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Project Report
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A Summary of the DABS Transponder Design/Cost Studies

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1 March 1974

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16. Abstract

One of the major concerns in the DABS development program has been the cost of the DABS transponder. In order to realistically assess the impact on transponder cost of the many alternative techniques and design choices being considered for DABS, four study contracts were awarded to avionics manufacturers to design and estimate costs of special circuitry (in Phase I) and complete transponders (in Phase II). This report summarizes the major results of these design/cost studies, which cover general aviation, military, and air carrier transponder designs (including a retrofit kit for the military APX-72 transponder).

The transponder design/cost studies have had a marked influence on the design of the DABS signal and message formats. Since the cost studies were basically intended for comparing link options for DABS, the transponder specifications used in these cost studies do not correspond in detail to current DABS transponder specifications. Therefore the cost data contained in this report cannot be taken to be completely representative of the cost of the finally specified DABS transponders.

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I. INTRODUCTION

The Discrete Address Beacon System (DABS) will provide the air traffic control surveillance and air-ground-air data link capability needed to support automation of the FAA air traffic control (ATC) system of the 1980's and 1990's. Evolution from the present ATCRBS beacon system to the DABS system requires that present transponders be replaceable with DABS transponders at a cost acceptable to aircraft owners. Hence, a major concern of the DABS development program has been a link design which permits simple, low cost implementation of DABS message and address processing and which will also allow a high degree of compatibility in transponder functions between ATCRBS and DABS transponders.

In order to realistically assess the effect on transponder cost of the many alternative techniques under consideration for DABS, contracts were awarded to four avionics manufacturers to estimate the cost of DABS-peculiar circuitry and complete DABS transponder designs. Air carrier, military, and general aviation types of transponders were studied, with each contract covering one type. These studies provided design vs. cost trade-off relationships which were used by Lincoln Laboratory in establishing the DABS link and transponder design. Each contractor was selected on the basis of his experience in the design and manufacture of a particular type of ATCRBS transponder. Table 1 lists the contractors and transponder types studied by each.

The transponder design/cost studies were conducted in two phases: the first phase providing relative costs of several basic DABS transponder alternatives and the second phase providing the "paper design" and cost analysis of each of three complete transponders, each with different characteristics specified. Phase 1 (3 months) determined the relative costs of:

- several DABS uplink and downlink operating frequencies,
- several modulation formats,
- a range of reply delay accuracies, and
- dual antenna input, diversity combining capability.

Table 1. DABS/transponder design cost study contractors.

Contractor	Transponder Type Studied	Abbrev.
Bendix Avionics Div. Ft. Lauderdale, Florida	General Aviation	GA 1
Hazeltine Corp., L. I. combined with Genave, Indianapolis, Indiana	General Aviation	GA 2
Collins Radio Co. Cedar Rapids, Iowa	Air Carrier	AC
Bendix Communications Div. Towson, Maryland	Military	MIL

A description of the range of alternatives studied in Phase 1 is given in Table 2. Detailed performance specifications were not stipulated in Phase 1; rather, a range of performance was to be investigated to determine the most cost-sensitive parameters. Sharp changes in cost vs performance relationships were specifically sought. Each contractor was instructed to use one of his currently manufactured ATCRBS transponders as a baseline for cost comparison with each of the DABS alternatives. Thus, Phase 1 provided cost comparisons of many DABS alternatives relative to current ATCRBS transponder technology and these data were produced by experienced transponder engineers currently working in the industry. These results are presented in Section II.

Phase 2 (approximately 3-4 months) addressed the costing of complete transponder designs whose characteristics were selected on the basis of the Phase 1 relative cost results. Three different transponders were specified in detail for costing in Phase 2, the major difference among them being the uplink modulation format and data rate. A description of the three basic transponder design options studied is given in Table 3. For each of these, there were a number of versions costed, each having different message handling capabilities. These versions are listed in Table 4. No message output devices were included in these transponder design/cost studies.

The cost data contained in this report are taken entirely from the study contractor's reports to Lincoln Laboratory. It should be noted that the transponders specified for costing in Phase 2 do not correspond in detail to DABS transponder specifications now emerging at the end of the first phase of the DABS development program. Thus, the transponder costs estimated in Phase 2 are not completely representative of the cost of the finally specified DABS transponders.

Table 2. Range of design alternatives for Phase 1 of transponder cost studies.

A. Uplink Modulation Alternatives

1. Frequency: 1030 MHz (on channel) and 970 MHz (off channel)
2. Modulation: Binary PAM, DPSK, FSK
3. Data Rate: 1, 2, 4 Mb/sec

B. Downlink Modulation Alternatives:

1. Frequency: 1090 MHz (on channel) and 1153 MHz (off channel)
2. Modulation: Binary PAM, PAM-NRZ, DPSK, FSK
3. Power: 50 to 500 W
4. Freq. Stability: Between extremes of present ATCRBS and crystal control

C. Reply Delay Accuracy

1. Delay Accuracy, absolute: ± 50, 100, 250 nsec
2. Delay Accuracy, jitter: 20, 50 nsec; 1 sigma
3. Return Delay, absolute: 3, 10, 100 μsec

D. Diversity

Determine cost of dual diversity design

Table 3. Specifications for Phase 2 complete transponder cost studies.

Parameter	Option 1	Option 2	Option 3
Frequency, uplink/downlink	1030/1090 MHz	1030/1090 MHz	1030/1090 MHz
Downlink modulation format	Redundant PAM-NRZ	Redundant PAM-NRZ	Redundant PAM-NRZ
Return delay accuracy, nsec	±500	±250	±250
Uplink data rate, Mb/sec	2	4	4
Uplink modulation format	PAM-NRZ	PAM-NRZ	DPSK
Uplink message length in single transmission, bits	13,50	50	50

Table 4. Transponder message handling capabilities considered in Phase 2.

Message Capability (Bits) Up	Down	Option 1	Option 2	Option 3	Description
Up 13	Down 0	R	-	-	Minimal Transponder
Up 50	Down 0	Q	U	X	Minimal Transponder
Up 50	Down 50	S	V	Y	Nominal Transponder
Up 16 x 50	Down 50	-	-	-	Nominal Transponder plus multiple segment uplink
Up 16 x 50	Down 16 x 96	-	-	-	Full data link capability (Nominal transponder plus multiple segment uplink and downlink)

II. RESULTS OF PHASE 1

Use of the clear frequency band at 970 MHz for the DABS uplink would eliminate interference from ATCRBS interrogations. However, the use of 1030 MHz has a pronounced advantage over any other frequency choice since it would permit using the same receiver for both DABS and ATCRBS interrogation signals. The design/cost studies provided an estimate of the cost saving in using a common receiver. The effect of ATCRBS interference on DABS was studied separately at Lincoln in order to assure that the link performance achievable on 1030 MHz would be acceptable.

The simple modulation formats considered for the DABS uplink did not strongly influence transponder cost. The same can be said of uplink data rate for the range of rates considered, i. e., from 1 to 4 Mb/sec.

Use of a DABS downlink signal format which can be generated by a simple pulsed oscillator, such as the ATCRBS transponder transmitter, has a definite cost advantage over any signal format which requires a more complex, or separate, DABS and ATCRBS modulator/transmitter. The design/cost studies show that the cost advantage of using the ATCRBS-type transmitter for DABS is significant; this fact motivated the search at Lincoln for NRZ-PAM formats which could survive in the presence of heavy ATCRBS fruit. A type of modulation specifically designed for immunity to ATCRBS fruit interference resulted.

The effect on cost of tight transponder reply delay tolerance was also studied but this parameter did not have as marked an effect on DABS link design as did operating frequencies and modulation formats.

Transponder delay errors of two general types can occur: bias errors (correlated from reply to reply) which govern the absolute range accuracy attainable by single sensors, and jitter errors (independent from reply to reply) which govern range (and range rate) estimation accuracy. Bias errors are dominated (in current ATCRBS transponders) by the variation in the time of detection of pulses as a function of received signal level. Use of a detection threshold which is set by the received pulse amplitude would significantly reduce the delay variation with signal level. Jitter errors are dominated by receiver noise and clock quantization errors in digital pulse processing circuitry. Synchronization accuracy requirements of the demodulator proposed for DABS place a bound on allowable jitter. Thus the final jitter tolerance requirement will be determined by uplink data rate, since the bit synchronization requirements are more stringent than the system tracking requirements. It was determined in Phase 1 that the overall transponder delay tolerance could be tightened to ±0.25 μsec without incurring a significant cost penalty and the resulting improvement in range accuracy would be useful in the system.

It was anticipated that the cost of dual input, diversity combining capability would be substantial, and these studies quantified this feeling. The relatively high cost of transponder diversity motivated further study at Lincoln of fade distributions due to aircraft antenna shielding, and reinforced interest in the possibility of employing ground diversity (making use of multiple sensor coverage).

The detailed results of Phase 1 are presented in matrix form in Tables 5 through 9. Operating frequency and modulation format combinations for both uplink and downlink are designated by the letters A through P. The cost of transmitter-receiver circuitry* employing these combinations of frequency and modulation format are presented as a percentage of the contractor baseline ATCRBS transponder transmitter-receiver costs. Tables 5 through 8 show the results of each of the four studies and Table 9 shows the average of the results of all four studies (equally weighted). For example, entries under option A denote the relative cost of DABS transponder transmitter-receiver circuitry using PAM formats on both 1030 and 1090 MHz. The costs shown in these matrices are for a nominal uplink data rate range of 2 to 4 Mb/sec downlink data rate of 1 to 2 Mb/sec and delay tolerance of ± 250 nsec. The logic circuitry costs were not included in these options.

Results of these studies can also be compared by plotting the cost data against the option designations as in Fig. 1. The results show a strong cost preference for PAM as the downlink modulation format. With regard to

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* The major sub-units of a transponder are defined in a later section. Transmitter-receiver circuitry referred to here includes modulator, transmitter-power supply, diplexer, preselector filters, mixer, IF amplifier, and demodulator circuits.

Table 5. Receiver-transmitter cost matrix from GA-1.

Cost in percent of ATCRBS Transmitter-Receiver		UPLINK 1030 MHz PAM	UPLINK 1030 MHz DPSK	UPLINK 970 MHz PAM	UPLINK 970 MHz DPSK
DOWNLINK 1090 MHz	PAM	A 134	B 147	C 160	D 171
DOWNLINK 1090 MHz	DPSK	E 208	F 222	G 235	H 246
DOWNLINK 1153 MHz	PAM	I 234	J 248	K 262	L 272
DOWNLINK 1153 MHz	DPSK	M 237	N 251	O 264	P 274

Note: Cost figures exclude DABS and ATCRBS logic circuitry costs.

Table 6. Receiver-transmitter cost matrix from GA-2.

Cost in percent of ATCRBS Transmitter-Receiver		UPLINK 1030 MHz PAM	UPLINK 1030 MHz DPSK	UPLINK 970 MHz PAM	UPLINK 970 MHz DPSK
DOWNLINK 1090 MHz	PAM	A 103	B 164	C 178	D 201
DOWNLINK 1090 MHz	DPSK	E 299	F 360	G 374	H 379
DOWNLINK 1153 MHz	PAM	I 220	J 282	K 295	L 318
DOWNLINK 1153 MHz	DPSK	M 416	N 477	O 491	P 514

Note: Cost figures exclude DABS and ATCRBS logic circuitry costs.

Table 7. Receiver-transmitter cost matrix from AC.

Cost in percent of ATCRBS Transmitter-Receiver		UPLINK 1030 MHz PAM	UPLINK 1030 MHz DPSK	UPLINK 970 MHz PAM	UPLINK 970 MHz DPSK
DOWNLINK 1090 MHz	PAM	A 143	B 161	C 164	D 182
DOWNLINK 1090 MHz	DPSK	E 171	F 189	G 192	H 210
DOWNLINK 1153 MHz	PAM	I 185	J 203	K 205	L 222
DOWNLINK 1153 MHz	DPSK	M 224	N 242	O 244	P 261

Note: Cost figures exclude DABS and ATCRBS logic circuitry costs.

Table 8. Receiver-transmitter cost matrix from MIL.

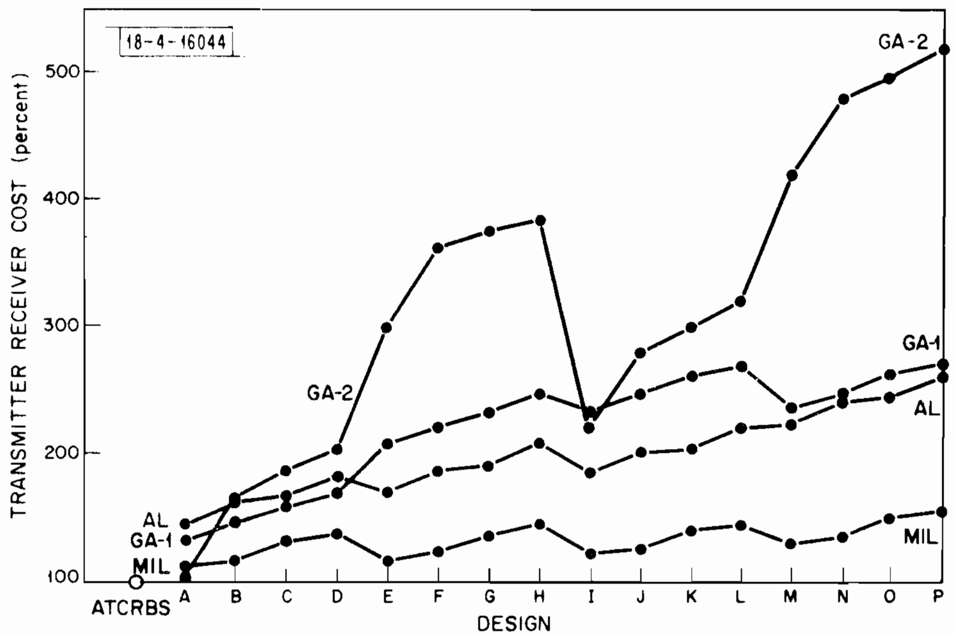
Cost in percent of ATCRBS Transmitter-Receiver		UPLINK 1030 MHz PAM	UPLINK 1030 MHz DPSK	UPLINK 970 MHz PAM	UPLINK 970 MHz DPSK
DOWNLINK 1090 MHz	PAM	A 114	B 119	C 134	D 139
DOWNLINK 1090 MHz	DPSK	E 118	F 123	G 139	H 143
DOWNLINK 1153 MHz	PAM	I 121	J 126	K 141	L 146
DOWNLINK 1153 MHz	DPSK	M 133	N 138	O 153	P 158

Note: Cost figures exclude DABS and ATCRBS logic circuitry costs.

Table 9. Receiver-transmitter average cost matrix results of all contractors averaged (equally weighted).

Cost in percent of ATCRBS Transmitter-Receiver		UPLINK 1030 MHz PAM	UPLINK 1030 MHz DPSK	UPLINK 970 MHz PAM	UPLINK 970 MHz DPSK
DOWNLINK 1090 MHz	PAM	A 123	B 145	C 149	D 171
DOWNLINK 1090 MHz	DPSK	E 197	F 220	G 224	H 245
DOWNLINK 1153 MHz	PAM	I 189	J 212	K 215	L 236
DOWNLINK 1153 MHz	DPSK	M 250	N 273	O 276	P 297

Note: Cost figures exclude DABS and ATCRBS logic circuitry costs.



FEATURES:	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
IMPROVED IF	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ENLARGED SPACE	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
IMPROVED THRESHOLD	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
DPSK DETECTOR		X		X		X		X		X		X		X		X
SECOND RECEIVER			X	X			X	X			X	X			X	X
SECOND TRANSMITTER									X	X	X	X	X	X	X	X
DPSK MODULATOR					X	X	X	X					X	X	X	X

Fig. 1. Cost patterns for DABS transmitter-receiver, all contractors.

the uplink, PAM and DPSK on 1030 MHz and PAM on 970 MHz appear to be competitive in cost. The use of 970 MHz, however, would have considerable impact on sensor cost. This point, together with the fact that the ATCRBS uplink is not as heavily utilized as the downlink, implies the desirability of pursuing DABS operation on 1030 MHz.

III. PHASE 2 SPECIFICATIONS

Three transponder specifications were written for Phase 2, each of which required the detailed design and costing of complete transponders with at least two different data link message handling capabilities. The essential characteristics of the three specifications are summarized in Table 3.

Phase 1 studies had indicated that the use of clear channels for DABS (at 970 and/or 1153 MHz) would result in increased transponder cost. Other studies had indicated that DABS operation in the ATCRBS frequency bands was feasible. Therefore, all three Phase 2 transponder specifications were based on the use of 1030 and 1090 MHz for the DABS uplink and downlink, respectively. The downlink signal format based upon the use of an ATCRBS-like pulsed transmitter to generate an NRZ-PAM format for DABS was specified in all three cases. Also, the use of parity check coding was specified on both uplink and downlink in all three cases.

Three different uplink modulation formats were specified for Phase 2 to permit a more detailed comparison of the two serious alternatives for DABS, i.e., NRZ-PAM and DPSK. Option 1, a low-cost design, used 2 Mb/sec NRZ-PAM modulation uplink, and a reply delay tolerance as required for ATCRBS transponders. This option represented a baseline against which to compare other more capable transponder configurations. The slow uplink data rate entailed logic complexity to handle long messages. Option 2, a more capable design, used 4 Mb/sec NRZ-PAM modulation uplink and a tighter delay tolerance. Option 3, the most innovative of the three, employed a 4 Mb/sec DPSK uplink and tighter delay tolerance.

The minimal message handling capability required was 50 bit uplink messages and no downlink message capability. The next level of complexity, designated the 'nominal' message handling capability, included the minimal capability plus an ability to transmit 50 bit downlink messages. Since there is interest in using DABS for the transmission of longer messages, a "full data link capability" was defined for costing in the AC study only. This study specified the handling of 800 bit uplink messages (handled in segments of 50 bits) and 1536 bit downlink messages.

The low uplink data rate of Option 1 allowed the transmission of only 13 message bits within the uplink time constraint imposed by the minimum specified ATCRBS transponder suppression time. This special minimal capability was costed along with the added capability to transmit 50 bit messages in two successive blocks, with a reply only after the second block.

The message handling capabilities included in each of the three transponder specifications are tabulated in Table 10 for each of the four cost studies. Costing the logic circuitry for each of these options required the definition of complete message formats and link operation protocols.

In order to obtain cost estimates for transponders without the data link feature, the GA-1 study was extended to include the design and costing of a transponder with no message handling capability. This surveillance-only DABS transponder was required to respond only to ATCRBS modes A and C, a DABS All-Call mode, and a discrete-address surveillance mode. If such a surveillance-only transponder were actually to be marketed, message handling capability could be added after initial installation via a plug-in data link converter when such service became available. This concept has some practical merit in that it would minimize the initial avionics cost to upgrade to DABS by allowing one to postpone message handling capability. Realizing DABS data link capability by the use of separate transponder and data link converter boxes is expected to be more costly than the integral design approach of both capabilities in one box. It should be noted that this concept of a surveillance-only DABS transponder is not being recommended; however, it may be useful to design message formats so as not to preclude this approach to DABS implementation should it appear desirable in the future.

The existence of several tens of thousands of one type of military transponder (APX-72) raises the question of a DABS retrofit kit. The MIL study designed and costed both an all-new military DABS transponder and a retrofit kit for the APX-72 for all three options of Phase 2. The retrofit kit approach resulted in the same physical envelope for the transponder and required no new aircraft wiring. (Control box cost was not addressed in the MIL study).

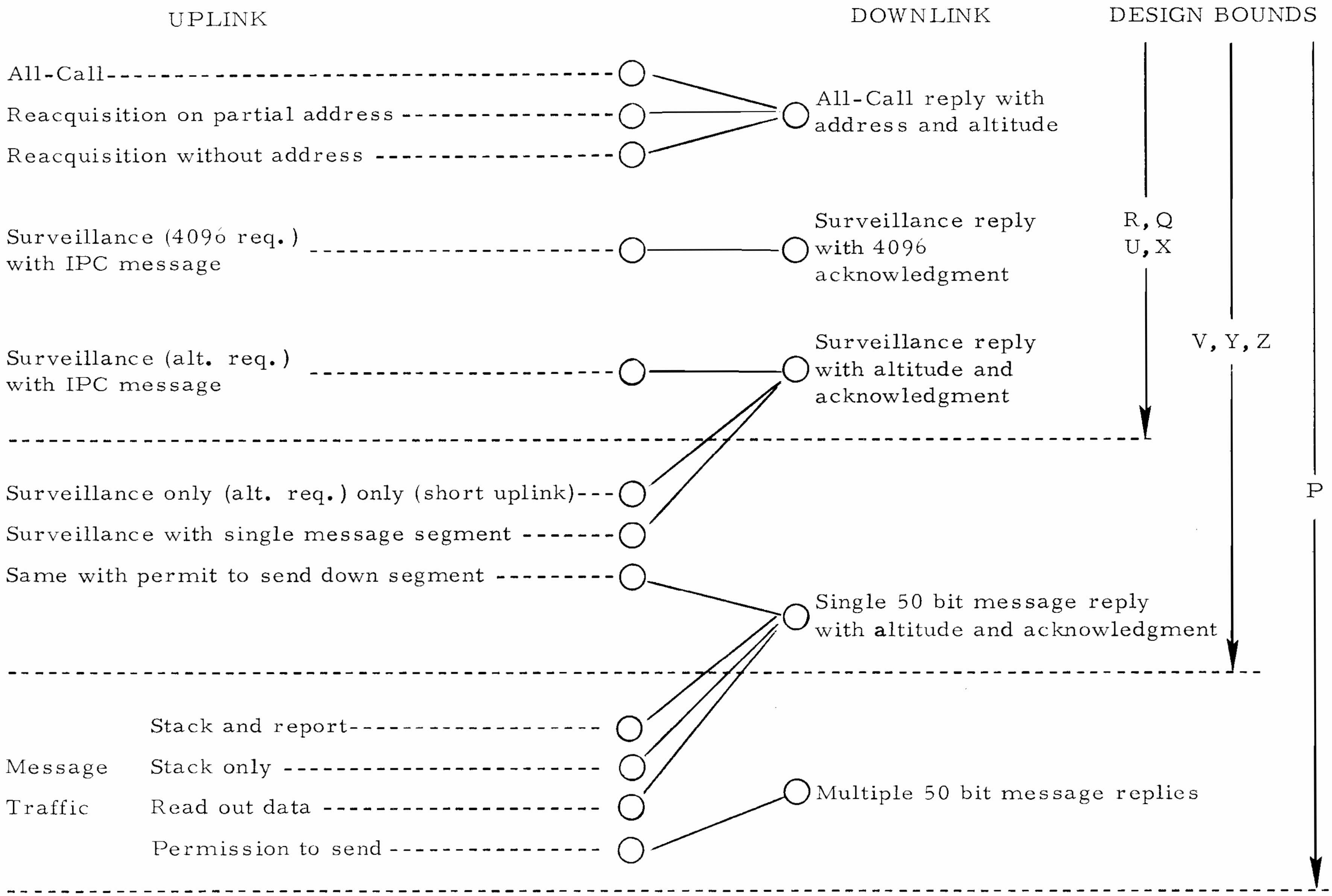
Table 10. Phase 2 transponder capabilities and study assignments.

Message Capability: Bit Content of Links — Up	Down	Option: Letter Designation/Study						Description
13	0	R	GA-1 GA-2 MIL					Special Minimal Transponder
50	0	Q	GA-1 GA-2 MIL	U	GA-1 GA-2 MIL AC	X	GA-1 GA-2 MIL AC	Minimal Transponder
50	50	S	GA-1	V	GA-1 AC	Y	GA-1 AC MIL	Nominal Transponder
16x50	50						AC	Transponder with extended uplink message capability
16x50	16x96						AC	Transponder with extended message capability (full data link capability)

The interrogation-reply pairs specified for each of the transponders costed in Phase 2 are listed in Table 11. An effort was made to obtain incremental costs of certain special modes such as the "re-acquisition mode" and the "DABS All-Call." The incremental costs associated with uplink message decoding and reply encoding were also estimated in the GA-1 study. Detailed bit assignments for each interrogation and reply type were evolved in discussions with the study contractors, with the idea of minimizing logic circuitry costs. The uplink and downlink message formats used in these studies are summarized in Table 12.

Derived transponder costs were listed in terms of material, labor, testing, overhead, profit, and distribution. The details of each contractor's cost breakdown were included in the final reports.

Table 11. Interrogation - reply pairs for the range of transponder designs.



Note: The "Stack only" uplink transmission does not elicit an immediate reply.

Table 12. Message formats used in Phase 2.*

UPLINK WITH MESSAGE

UTYP	UM	UTAG	UOC	USP	ADD/PAR
-4-	-52-	-4-	-4-	-2-	-24-
4	56	60	64	66	30

UPLINK, REACQUISITION

UTYP	USP	ADD-PAR
-4-	-2-	-24-
4	6	30

UPLINK WITHOUT MESSAGE

UTYP	UTAG	UOC	USP	ADD-PAR
-4-	-4-	-4-	-2-	-24-
4	8	12	14	38

DOWNLINK ALL-CALL REPLY

DTYP	CFLD	FULL ADDRESS	BB
-2-	-13-	-24-	
2	15	39	40

DOWNLINK, SURVEILLANCE REPLY

DTYP	CFLD	UMID	PBUT	TA	PARTL ADDRESS	BB
-2-	-13-	-4-	-4-	1	-15-	
2	15	19	23	24	39	40

DOWNLINK, REPLY WITH MESSAGE

DTYP	CFLD	UMID	PBUT	TA	PARTL ADDRESS	DM	PAR
-2-	-13-	-4-	-4-		-15-	-50-	-15-
2	15	17	23	24	39		108

Contents of uplink and downlink formats

UTYP	Format identifier
UM	Uplink message
UTAG	Message designator
UOC	Operational control
USP	Spares
ADD/PAR	Address and parity

DTYP	Format identifier
CFLD	Compulsory field, altitude 4096 emergency
UMID	Message designator
PBUT	Acknowledgement status
TA	Technical acknowledgement
DM	Downlink message
PAR	Parity

* The message formats specified for Phase 2 of this study are similar to but do not correspond in detail to those now emerging as the final DABS message format recommendations. These formats were judged to be realistic enough for assessing DABS logic cost and complexity.

IV. AVIONICS COST STRUCTURE

The final user cost of transponders depends on such factors as the size of the production run and the length of time over which the engineering and tooling costs are amortized. The batch sizes and amortization assumed by each of the four study contractors are given in Table 13.

A detailed breakdown of major cost components of a typical GA transponder with a user price (suggested list price) of $1,000 is shown in Table 14. The figures in this table are representative of the avionics industry and are given to indicate the level of detail to which the costing exercises were carried out.

Prediction of avionics costs well into the future was discussed with the study contractors. Major effects noted by the contractors were inflation, component supplier competition, and the effect of experience on lowering the cost of successive designs (the learning curve). This effect of the learning curve is shown in Fig. 2 for ATCRBS general aviation transponder designs dating from 1964. DABS transponder designs will clearly obtain the benefit of the ATCRBS learning curve because of the high degree of circuit compatibility between DABS and ATCRBS. The major difference between DABS and ATCRBS circuitry is in the amount of logic. Large scale integration (LSI) will have an effect on future costs of DABS logic circuitry but the magnitude of the effect is difficult to predict (because of the sensitivity to such factors as competition, market evaluations, etc.).

In general, the transponder designs of Phase 2 were based on ATCRBS technology and assumed no major technical innovations in avionics design. In this regard the studies provide conservative but realizable upper bounds on costs. Although the designs and costs of Phase 2 did not have the benefit of laboratory verification of performance, only the DPSK circuitry was a departure from ATCRBS techniques and these circuits were conservatively designed. It is believed that further design effort and manufacturing experience will tend to reduce the actual costs of DABS circuitry with respect to the cost estimates developed in Phase 2.

Table 13. Production run sizes and rates.

Contractor	Production Quantity Per Year	Production Quantity Total of this Design
GA 1	1,000	3,500 to 5,000
GA 2	1,000	not announced
AC	200	1,000
MIL	6,000	6,000

Table 14. Cost breakdown for a representative general aviation transponder with a final list price of $1,000.

Material	$240
+ 5% for burden	12
+ Labor	56
+ 125% (of labor) for burden	70
+ Inventory cost	378
+ Amortized tooling + Amortized engineering	57
= Factory cost	435
+ 15% for G & A	65
+ 10% for profit	50
= Total cost	550
+ 82% for distribution	450
= List Price	$1000

Notes:

1. Material burden represents shrinkage and items lost in tests.
2. Labor burden pays for facilities, supervision, inspection, quality control.
3. Amortization of tooling and engineering is carried over the total production run.
4. The above figures are based on a production rate of 1000 to 1500 units annually and a total production of 5000 units.

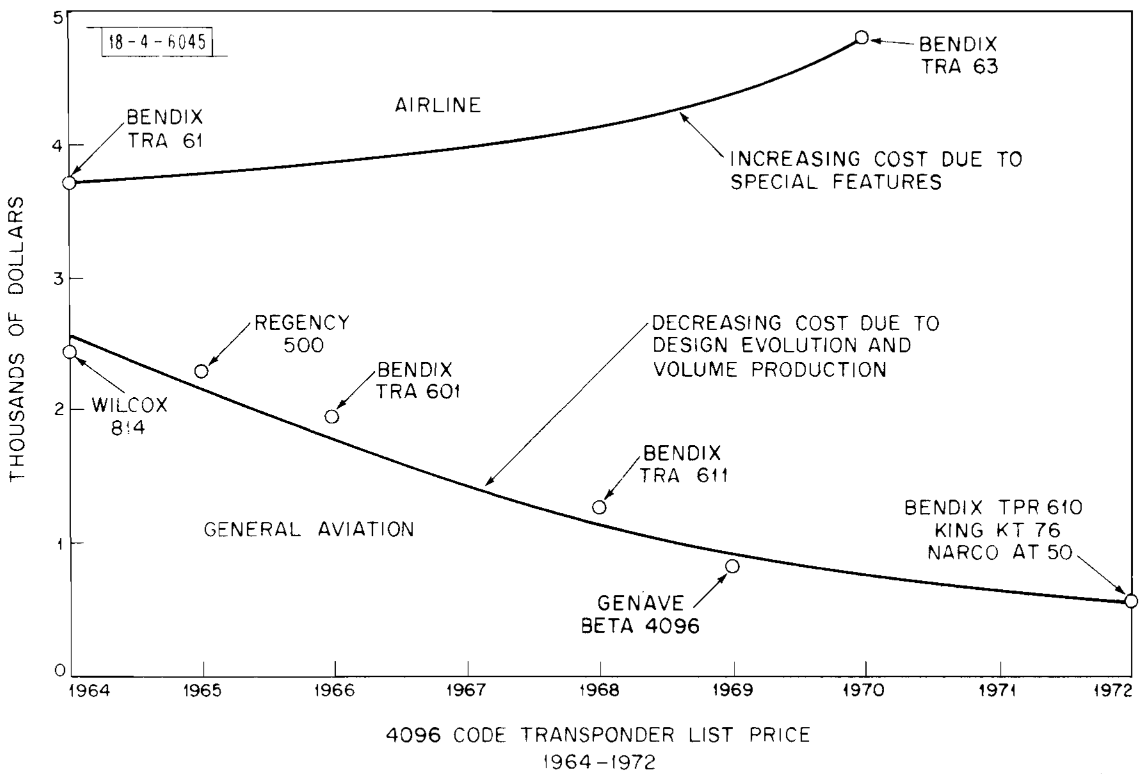


Fig. 2. Transponder costs from 1964 to 1972, reflecting the learning curve effect.

V. RESULTS OF PHASE 2

Phase 2 involved costing complete transponder designs and presenting cost breakdowns for five major sub-units of a transponder. The cost data have, therefore, been organized to show the major sub-unit costs relative to ATCRBS baseline transponder costs. Letter designations have been given to the major sub-units of a transponder as follows:

T = Transmitter including RF generator, modulator, HV power supply

R = Receiver, including preselector filter, diplexer, mixer, IF amplifier, PAM detector

V = Video processor, including DPSK demodulator, synchronization circuits, PAM threshold setting

L = Logic section, including mode decoding, parity checking, parity encoding, control logic

M = Mechanical, including case, connectors, knobs, switches, low voltage power supply

Cost data of Phase 2 are presented in the form of bar charts with overall bar length proportional to total transponder cost. The actual cost (as a percent of the ATCRBS baseline transponder cost) is indicated at the top of each bar. Each bar is also divided into sub-lengths indicating the fractional cost of each of the five units T, R, V, L, and M. Each bar segment pertaining to a sub-unit may also be used to compare the cost of the subsystem to the cost of the same sub-unit in the ATCRBS baseline transponder (separate baseline cost for each contractor). Figure 3 shows a comparison of the ATCRBS transponders used by the four cost contractors. Figure 4 depicts the relative costs of the sub-units of each of the ATCRBS baseline transponders more clearly by making the total bar lengths the same for all baselines.

Figure 5 shows the transponder dollar costs and relative subsystem costs for all Phase 2 designs studied by contractor GA-1. The basic characteristics of each option are summarized below the bars and the letter designations above the bars are used in the text to refer to the various options. Figure 6 presents the same results for the GA-2 study.

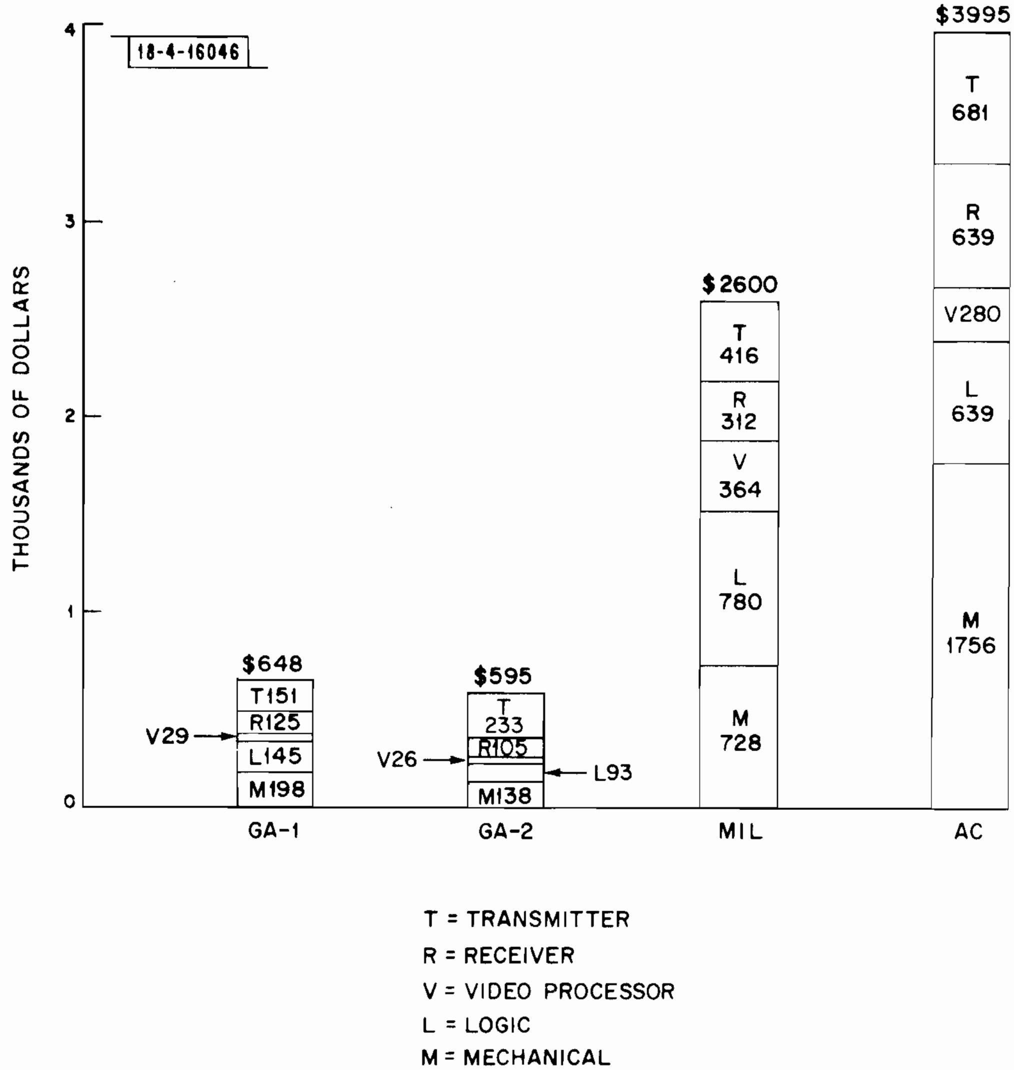


Fig. 3. The ATCRBS baseline transponder costs used in the four studies.

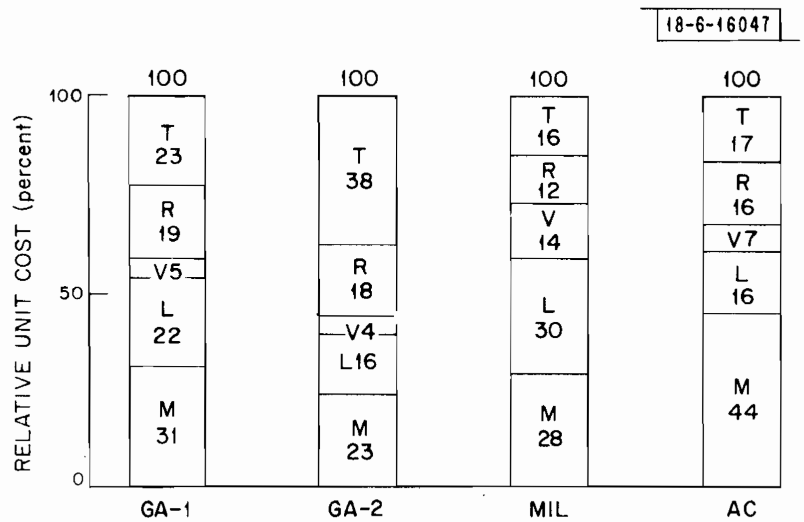
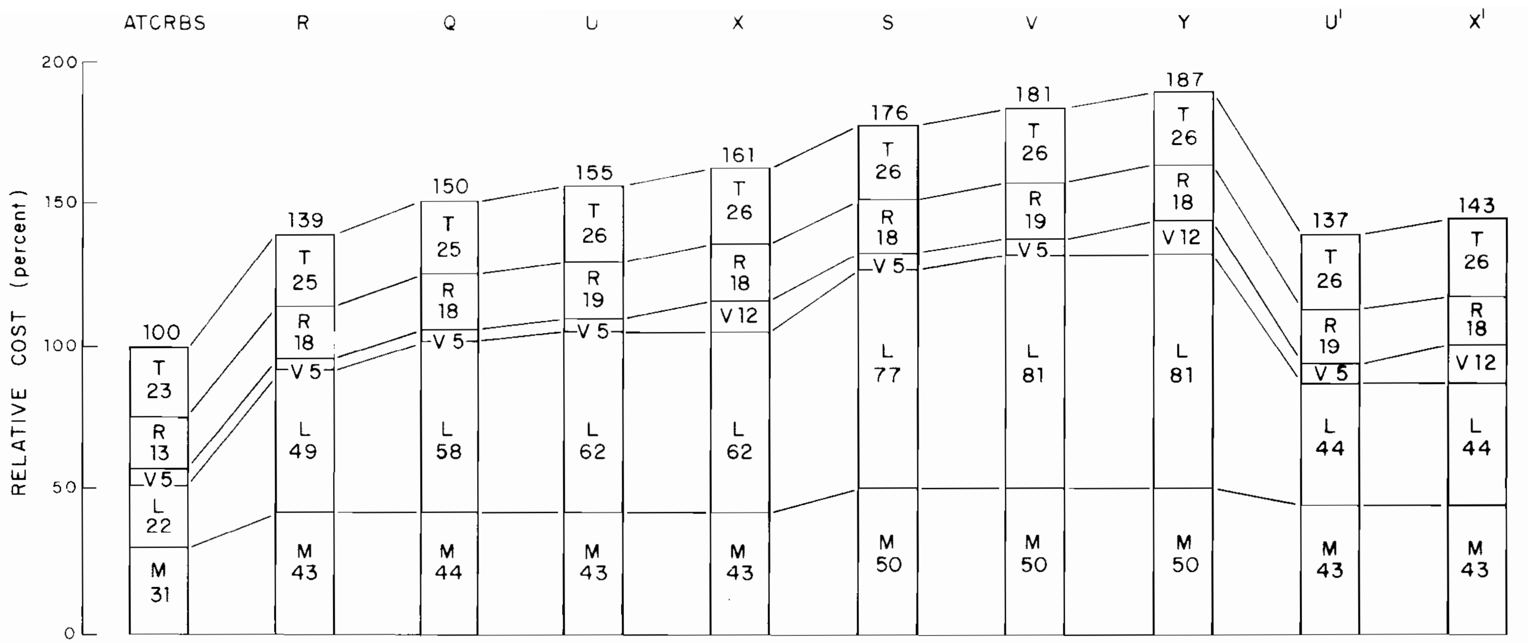


Fig. 4. Normalized costs for the four ATCRBS baseline transponders used in the studies.



	R	Q	U	X	S	V	Y	U'	X'
DATA RATE (Mb/s)	2	2	4	4	2	4	4	4	4
NO. OF UPLINK MESSAGE BITS	12	12+38	50	50	12+38	50	50	50	50
DOWNLINK TRANSMISSION INCLUDES	ACK	ACK	ACK	ACK	ACK +50	ACK +50 BITS	ACK +50 BITS	ACK +50 BITS	ACK +50 BITS
UPLINK MODULATION	PAM	PAM	PAM	DPSK	PAM	PAM	DPSK	PAM	DPSK

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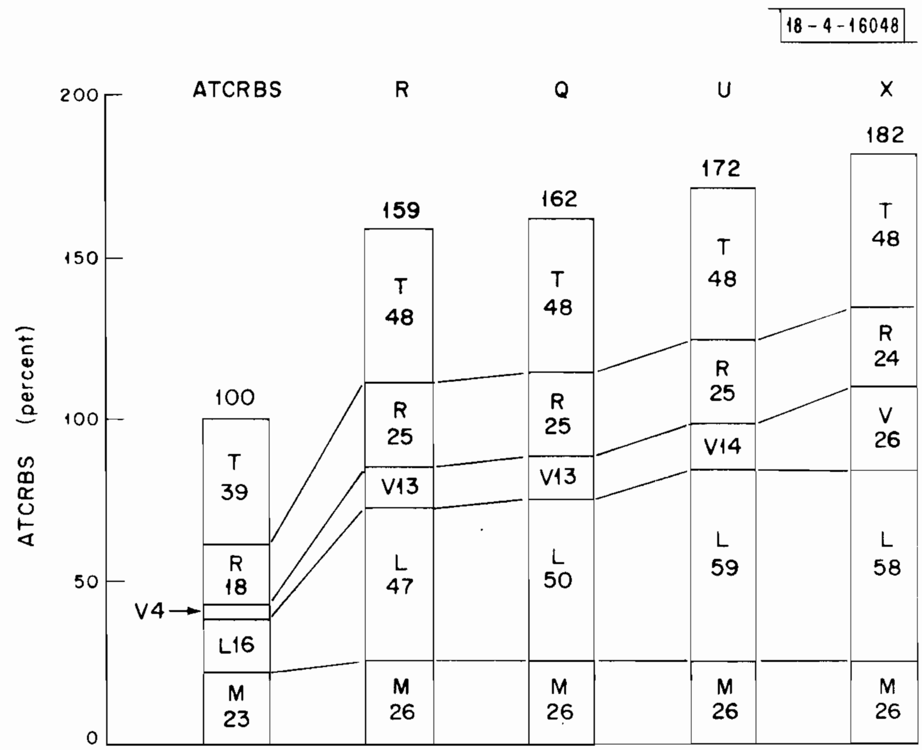
Fig. 5. Phase 2 results of the GA-1 study.



	R	Q	U	X
UPLINK DATA RATE (Mb/s)	2	2	4	4
NO. OF UPLINK MESSAGE UNITS	12	12+38	50	50
DOWNLINK TRANSMISSION INCLUDES	ACK	ACK	ACK	ACK
UPLINK MODULATION	PAM	PAM	PAM	DPSK

Fig. 6. Phase 2 results of the GA-2 study.

In the MIL study, each transponder specification required a new military transponder design and a retrofit kit for the widely deployed APX-72 transponder to upgrade it to the various DABS capabilities denoted by the Phase 2 options. Figure 7 shows the cost data for new military transponders. According to the contractor, the new military transponder costs are close to the baseline APX-72 cost because of the more stringent performance requirements placed on the APX-72, the unique buying policies of the DOD and because of the availability of new, low cost components for a new overall design.

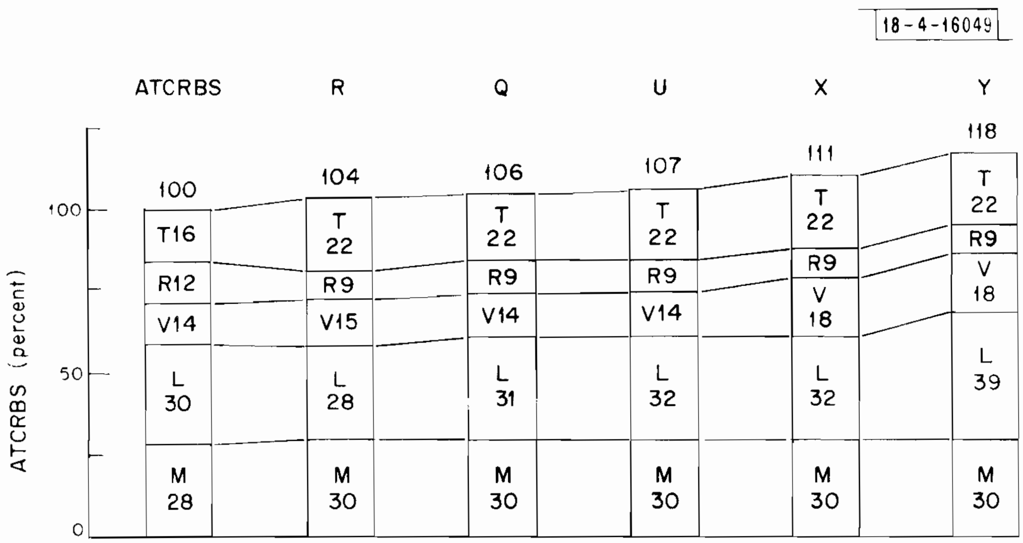
Figure 8 shows the APX-72 retrofit costs. The retrofit was limited to the same mechanical dimensions and the use of the same aircraft wiring. The approach taken by the MIL study contractor (who designed and built the original production run of APX-72's) was to redesign the lower tray containing the RF and video sections and to use this space and the spare frame in the main case for a DABS logic circuit card. Thus, retrofit of an APX-72 would involve only the exchange of the lower tray and installation of wiring for a new logic card.

Figure 9 shows the results of the AC study which did not consider Option 1 but did investigate the implementation of full data link capability with DABS. The cost of full data link capability is not relevant, to first order, to DABS signal format selection. Moreover, this cost is sensitive to the details of the link protocols specified and this data link costing was done by one contractor so no comparison can be made with other design approaches. For these reasons the cost data for full data link capability are not presented here.

The cost of dual input, diversity combining transponders is shown in Fig. 10 relative to the cost of single input transponders for Option X, which included a 4 Mb/sec DPSK uplink.

Since the cost between the 2 and 4 Mb/sec NRZ-PAM transponder (Options R, Q, and U) is small, the prime candidates that emerge from the cost studies are the 4 Mb/sec NRZ-PAM (Option U) and the 4 Mb/sec DPSK transponder (Option X). The cost of a 4 Mb/sec transponder (Option X) is compared directly to the ATCRBS baseline transponder for each of the studies in Fig. 11.

The cost of a surveillance-only DABS transponder with a 4 Mb/sec DPSK uplink is compared to the ATCRBS baseline and Phase 2, Option 3 minimal transponder cost in Fig. 12. This exercise was carried out only in the GA-1 study.



	R	Q	U	X	Y
UPLINK DATA RATE (Mb/s)	2	2	4	4	4
NO. OF TRANSMISSION INCLUDES	12	12+38	50	50	50
DOWNLINK TRANSMISSION INCLUDES	ACK	ACK	ACK	ACK	ACK+50 BITS
UPLINK MODULATION	PAM	PAM	PAM	DPSK	DPSK

Fig. 7. Phase 2 results of the MIL study for new military transponders.

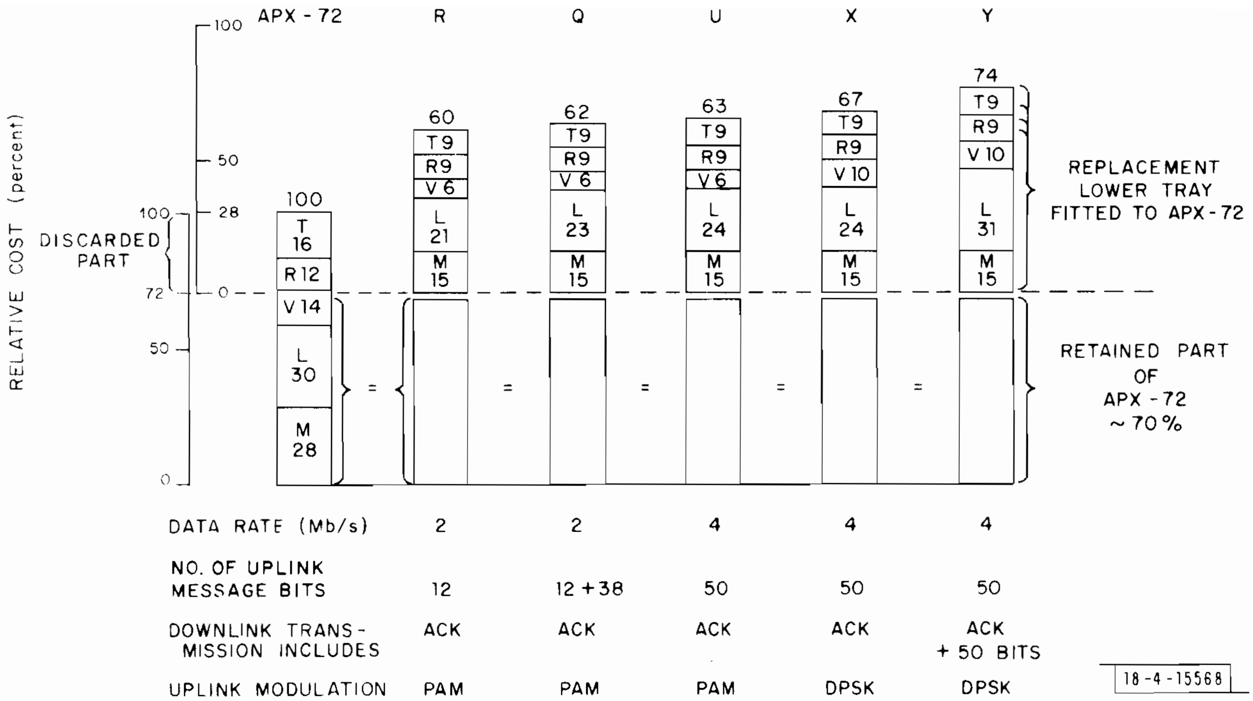


Fig. 8. Phase 2 results of MIL study for retrofit kits for APX-72.

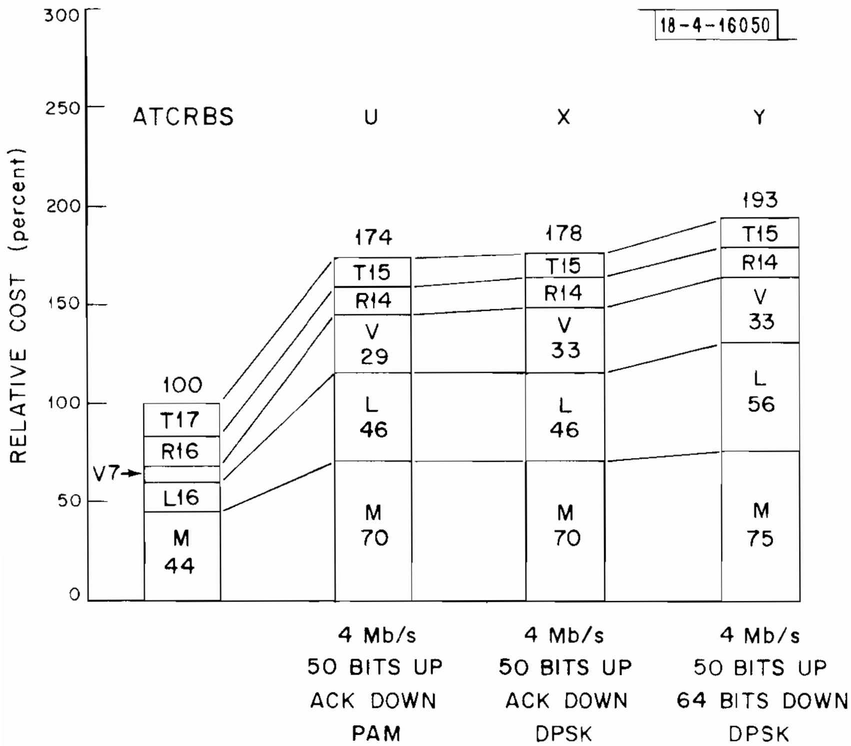


Fig. 9. Phase 2 results of the AC study.

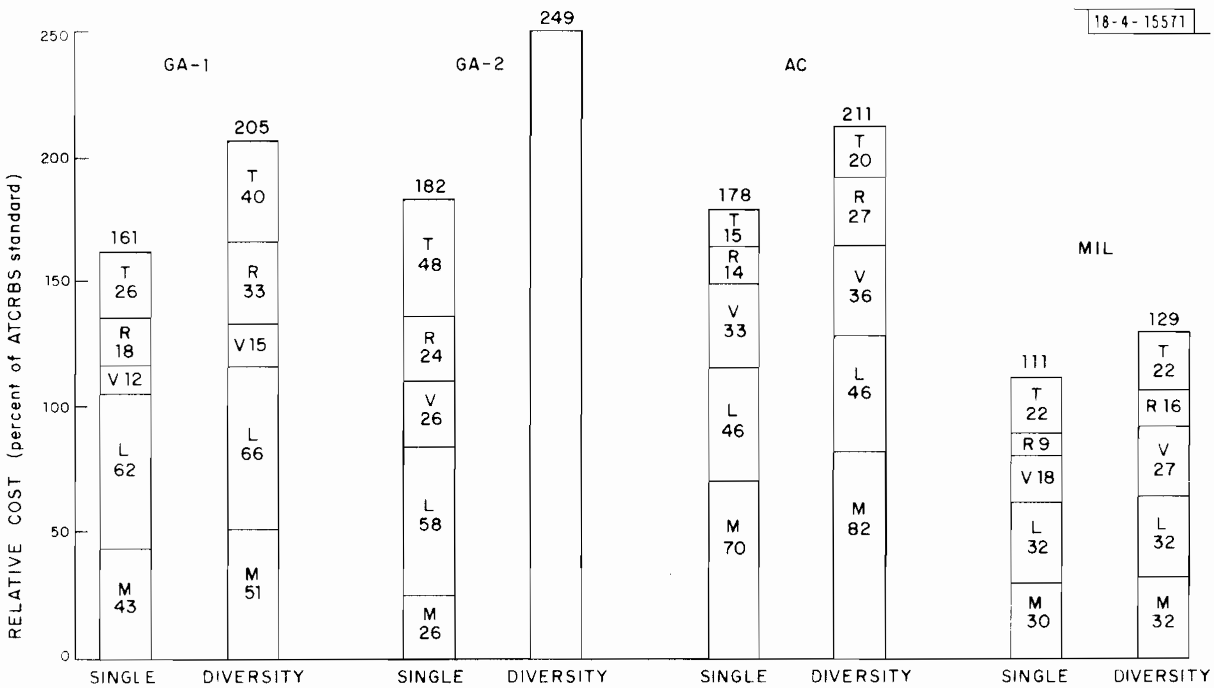


Fig. 10. Cost comparison of single input vs diversity transponders (both 4 Mb/sec DPSK uplink).

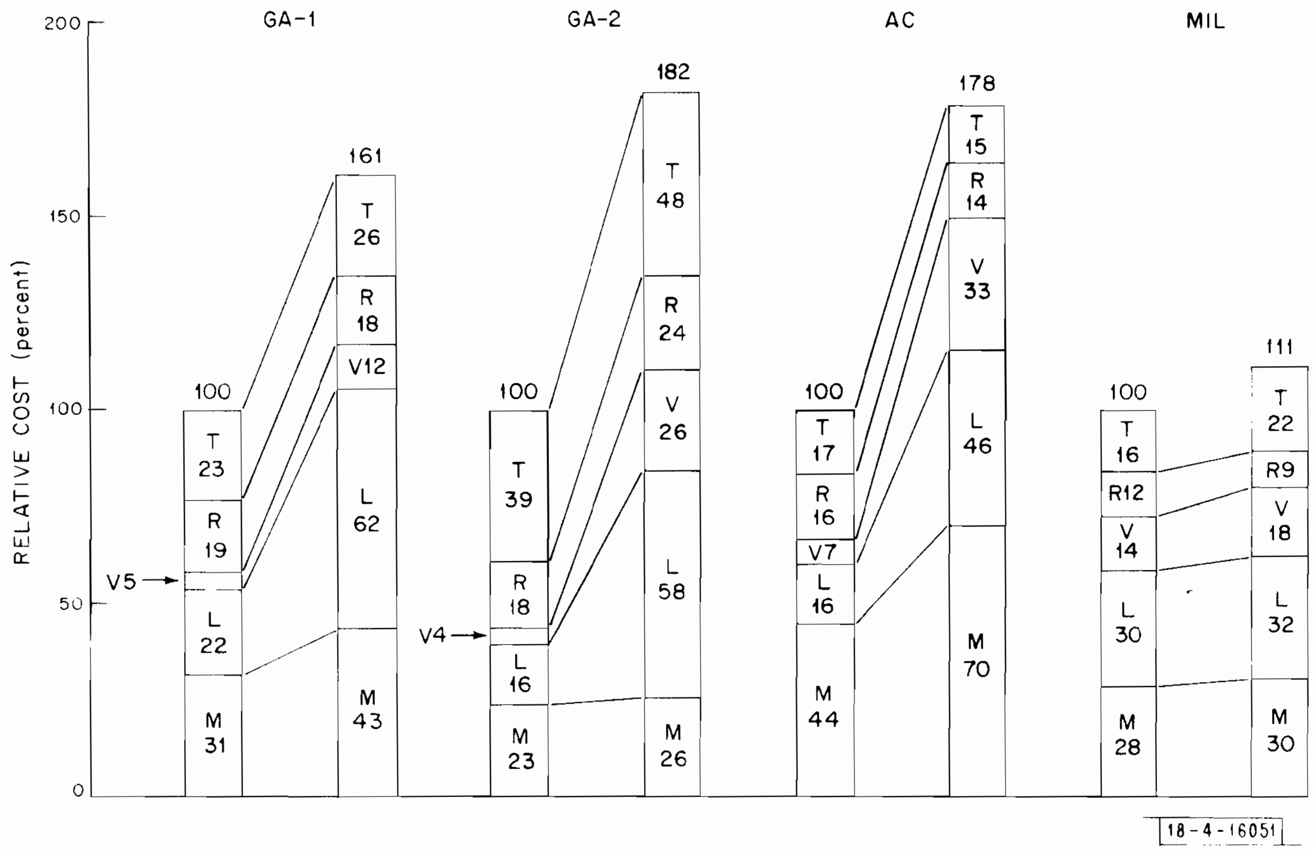


Fig. 11. Cost comparison of 4 Mb transponders (Option X, DPSK uplink) to ATCRBS baseline.

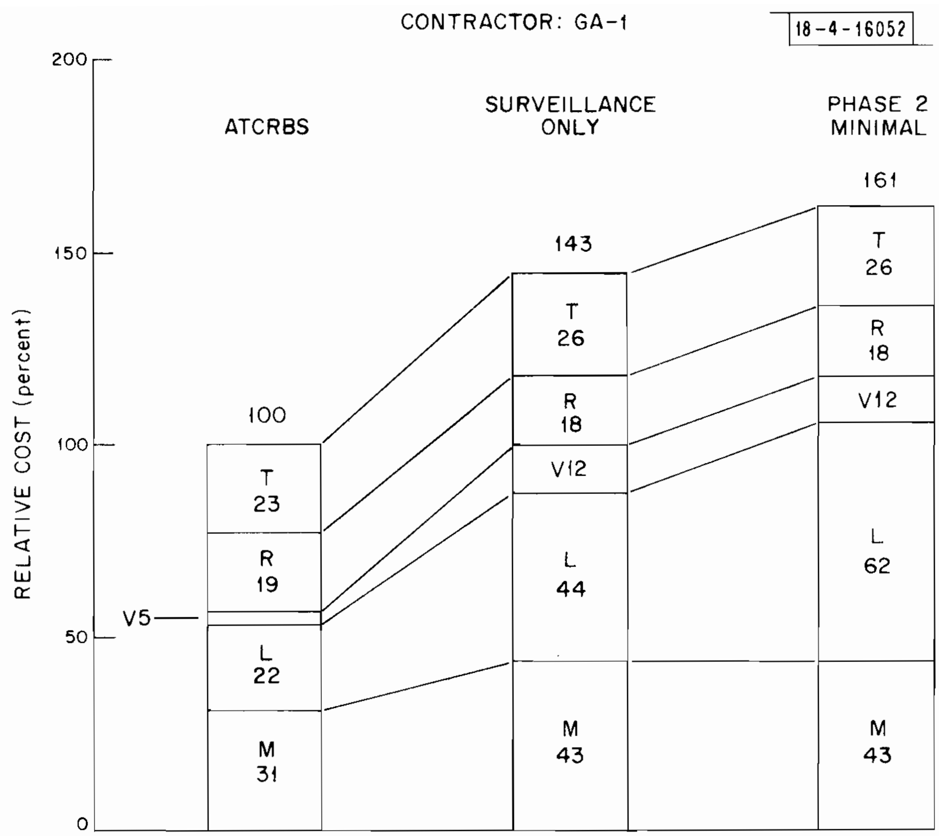


Fig. 12. "Surveillance only" transponder cost compared to ATCRBS and full Phase 2 "minimal" design (Option X, DPSK uplink).

VI. CONCLUSIONS

The cost data contained in this report are taken entirely from study contractor reports. Relative costs of many frequency and data modulation alternatives for DABS were studied in Phase 1. Several serious alternatives that emerged from Phase 1 were then put into perspective with overall transponder costs in Phase 2. The transponder characteristics specified for these cost studies do not correspond in detail to final DABS transponder specifications but were adequate for the purpose of comparing link options and putting them in perspective with regard to overall transponder cost.

The Phase 1 results indicated that the use of a downlink modulation type which could be generated by the transmitters currently used in ATCRBS transponders would have a substantial cost advantage over modulation types requiring more complex modulators and transmitters. The DABS downlink modulation was thus designed around the type of low cost transmitter available and the link performance depends heavily on employing advanced signal processing techniques at the sensor.

With regard to the uplink, transponder cost depends on receiver/demodulator complexity, and so only simply demodulated binary modulation schemes were considered. The studies showed that there are several uplink modulation alternatives that are comparable in transponder cost, the prime candidates of which were taken as PAM or DPSK on 1030 MHz and PAM on 970 MHz. The use of two uplink frequencies (to accommodate both ATCRBS and DABS functions) entails complexities in sensor and transponder RF design which are best avoided, if possible. Thus the prime uplink frequency choice to be studied was 1030 MHz unless and until it was determined that the ATCRBS interference jeopardized DABS performance goals. Separate studies at Lincoln Laboratory have since established that the 1030 MHz channel can support DABS uplink operation, and so both PAM and DPSK emerged from Phase 1 as serious candidates for the DABS uplink modulation.

The major conclusions of Phase 2 are:

1. Given that DABS must accommodate 50 bit ATC uplink messages, there is no significant cost advantage in using a low uplink data

rate (~ 2 Mb/sec) and multiple transmissions to deliver a single 50 bit message compared to using a higher data rate (~ 4 Mb/sec) using only one transmission on the time-constrained ATCRBS channel.

2. There is an insignificant difference in overall transponder cost between PAM and DPSK uplink modulation (4 Mb/sec). When weighed against the link performance advantages offered by DPSK, the cost-effective choice is DPSK for the DABS uplink.

3. The increase in the amount of information processed by the DABS transponder compared to ATCRBS transponders results in a significant increase in overall transponder cost*. The cost estimates for logic circuitry are believed to be quite accurate, based on current component technology. The use of LSI in reducing logic costs appears promising but has not been pursued in these studies.

4. Transponder diversity, one way of combatting the effect of aircraft antenna shielding to achieve high link reliability, results in a significant transponder cost increment and would significantly affect the acceptability of DABS to the general aviation user.

Several additional comments on the results of the cost studies, which may not warrant consideration as formal conclusions, follow.

It is believed that the transponder delay tolerance can be tightened to ±0.25 μsec without a cost penalty. This reduced tolerance can be achieved using existing techniques for both PAM and DPSK. (A threshold circuit, required in PAM demodulators for interference immunity, will also provide less sensitivity to effects of received signal level on detection time. DPSK inherently allows accurate synchronization with little variation as a function of received signal level.)

The familiarity of the designers participating in the studies with ATCRBS PAM demodulation techniques leads one to believe that PAM costs are accurately estimated. Although DPSK was not new to these designers, the

* The military transponder is the exception, perhaps because other performance requirements tend to dominate its cost.

design of low cost circuits for DPSK synchronization and demodulation was unfamiliar enough to cause the designers to be conservative in their choice of components and circuits. The DPSK demodulators were intended to achieve near optimal performance in noise and interference. There is no technical risk connected with DPSK in that the circuits used in these studies will work as specified. Experimental work done at Lincoln Laboratory supports this conclusion.

The recommended DABS link design will reflect quite clearly the results of the transponder design/cost studies summarized here.