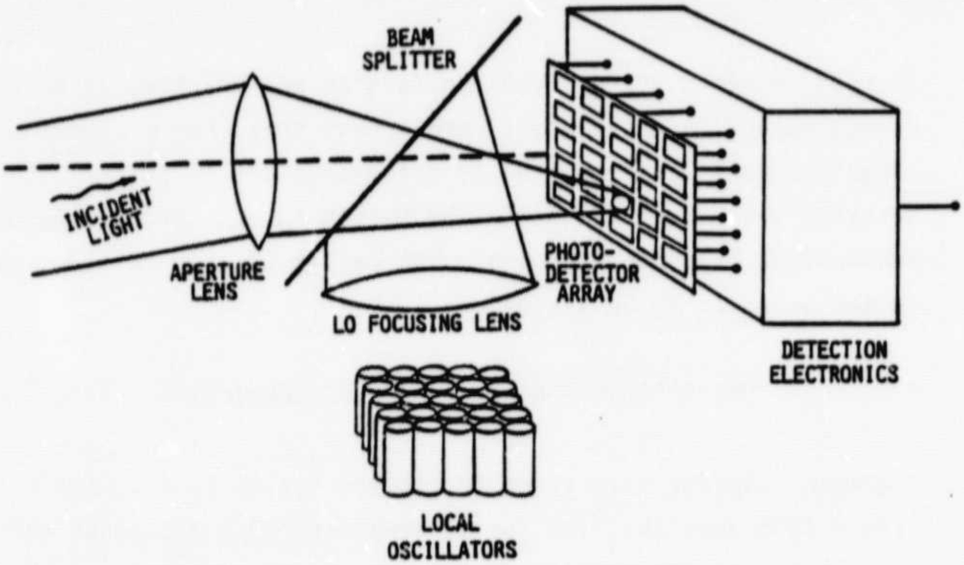
(b) Focusing Receiver

FIGURE 6-15: ACQUISITION TECHNIQUES FOR A DIRECT DETECTION RECEIVER. THE COLLIMATING RECEIVER (a) CREATES A LARGER SPOT THAN THE FOCUSING RECEIVER (b). WITH FOCUSING, THE DETECTOR HAVING MAXIMUM OUTPUT SPECIFIES THE SPATIAL MODE TO WITHIN DIFFRACTION LIMITED ACCURACY, WHEREAS WITH COLLIMATION, FEWER DETECTORS ARE USED, BUT THE OUTPUTS OF SEVERAL MUST BE SIMULTANEOUSLY PROCESSED TO DERIVE THE ARRIVAL ANGLE.

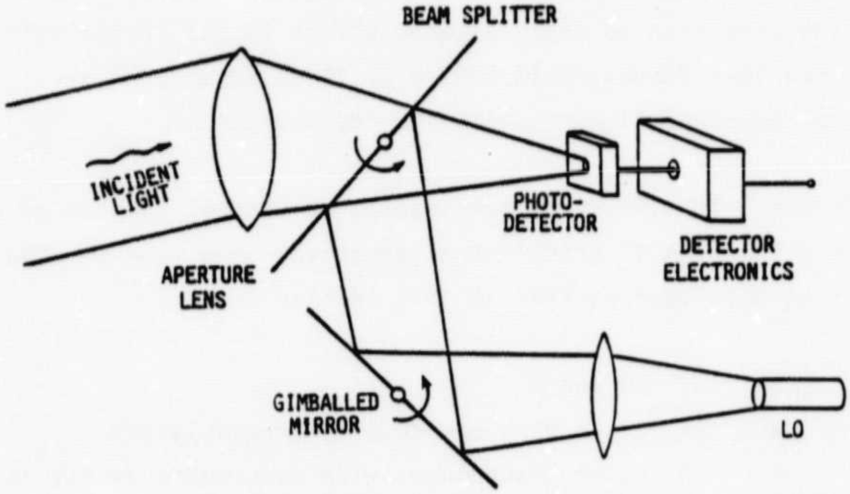
Once arrival angle is estimated, the optics are mechanically reboresited to center the spot and tracking can begin. Use of nondiffraction limited optics makes tracking somewhat forgiving of pointing error and constitutes a real advantage for direct detection, especially in wide FOV situations. Because of limited relative motion between the two TDAS's, wide FOV would not be a requirement. This is fortunate from the point of view of avoiding solar blackouts when the sun is in the FOV.

The situation for a heterodyne receiver is somewhat different. The focal plane array technique can be used by analogy to direct detection, but with a difference. Figure 6-16(a) shows an acquisition front end in which separate local oscillators illuminate each detector. Each oscillator must be focused to a spot contained almost wholly within the detector, and its spatial spectral purity must be high, or else one input mode will be detected in several cells. This receiver is shown for illustrative purposes only, since it has little to recommend it for actual space applications. A more realistic version is shown in Figure 6-16(b), where the beam of one LO is effectively made to scan via gimballed mirrors and have the heterodyned signal impinge on a single detector of size only slightly in excess of the diffraction limited spot. An actual receiver would differ considerably in that a coarse and fine acquisition stage would be accomodated. A more recently developed method for multimode heterodyne detection uses a technique of spherical mode mixing in which an opaque plane with an aperture lies behind the focusing lens and in front of the photodetector. Near field (Fresnel) diffraction from the aperture spatially separates the modes into spherical waves which are then incident on a detector array. The technology for this approach is still in development.

These multimode techniques are used because in actual operations it would not be adequate to focus the input to a diffraction limited spot on a large photodetector surface and mix it with an LO collimated to fill the detector surface. The LO signal incident on those portions of the surface devoid of input would induce shot noise and push the system away from quantum limited operation.



(a) Multi-oscillator Method



(b) Scanning LO Technique

FIGURE 6-16: ACQUISITION TECHNIQUES FOR A HETERODYNE RECEIVER. RECEIVER (a) IS THE LOGICAL EXTENSION OF THE METHOD USED FOR DIRECT DETECTION, BUT BECAUSE IT REQUIRES AN LO ARRAY, IT IS NOT OF PRACTICAL VALUE. BY USING A GIMBALLED MIRROR ASSEMBLY, A SEQUENTIAL SCANNING VERSION IS OBTAINED (b). ROTATION OF THE MIRROR THAT REFLECTS THE LO LIGHT SELECTS SPATIAL MODES WITHIN THE FOV, WHILE THE BEAM-SPLITTER ROTATION CENTERS THE SPOT ON THE PHOTODETECTOR.

In most respects, heterodyne acquisition and tracking is more complex than direct detection. One way to ameliorate this, for a system that is for link budget reasons better suited to heterodyne, is to perform the acquisition/tracking via direct detection and switch to a heterodyne receiver for communications (see Figure 6-17). The merits of this in terms of spacecraft burden have yet to be evaluated.

6.5 IMPLICATIONS FOR NEW TDAS USER SERVICES

A ground rule for this study forced the system to accomodate all established TDRS services, and the alternatives that are posed satisfy that rule. In considering the new services to be provided for the first time by TDAS, however, there is room to inspect the many tradeoffs between quality of service and TDAS spacecraft burden. In the following we confine attention to those aspects driven by the crosslink alternatives, since this issue should rank with those considered earlier in influencing the recommendation of crosslink implementation.

Figure 6-18 summarizes the impacts on various aspects of new user services as a function of crosslink alternative. The four alternatives shown are those developed earlier in this section:

- A: 60 GHz
- B: Laser with demodulation/remodulation
- C: Laser transponder with heterodyne detection
- D: Laser transponder with direct detection.

In reading Figure 6-18, we will find that alternatives A, C, and D have much in common as a result of adopting the transponder approach. Alternative B is found to differ with these three in almost all aspects. Where the table contains a dash entry, there is no restriction of the indicated feature under the corresponding alternative.

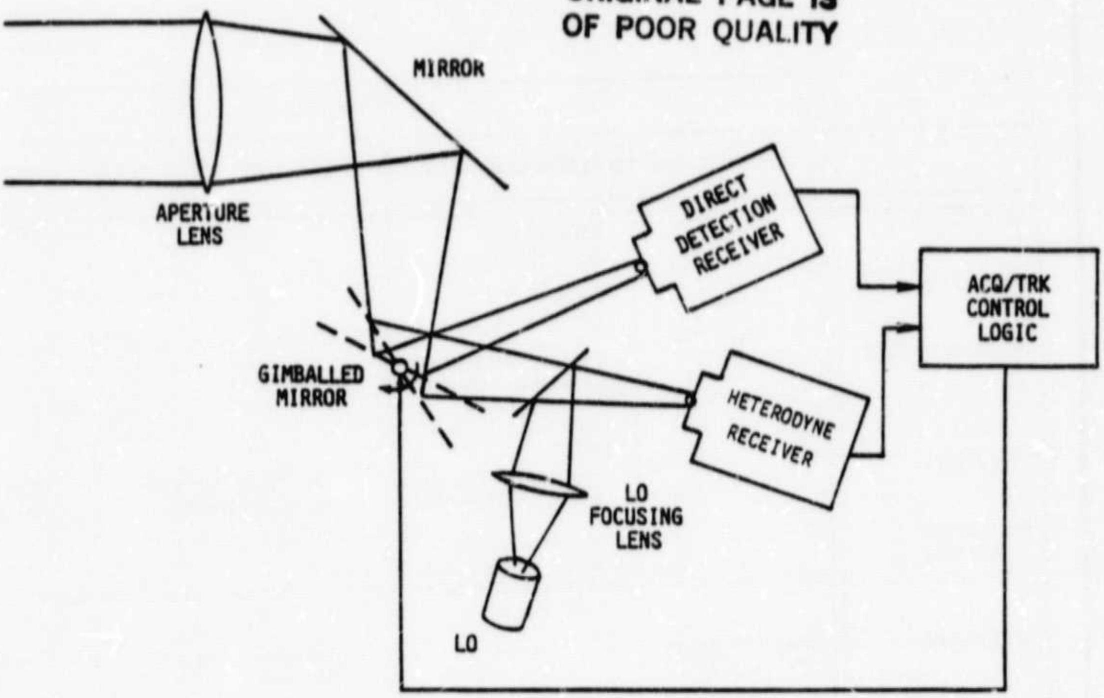


FIGURE 6-17: A FEASIBLE MEANS TO OVERCOME SOME OF THE COMPLEXITY OF ACQUISITION VIA HETERODYNE RECEPTION. IN THIS SYSTEM THE INITIAL PHASE OF ACQUISITION IS PERFORMED BY A DIRECT DETECTION RECEIVER. SINCE THE ACQUISITION SIGNAL STRENGTH CAN BE FAR LESS THAN THAT REQUIRED TO SUPPORT THE DATA RATE, SPOILED BEAMS AND LESS EFFICIENT PHOTO-DETECTION WILL SUFFICE. FOLLOWING ACQUISITION, THE GIMBALLED MIRROR IS ROTATED TO CAUSE THE SIGNAL TO IMPINGE ON THE HETERODYNE RECEIVER. THIS MORE EFFICIENT RECEIVER PROVIDES CROSSLINK RECEPTION. MIRROR CONTROL IS EXERCISED BY ACQUISITION/TRACKING LOGIC THAT TAKES OUTPUTS FROM BOTH RECEIVERS.

ORIGINAL PAGE IS
OF POOR QUALITY

	APPROACH			
	A (XPDR, 60 GHz)	B (LASER DEMOD/REMOD)	C (LASER XPDR, HETERODYNE)	D (LASER XPDR, DIRECT)
DATA RATES	—	Potentially Restricted	—	—
MODULATION	—	Commonality Preferable	—	—
MULTIPLE ACCESS	—	Onboard despreading required. Could force trade of services vs TDAS burden.	—	—
LASER USER	—	Same laser for user and XL preferable	Same laser for user and XL preferable	Same laser for user and XL preferable
NAVIGATION (ACQ/TRK)	—	Possible differences in services to front and back side users	—	—
SCHEDULING	Flexibility vs TDAS burden	—	Flexibility vs TDAS burden	Flexibility vs TDAS burden

FIGURE 6-18: IMPACT OF CROSSLINK ALTERNATIVES ON NEW USER SERVICES FOR TDAS. THE CAPACITY TO DELIVER NEW USER SERVICES IN THE TDAS ERA IS DEPENDENT IN SOME DEGREE UPON THE CROSSLINK IMPLEMENTATION. SIX SPECIFIC AREAS IN WHICH THERE IS IMPACT ARE EVALUATED ABOVE. IN MANY CASES THE DISTINCTION AMONG APPROACHES IS TIED TO WHETHER THE APPROACH EMPLOYS DEMOD/REMOD OR TRANSPONDING TECHNIQUES FOR THE CROSSLINK. DASHED ENTRIES INDICATE THAT THE ALTERNATIVE DOES NOT RESTRICT NEW SERVICES.

With respect to the selection of data rates to be made available, the transponding approaches are nonrestrictive. In B, however, the implementation of a continuum of data rates will require that the onboard demodulator maintain the same flexibility as the TDRS service demodulator. Presumably one can argue that there is some sharing of hardware here, but the amount of new service (throughput) being considered would seem to call for more demod/remod hardware than would be found in a TDRS-only replacement. Then there is evidently a trade between restricting the user data rates and increasing the complexity of the equipment for demod/remod.

Similarly, modulation formats are a matter of indifference for the transponding options; but minimization of the number of types represents a savings in the demod/remod hardware of Alternative B.

The multiple access user is not constrained directly by any of the alternatives. In the transponding options, the critical signal processing tasks — beamforming, PN despreading — may be performed at any location. This is not the case with B; the demodulation requirement forces beam forming and despreading at the blind side TDAS. These factors only indirectly constrain the user service if the TDAS hardware burden becomes excessive to the point that services must be curtailed. As an example, imagine that the TDAS could not accomodate 20 PN despreaders (the baseline system has 20 MA channels per spacecraft); if only 10 could reasonably fit because of the prior demod/remod burden, MA availability would certainly deteriorate as seen by the users.

The laser user is unconstrained by the RF alternative, A. For the laser XL Options (B, C and D) it would appear that there could be some advantage if the user and the crosslink employed the same laser. Equipment commonality in the TDAS would result with respect to sparing and redundancy. Any benefit to the use of disparate lasers must be traded against the increased burden in the TDAS.

User navigation (acquisition and tracking) is another area in which the impact varies according to the use of a transponding or nontransponding alternative. With the transponding mode, the type of navigation services provided for TDRSS extend rather directly to TDAS. With B, navigation for blind side users is somewhat different in that PN code lock and doppler extraction are both performed within the first TDAS. As discussed earlier, this need not be the case for front side users, raising the possibility of a navigation service that provides differing accuracies, response times, etc., depending on where the user spacecraft is located. Other constraints could arise from decisions to limit the TDAS burden — for example, the impact on ranging accuracy of a decrease in the supportable PN rate because of PN generator power consumption.

User scheduling under heavy loading may be to some degree affected by the crosslink implementation. The demod/remod approach would appear to have an advantage here in that scheduling a crosslinked user does not depend on having a contiguous block of spectrum available on the crosslink. The time-division multiplexing associated with demod/remod is more flexible in its use of resources than the TDMA used in the transponding alternatives. To make FDMA equally flexible is certainly feasible, but at the expense of making the crosslink frequency band assignments quite general.

Based on the above, we can conclude that crosslink architecture has a moderately high degree of interrelation with the new user services that the TDAS era plans to provide. Alternative A appears to be the most forgiving in this regard, and B the least. The laser transponder alternatives are intermediate and essentially equal.

6.6 CROSSLINK SUBSYSTEM WEIGHT AND POWER

In the TDAS Space Technology Assessment, Volume VII of this report, weight and power estimates for the crosslink subsystems are made, and the results are summarized in Figure 6-19. The dominant feature of the chart is the weight and power for the demodulate/remodulate unit in the Nd:YAG system.

FIGURE 6-19: CROSSLINK SUBSYSTEM WEIGHT AND POWER SUMMARY (1 GBPS)

	TRANSMITTER		RECEIVER		MOD/DEMOD		TOTAL	
	LBS	W	LBS	W	LBS	W	LBS	W
60 GHz XPDR	320	170	140	30			460	200
Nd:YAG MOD/DEMOD	250	400	270	300	640	664	1160	1364
CO_2 XPDR	270	270	170	65			440	335
GaAs XPDR* (HETERODYNE)	165	200	75	50			240	250
GaAs XPDR* (DIRECT DET.)	240	300	85	50			325	350

ORIGINAL PAGE IS OF POOR QUALITY

* GaAs WEIGHT AND POWER ESTIMATES MAY BE LESS ACCURATE THAN THOSE FOR THE OTHER TECHNOLOGIES DUE TO DIFFICULTY IN DATA GATHERING.

STANFORD TELECOMMUNICATIONS INC.

Even without the modem, the YAG transmitter/receiver combination is by far the most power consuming alternative; its weight is close to that of CO_2 and 60 GHz. The GaAs alternatives are lightest: direct detection requires more transmit power because of the link inefficiency. From a weight and power standpoint, there is great incentive to pursue the GaAs system. With the modem included, the Nd:YAG system requires 700 lbs and 1000 W more than any other alternative.

6.7 CROSSLINK TECHNOLOGY SUMMARY

Highlights of the crosslink technology assessment of Volume VII are summarized in Figure 6-20. The technology risk items for each of the return crosslink approaches is listed and accompanied by an overall risk assessment. The lowest risk area is 60 GHz; GaAs and Nd:YAG are medium, and CO_2 is rated high risk. The major problem with CO_2 is not that the risk items present such insurmountable problems, but that the required effort is not being made to solve them. By contrast, there is great hope that the outstanding issues for 60 GHz and GaAs will be solved within the required time.

Impact on services was addressed in Section 6.5. Nd:YAG, by requiring a demodulation/remodulation approach, makes a number of demands upon both the communication and navigation services.

Weight and power results are classified according to low, medium, or high. GaAs has the edge here, followed by 60 GHz and CO_2, for which the results are nearly equal. Nd:YAG is high primarily because of the modem equipment.

FIGURE 6-20: CROSSLINK TECHNOLOGY SUMMARY

	OVERALL RISK	RISK ITEMS	IMPACT ON TDAS SERVICES	WEIGHT/ POWER	TECHNOLOGY STATUS
60 GHz	LOW	• LNA • IMPATT POWER COMBINING	LOW, EXCEPT NO CAPACITY FOR HIGHEST DATA RATE USER SERVICE	MEDIUM	ACTIVE
ND:YAG	MEDIUM	• SPACECRAFT BURDEN • PUMP	HIGH	HIGH	LESS ACTIVE
CO2	HIGH	• LASER LIFETIME • DETECTOR CRYOGENICS • MODULATOR	LOW	MEDIUM	DORMANT
GAAS (HET)	MEDIUM	• COHERENT POWER COMBINING • HETERODYNE RECEIVER • TRACKING LOOP	LOW	LOW	VERY ACTIVE
GAAS (DIR)	MEDIUM	• POWER COMBINING	LOW	LOW	VERY ACTIVE

STI STANFORD TELECOMMUNICATIONS INC.

SECTION 7

BASELINE TDAS SPACE SEGMENT ARCHITECTURE

The preceding three chapters have presented all the options studied for the TDAS space segment. Now the arguments can be presented that lead to the selection of the baseline system. In context of this report, baseline designates the current best version of the system. It is always to be viewed as a candidate for change and improvement; we will not even exit this chapter without suggesting at least one modification that was not subjected to analysis under contract. Subsequent effort on TDAS can be expected to produce yet more substantial recommendations for change. But the space segment baseline presented here represents the summation of our current knowledge and intuition about that facet of TDAS architecture.

The baseline to be specified comprises three elements: The constellation and network, the TDAS spacecraft, and the crosslink. After stating the baseline, the supporting arguments are given.

CONSTELLATION/ NETWORK	TDAS SPACECRAFT	CROSSLINK
2	III	C
• TWO SPACECRAFT, ONE FRONTSIDE (100° W) ONE BACKSIDE (98° E), WITH CROSSLINK	• ENHANCED TDRS WITH: SMA, WSA, MBA, LSA, AND XL	• GaAlAs LASER TRANSPONDER WITH HETERODYNE DETECTION

FIGURE 7-1: BASELINE TDAS SPACE SEGMENT ARCHITECTURE

In Chapter 5, the constellations and spacecraft options were matched one-to-one and will be discussed jointly below. The crosslink, whose selection is somewhat independent, is discussed afterward.

7.1 CONSTELLATION/SPACECRAFT SELECTION RATIONALE

Key reasons for the selection are summarized below.

- Because of the 162° spacing between the satellites, coverage is quite good: 98% at the minimum for any orbit $\geq$ 200 km, and 100% for most orbits.

- Because of the networking and data capacity inherent in this configuration, Option 2 is capable of fulfilling all the TDAS architectural goals.

- Option 2 shares with 3A the minimum crosslink burden amoung the options that use crosslinking. There is but one high capacity crosslink, as opposed to two in Option 1C and three in Option 3B.

- Tracking is satisfactory in most cases, except for certain low-altitude high-inclination orbits. Although the TDAS constellation will rotate relative to these orbits, the effect of this transient on tracking may be significant and requires further investigaton.

- The extra investment in a third operational TDAS S/C is believed to not yield sufficienct benefit. Option 2 provides good coverage and good navigation in all but a few cases, and it does not seem wise to overdesign for those few exceptions.

- Use of TDRS Enhancement III permits realization of the constellation's potential to achieve all the TDAS architectural goals.

- Enhancement III, although heavier and more power consuming than the other two, will still fit within the anticipated launch capabilities for the 1990's. Its weight exceeeds the current 5000 lb STS payload limit, which would have to be modified to permit STS launch.

- The technological risks in implementing the enhanced subsystems do not seem to be excessive. Ongoing research supplemented by programs that can be put in place soon enough to yield results by 1988 should suffice to provide the technology needs of TDAS.

7.2 CROSSLINK SELECTION RATIONALE

Key reasons for the selection are summarized below:

- The weight/power penalty of a demodulate/remodulate option is severe and leads to the choice of a transponder technique.

- The risk items for GaAlAs are not insignificant, but they are all areas of quite active current effort, and are very likely to be solved within the required time.

- The transponding approaches have low impact on TDAS services (except at 60 GHz, where there is difficulty achieving the ultra-high rate access), whereas the demod/remod technique has substantial adverse impact on the communication and navigation services.

- The GaAlAs system has the lowest projected weight and second lowest power consumption of the alternatives.

A 60 GHz crosslink is also a strong contender, and we recommend that it be retained as the alternative to the laser. NASA should watch closely and also participate in the development of both technologies over the next few years, and in this way be ready to pursue whichever becomes the better course.

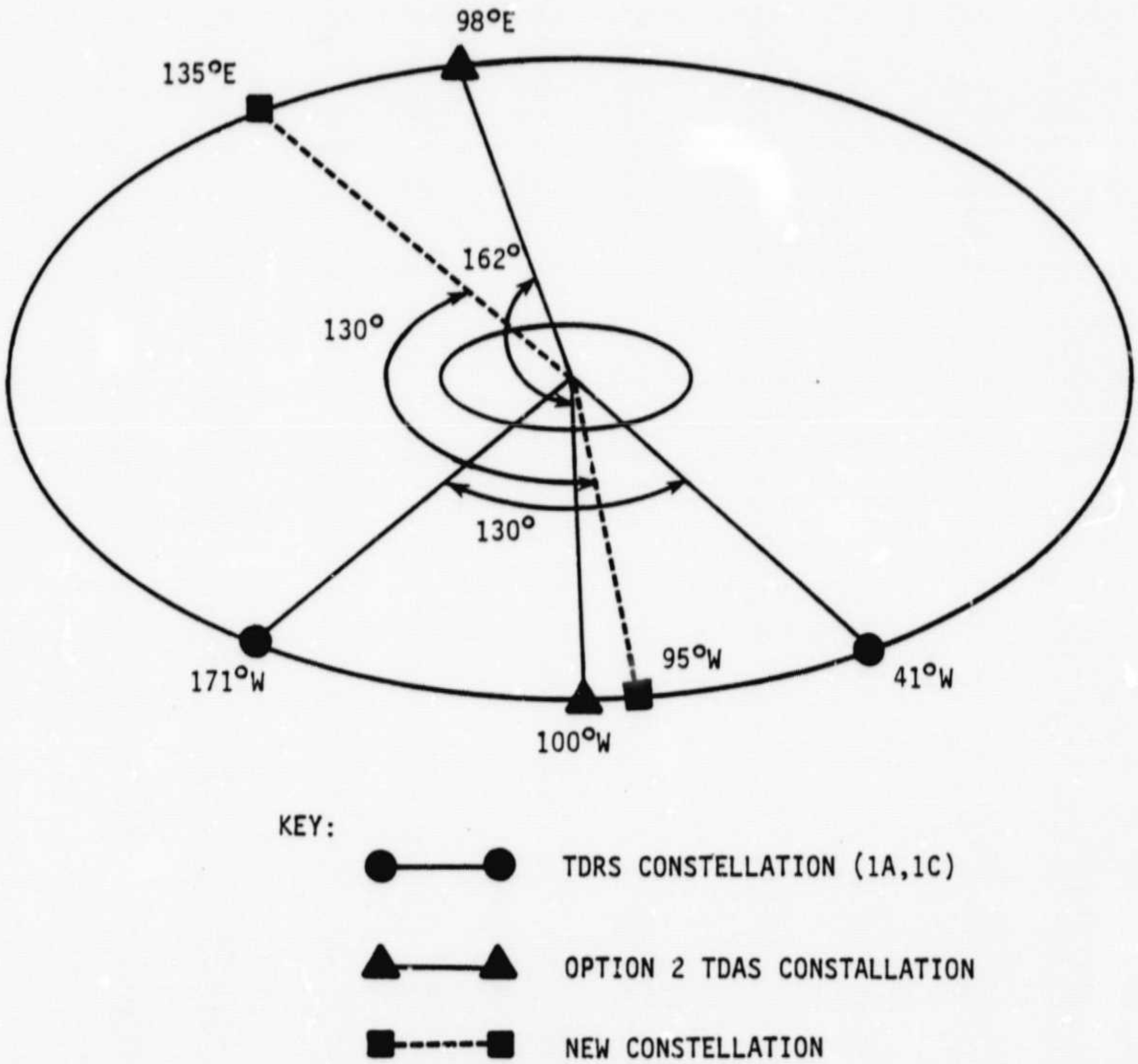
7.3 A CONSTELLATION ALTERNATIVE TO PURSUE

A constellation that was not directly evaluated in the study, but has some appeal based on the findings, is shown in Figure 7-2. The placements for the TDRS-type and the Option 2 constellations are shown. The new constellation, connected by dotted lines, is obtained by rotating the TDRS constellation 144° to the west. The result is a frontside-backside pair, as in Option 2, but with a 130° spacing. It appears that this constellation combines the best features of Options 1C and 2. The two spacecraft perform the roles that they do in Option 2; the frontside TDAS sees all the ground stations, and the backside has a high rate return crosslink to the front. Some ZOE, or coverage, is sacrificed to gain better USAT tracking. For backside satellite tracking, the satellite at 135° E is visible from Hawaii and Guam as well as the BRTS site in Australia.

The new constellation is a potential alternative to Option 2. Future work should be pursued to clarify its utility for TDAS.

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 7-2: A NEW CONSTELLATION ALTERNATIVE DETERMINED FROM THE RESULTS OF THE CURRENT STUDY



SECTION 8

THREAT MODEL DEVELOPMENT/SECURITY ANALYSIS

This task is concerned with developing a TDAS threat model, and via its use assuring the security of the command and data links of the TDAS. Requirements for secure operation shall, as a result, be developed.

8.1 THREAT MODEL DEVELOPMENT

The initial effort on this task was to identify the particular links and frequencies for which threat assessment is to be accomplished. These are (i) the ground-to-space links for command and control (30 GHz), the space-to-ground links for telemetry and user data (20 GHz), (iii) the crosslinks (laser or 60 GHz), (iv) the TDAS-to-user links (2, 15 or 60 GHz), and (v) the user-to-TDAS links (2, 15 or 60 GHz).

To begin the study, material developed under a comparable effort was reviewed. This was the Satellite Control Satellite (SCS)* study performed by Stanford Telecommunications, Inc. and Ford Aerospace. In this study, all the links identified above were investigated for jam resistance, but not all frequencies considered for TDAS were taken into account. The findings are summarized below. The link from node A to B is denoted A/B.

<u>USAT/TDAS</u>

This link is not jammable from Earth at W-band due to antenna discrimination and the O_2 absorption effect. If the link bandwidth exceeds 1 GHz, however, there may be a slight susceptibility due to the variability of the absorption across the band. This suggests that bandwidth efficient modulation should be used at high data rates. Short period of vulnerability (< 5 min) due to geometry (low antenna discrimination) can be eliminated by scheduling the user into two different TDAS's.

* A.k.a. SCRDS (Satellite Control and Data Relay System) at its inception.

At S- and K-bands, earth-band jamming is possible. Antenna discrimination at TDAS will be sufficient in most cases to permit observation, but there could be line-of-sight outages lasting a few minutes.

A laser single access link is not jammable from earth due to the turbulence-induced dispersion of the jamming. The potential of an airborne threat is less clear, but it would be geometry-dependent and short term.

TDAS/TDAS

The combination of O_2 absorption and antenna discrimination makes a 60 GHz crosslink unjammable as long as the bandwidth is < 1 GHz. For wider bandwidths some O_2 discrimination is lost, and there is potential for jamming. The potential threat is to return links, while forward links should be safe. For satellites spaced 130° apart there is no geometric vulnerability, but at 162° spacing there is susceptibility to an airborne threat.

For a laser crosslink there is no susceptibility when the satellite spacing is 130°; at 162°, there is the airborne threat possibility. Assuming that the crosslink EIRP is proportional to data rate, the crosslink could up to 7.8 dB more secure than a 300 Mbps LSA link (comparing 1.8 Gbps to 300 Mbps).

TDAS/GROUND

Analysis at 14 GHz shows that sidelobe cancelling or screening is needed against the worst case airborne threat. Results at 20 GHz are extrapolated to be similar.

GROUND/TDAS

A 60 Kbps command link would require spread spectrum protection of about 30 dB (120 MHz bandwidth) at 14 GHz. The mainbeam exclusion of jamming improves of course at 30 GHz (for a fixed size ground station dish no larger than 60 ft), in which case no antenna discrimination beyond keeping the jammer out of the mainbeam is required. In difficult circumstances where the earth station is near a CONUS border (e.g., Sunnyvale), antenna offpointing or null-steering at the TDAS spacecraft are options to be considered.

TDAS/USAT

In this case the jammer could have a substantial path advantage (23,500 mi/ 200 mi = 41.4 dB). At 60 GHz the combination of atmospheric absorption and antenna discrimination is sufficient to eliminate the threat, but this would not be the case at S- or K-band. A spread spectrum forward link would be called for in that event.

8.2 RFI SUSCEPTIBILITY

The constellations proposed for TDAS have spacecraft in quite different positions than those of TDRS. In the baseline constellation the backside satellite is at 96°E. From that location, visibility of Eastern Europe is at very low elevation, with the westernmost parts of the Soviet Union at higher elevations. A satellite in this location could experience an S-band RFI environment comparable to TDRS-E. The modified constellation in which the backside satellite is at 135°E (Japan) is probably subject to a lesser RFI environment.

FEC coding has been shown to be quite effective for RFI mitigation. Use of coding for high data rate uses, however, may press bandwidth requirements, especially on the crosslinks.