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# Project Report
## Discrete Address Beacon System

ATC-27

T. J. Goblick
P. H. Robeck

## A Summary of the DABS Transponder Design/Cost Studies

1 March 1974

Prepared for Federal Aviation Administration by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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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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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.

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 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 |

## 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

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 |
| | DPSK | E 208 | F 222 | G 235 | H 246 |
| DOWNLINK 1153 MHz | PAM | I 234 | J 248 | K 262 | L 272 |
| | DPSK | M 237 | N 251 | O 264 | P 274 |

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 |
| | DPSK | E 171 | F 189 | G 192 | H 210 |
| DOWNLINK 1153 MHz | PAM | I 185 | J 203 | K 205 | L 222 |
| | DPSK | M 224 | N 242 | O 244 | P 261 |

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 |
| | DPSK | E 197 | F 220 | G 224 | H 245 |
| DOWNLINK 1153 MHz | PAM | I 189 | J 212 | K 215 | L 236 |
| | DPSK | M 250 | N 273 | O 276 | P 297 |

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

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.

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).

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 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 | $T_A$ | PARTL ADDRESS | BB |
|---|---|---|---|---|---|---|
| -2- | -13- | -4- | -4- | 1 | -15- | |
| 2 | 15 | 19 | 23 | 24 | 39 | 40 |

DOWNLINK, REPLY WITH MESSAGE

| DTYP | CFLD | UMID | PBUT | $T_A$ | 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.

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<br>+ 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.

## 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.

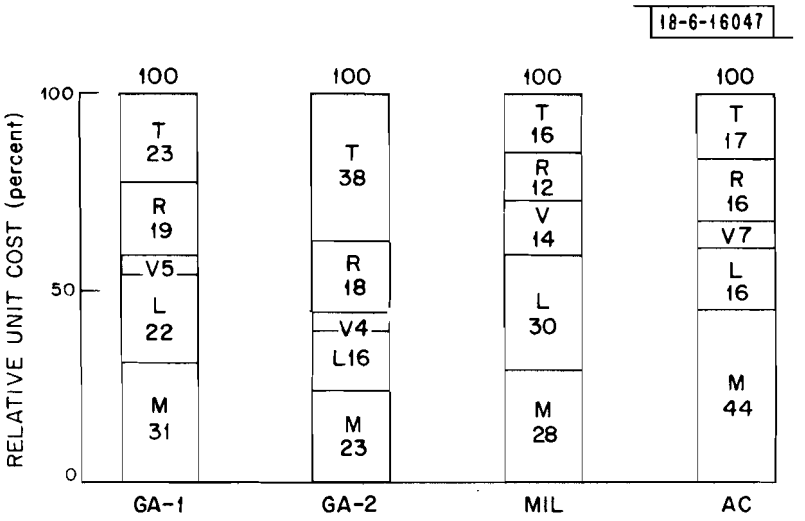
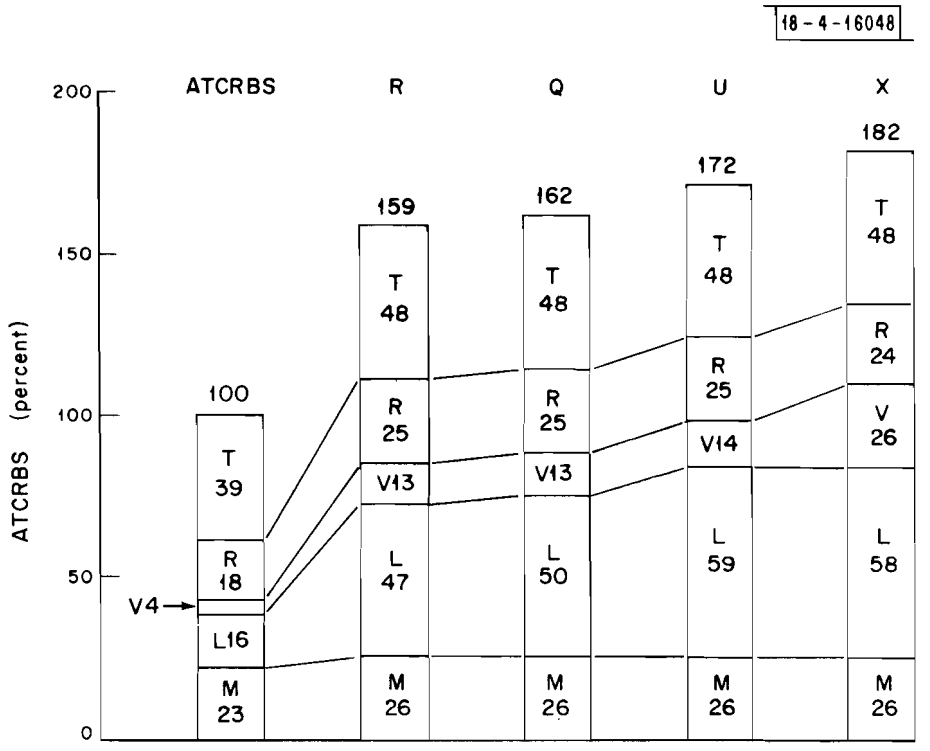



Fig. 4. Normalized costs for the four ATCRBS baseline transponders used in the studies.




| | 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.

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.

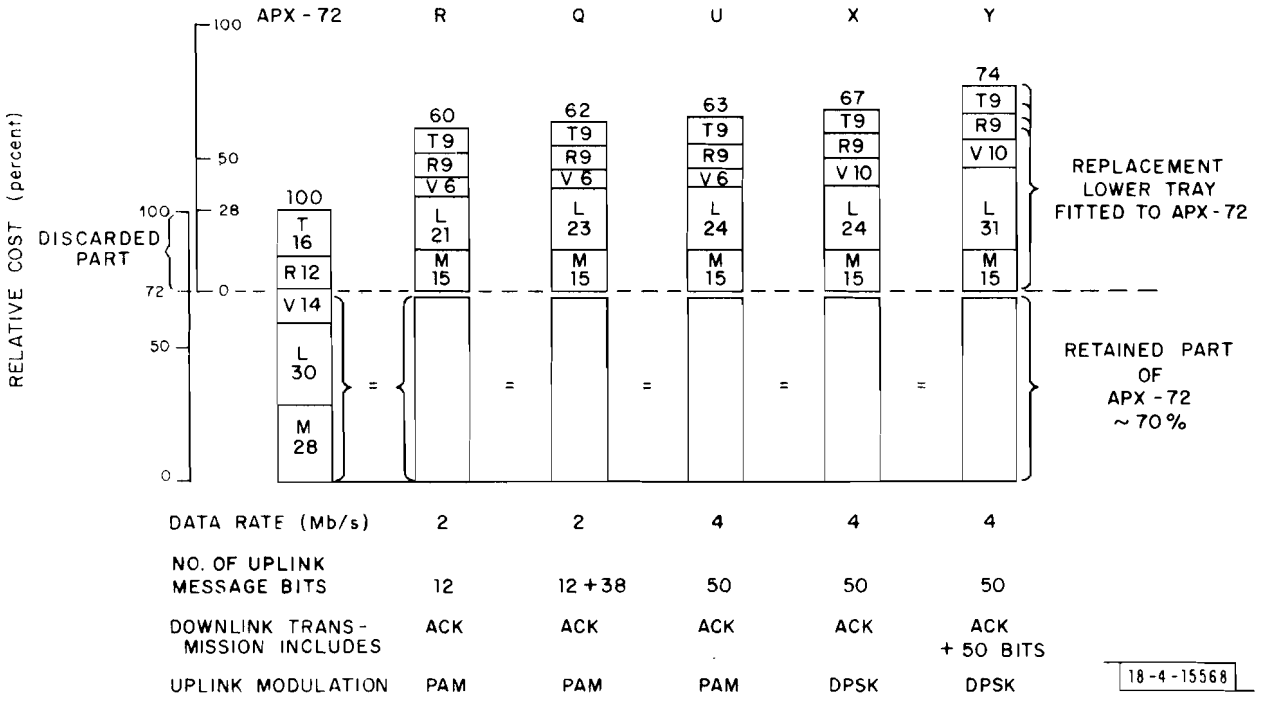



Fig. 8. Phase 2 results of MIL study for retrofit kits for APX-72.

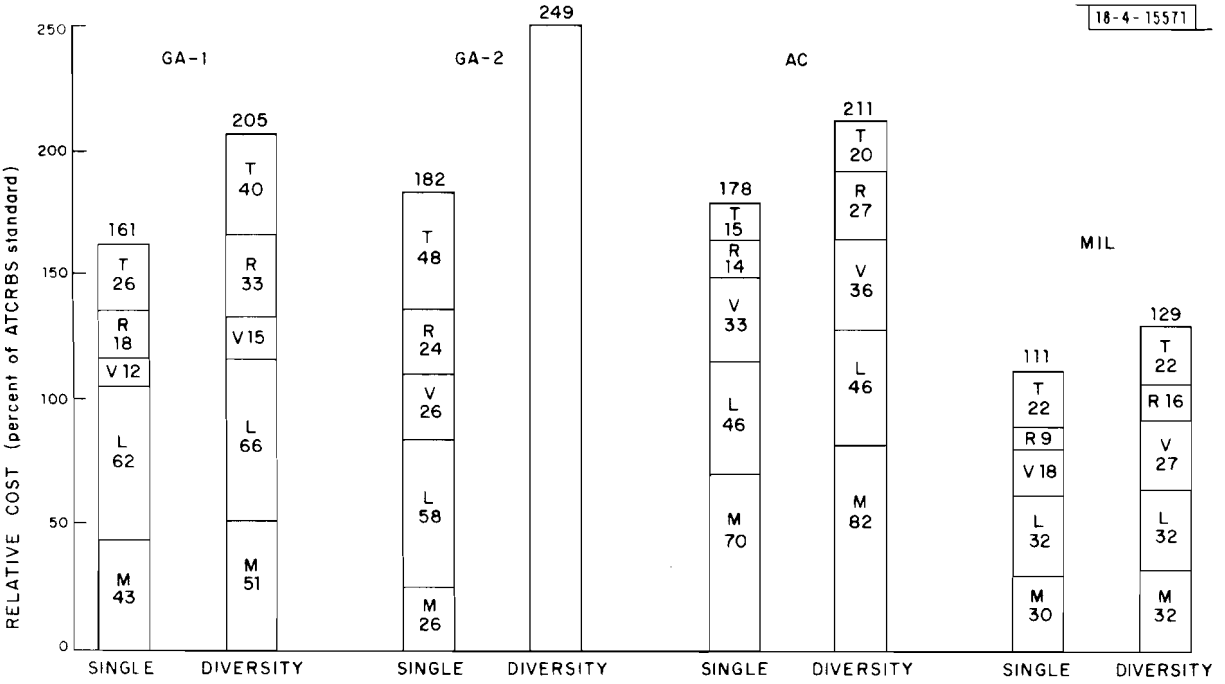



Fig. 10. Cost comparison of single input vs diversity transponders (both 4 Mb/sec DPSK uplink).

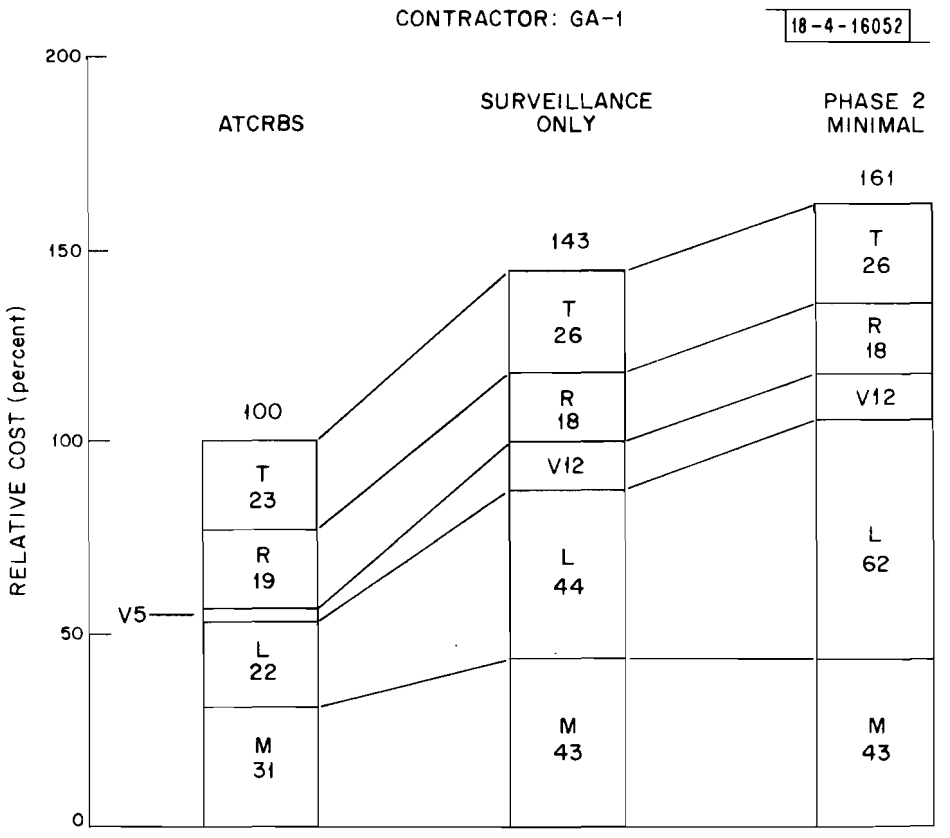



Fig. 12. "Surveillance only" transponder cost compared to ATCRBS and full Phase 2 "minimal" design (Option X, DPSK uplink).

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.