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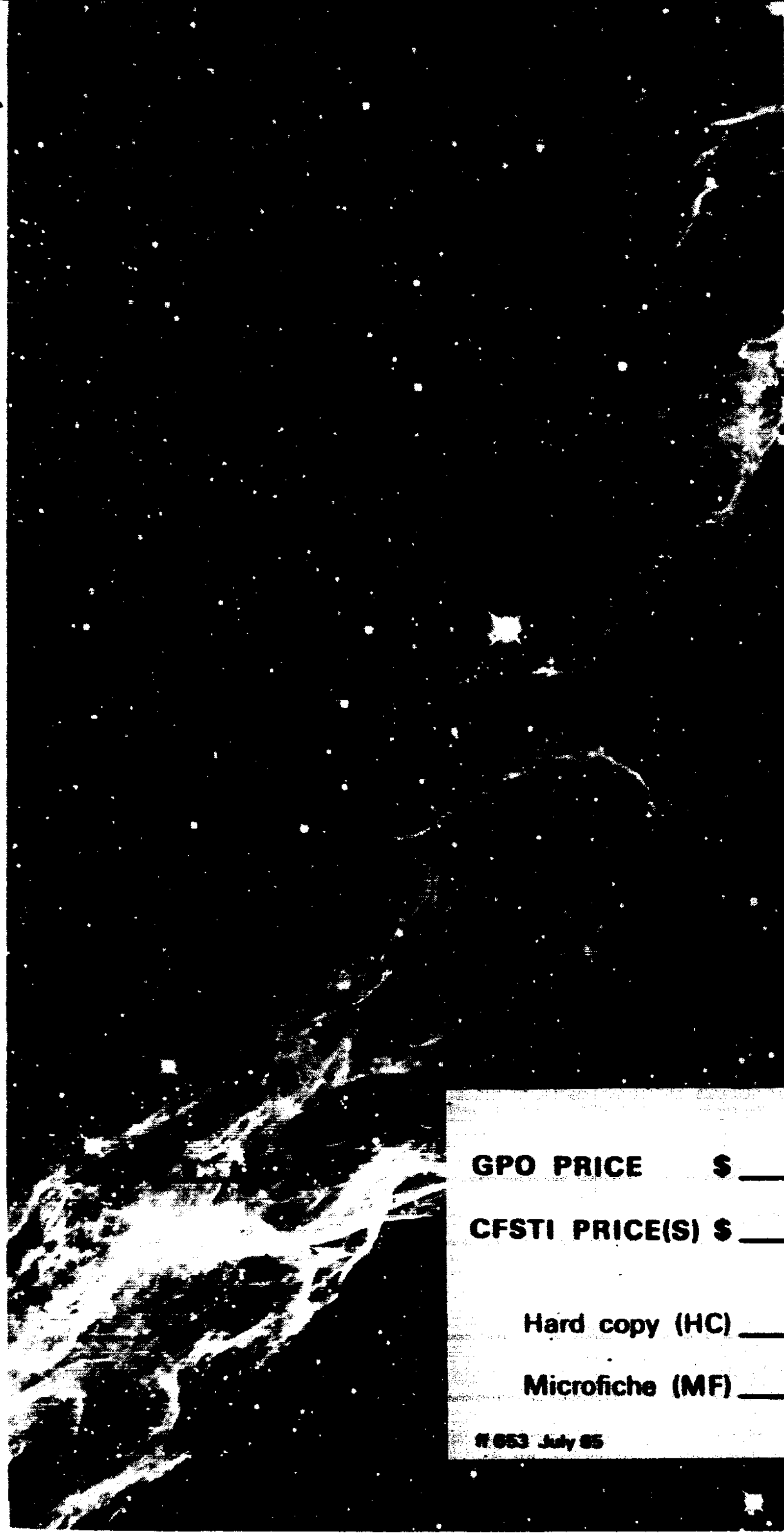

Report No. C-6

SPACECRAFT COST ESTIMATION

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by

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SPACECRAFT COST ESTIMATION

1. INTRODUCTION

Reliable cost estimates of future space programs are needed for the selection of optimum space exploration plans, for program approval and for satisfactory budgeting and management. Previous studies (Beverly, Stone and Vickers 1964, Beverly and Stone 1964) have developed empirical cost estimation formulae based on spacecraft and subsystem weights. The root mean square percentage error (RMSPE) in calculated costs as compared with budgeted or actual costs using the most recent formula was approximately $\pm$ 30 percent for the 12 programs considered and the model has subsequently been used to provide cost estimates for long range planning purposes.

The previous studies raised questions about the influence on cost of subsystems other than telecommunications and data handling on which the model was based and about the accuracy of predictions for future spacecraft which might incorporate significant advances in technology and/or be designed for different mission profiles.

This study was undertaken to establish the relative cost significance of each of the spacecraft subsystems and to further investigate the accuracy with which a linear model based on spacecraft weights could be expected to predict future spacecraft costs. As a result of the subsystem cost significance investigation, a new linear cost estimation equation was evolved which includes three subsystem weights as parameters. This equation yields a significant reduction in RMSPE and was employed in evaluating predictability.

This cost estimation equation and previous editions were developed to predict only the cost related to fabricating a spacecraft with its scientific payload. The equation does not predict costs related to launch vehicles, operational support, mission ground support equipment and data analysis. Although the method does not include a means for estimating those costs mentioned above, it may be coupled with proven estimation techniques for such categories to provide total cost estimates for future programs.

Once these total cost estimates have been established they can be utilized to determine cost-effectiveness of future missions which will allow long range planners to evaluate the mix of missions for the exploration of space within given budget constraints. In addition these total cost estimates can provide reasonable estimates for budget requirements and when used in concert with cost profile techniques will permit cost planners to budget individual program costs on a yearly basis.

2. INPUT DATA

The earlier studies had indicated that the definition of subsystem functions and therefore the allocation of weights to the various subsystems were not uniform throughout NASA and its contractors. Very detailed weight breakdowns were therefore obtained for as many "historical" programs as possible during the initial phase of this effort. These programs were:

Ranger 1-5*	Syncom ↑
Ranger 6-9*	OGO A-E△
Surveyor 1-7*	IMP A-C°
Mariner R*	IMP D-E°
Mariner 64*	Relay+

Data supplied by:

* Gaylord E. Nichols, Jr. and Robert Osborne, Jet Propulsion Laboratory, California Institute of Technology.

△ C. D. Ashworth - Program Manager, OGO - NASA Headquarters.

o F. W. Gaetano - Program Manager, IMP - NASA Headquarters.

\+ D. P. Rogers - Program Manager, Relay - NASA Headquarters.

↑ H. N. Stafford - Program Manager, Syncom - NASA Headquarters.

A standard set of functional definitions was constructed and the weights were then distributed among the six subsystems structure, propulsion, power, guidance and control, telemetry and data handling, and experiments. The definitions and a program example are given in Appendix A. It was difficult to determine completely unambiguous allocations for some weights in spite of the definitions employed. These "errors" will give rise to an intrinsic error in the cost estimates.

We have used NASA budgeted cost information (NASA 1966) as the basis for comparison with calculated costs. Since a number of these programs are not yet complete, it is to be expected that actual program costs will differ from the budgeted data used in this study. Past experience indicates that increases or decreases in costs of as much as ten to fifteen percent could occur.

3. ANALYSIS OF INDIVIDUAL SUBSYSTEM COST SIGNIFICANCE

The BMD 02R computer code (UCLA 1964) which performs stepwise linear regression calculations was used to obtain a measure of the relative significance of each of the spacecraft subsystems with the exception of experiments.* The weight and cost data for the programs were used to write 10 equations of

* It had previously been determined (Beverly and Stone 1964) that on the average the cost per pound of experiments is approximately equal to the cost per pound of the remainder of the spacecraft and hence need not be considered explicitly in the cost calculation for a given program. This was verified for the programs considered here (see Appendix B).

the type

$$C_B = \frac{N\, W_T}{W_{S/C}} \left(C_S\, W_S + C_P\, W_P + C_{Pwr} + C_{GC}\, W_{GC} + C_{TD}\, W_{TD}\right) \qquad (1)$$

where

C_B = NASA's budgeted spacecraft cost

N = The number of complete spacecraft including full prototypes, flight spares and flight models

W_T = The total weight of the spacecraft

$W_{S/C}$ = The weight of the spacecraft less experiments

W_S = The weight of the structure subsystem

W_{TD} = The weight of the telecommunication and data handling subsystem

W_P = The weight of the propulsion subsystem

W_{GC} = The weight of the guidance and control subsystem

W_{Pwr} = The weight of the power subsystem

$C_{TD}, C_S,$
C_P, C_{GC}
and C_{Pwr} = The linear regression coefficients for the subsystems included in the equation with units of millions of dollars per pound

where all weights are in pounds. For the sake of clarity and a more realistic appraisal of the differences between budgeted and calculated costs the term C_{MS} (mission support costs) has been eliminated and, as defined above, C_B is budgeted spacecraft cost only.

The computer program first determines which subsystem weight taken singly will yield the minimum sum of the squared errors (difference between calculated cost and budgeted cost). The equations were normalized so that the errors computed were percentage errors. This is essential since the costs of the space programs involved vary widely and a selection based on absolute errors will be heavily weighted by the high cost programs. The corresponding coefficient is calculated for the case where

$$C_{S/C} = \frac{N\ W_T}{W_{S/C}} (C_1\ W_1) \ . \tag{2}$$

Having selected this subsystem, the method then selects the subsystem which will yield the largest error reduction when used in combination with the first variable selected, i.e.,

$$C_{S/C} = \frac{N\ W_T}{W_{S/C}} (C_1\ W_1 + C_2\ W_2) \ . \tag{3}$$

The coefficients C_1 and C_2 are determined for this equation. The process is continued until all subsystems have been included. The order of selection is therefore an indication of the influence of a subsystem on the accuracy of the cost estimation assuming, of course, a linear cost model with independent variables.

Table 1 shows the relative significance of the subsystems and the root mean square percentage error associated with each step of the calculation.

Table 1

RELATIVE COST SIGNIFICANCE OF SPACECRAFT SUBSYSTEMS

Subsystem in Order of Decreasing Significance	Root Mean Square Percentage Error
Telecommunications and Data Handling	± 38%
Structure plus TD	± 27%
Propulsion plus TD and S	± 18%
Guidance and Control plus TD, S and P	± 15%
Power plus TD, S, P and GC	± 15%

4. MULTIVARIABLE COST ESTIMATION MODEL

It is very apparent from the results shown in Table 1 that inclusion of more than one subsystem can effect substantial reductions in the RMSPE. We therefore decided to develop a multivariable model before proceeding to the predictability question so that the best model would be used in that study. The use of several variables requires that more data be derived to utilize the model. It is therefore desirable to achieve a balance between the number of parameters and the value of the RMSPE. From Table 1 it can be seen that a model using just the first three subsystems (TD, S and P) can provide a level of accuracy nearly as good as a five parameter model. To further validate the choice of these three subsystems as the best for model purposes, numerous other groupings of three subsystems were tried. The RMSPE for all groupings tested were higher than for these three, TD, S and P. Examination of the partial correlation coefficients, which are calculated as part of the computer program, suggests a further simplification. These coefficients, which are shown in Table 2, numerically indicate the interdependence of any two variables used in the equation. The relatively high correlation (0.87) between telecommunications and data, and structure as compared to the correlation of

Table 2

CORRELATION MATRIX - TEN PROGRAMS

	TD	S	P
TD	1.0	0.87	0.33
S	0.87	1.0	0.39
P	0.33	0.39	1.0

propulsion with either telecommunications and data (0.33) or structure (0.39) suggests the possibility that the weights for the first two subsystems might be combined with only nominal increase in error. Calculations for the equation

$$C_{S/C} = \frac{N\ W_T}{W_{S/C}} C_{STD} (W_S + W_{TD}) + C_P\ W_P \qquad (4)$$

were performed and gave a RMSPE of $\pm$ 19 percent. This accuracy was judged to be adequate and this model was adopted for all remaining studies.

It should be stressed that the coefficients and subsystem weights yield an estimate of total spacecraft costs and the individual terms should not be construed as expressing the cost of a particular subsystem.

5. PREDICTABILITY

The 10 programs on which our analyses have been based are statistically very small. Further, as a result of advances in technology, it is possible that a future program could not be considered as a member of the population used to determine the coefficients of the model. Therefore, a question arises as to the confidence which can be placed in the cost estimates of programs other than the ten used here. Thus we have considered predictability in more detail.

The programs were examined to see if they included sufficiently diverse types of spacecraft to constitute a good sample. Indeed, there is a wide range of all the relevant parameters; total cost, total weight, type of mission, etc. The range of subsystem makeup is illustrated in Table 3 which contains percentage weight of each of the subsystems for the 10 programs. The time span covered by these programs is sufficiently long to have included both advanced technology and inflationary trends.

To more quantitatively establish the confidence with which this model may be used to estimate costs for other programs, the most heterogeneous group of 7 programs was selected. Data for the 7 programs are given in Table 4 together with data for the remaining three programs.

The seven programs were used in the linear regression computer code to obtain the coefficients for Eq. 4 (rounded to two significant figures) yielding

Table 3

PERCENTAGE WEIGHT OF THE SUBSYSTEMS FOR THE TEN PROGRAMS

Program	Total Weight of one S/C in lbs	% Weight of Telecommun. & Data	% Weight of Structure	% Weight of Propulsion	% Weight of Guidance and Control	% Weight of Power	% Weight of Experiments
Ranger 6-9	788	11	34	2	8	32	13
Ranger 1-5	612	11	32	2	8	27	20
Surveyor 1-7	787	7	37	29	11	13	3
Mariner R	437	19	30	4	12	24	11
Mariner 64	555	20	25	4	15	28	8
Syncom	84	38	24	12	11	15	0
OGO A-E	1038	15	37	0	10	17	18
IMP D-E	204	8	18	42	1	21	10
IMP A-C	135	10	32	0	1	30	27
Relay	184	24	24	0	2	43	7

Table 4

SPACECRAFT WEIGHT DATA (IN POUNDS) AND NUMBER OF SPACECRAFT IN INDIVIDUAL PROGRAMS

Program	No. of S/C	W_T	$W_{S/C}$	Telecommunication and Data	Structure	Dry Propulsion	Guidance and Control	Power	Experiments
Ranger 6-9*	5	788	684	88	265	18	61	252	104
+Ranger 1-5*	6	612	488	66	194	12	53	163	124
Surveyor 1-7	13	787	761	54	294	229	84	100	26
Mariner R*	3	437	390	84	133	17	53	103	47
Mariner 64	4	555	510	113	137	24	81	155	45
Syncom*	4	84	84	32	20	10	9	13	0
OGO A-E*	6	1038	848	158	401	0	108	181	190
IMP D-E*	2	204	183	16	37	86	2	42	21
IMP A-C	4	135	99	14	43	0	2	40	36
Relay*	4	184	172	45	45	0	4	78	12

* Most heterogeneous group of 7 programs.

\+ Rangers 1-2 and 3-5 were combined to derive a representative spacecraft weight for Rangers 1-5. This latter step was necessary because the costs of Ranger 1-2 and Rangers 3-5 are reported as an aggregate.

$$C_{S/C} = \frac{N\ W_T}{W_{S/C}}\ 0.038\ (W_S + W_{TD}) + 0.023\ (W_P)\ . \qquad (5)$$

The root mean square error for the 7 programs was ± 14 percent. Equation 5 was then used to "predict" the cost of the remaining 3 programs with the results shown in Table 5 and Figure 1. The root mean square error of 31 percent of the predicted programs together with the range of individual errors is an indication that satisfactory predictions can be made. Further verification would be desirable and can be achieved by estimating costs for programs not considered in this analysis. This step will be taken as soon as additional data are available.

We conclude that, unless there are very major changes in the technology or concepts of future spacecraft, this model can be expected to yield usable cost estimates for new programs. Periodic revision of the coefficients using additional historical program data as it becomes available can probably serve to keep the model timely.

Table 5

CALCULATED SPACECRAFT COST USING MULTIVARIABLE COST MODEL

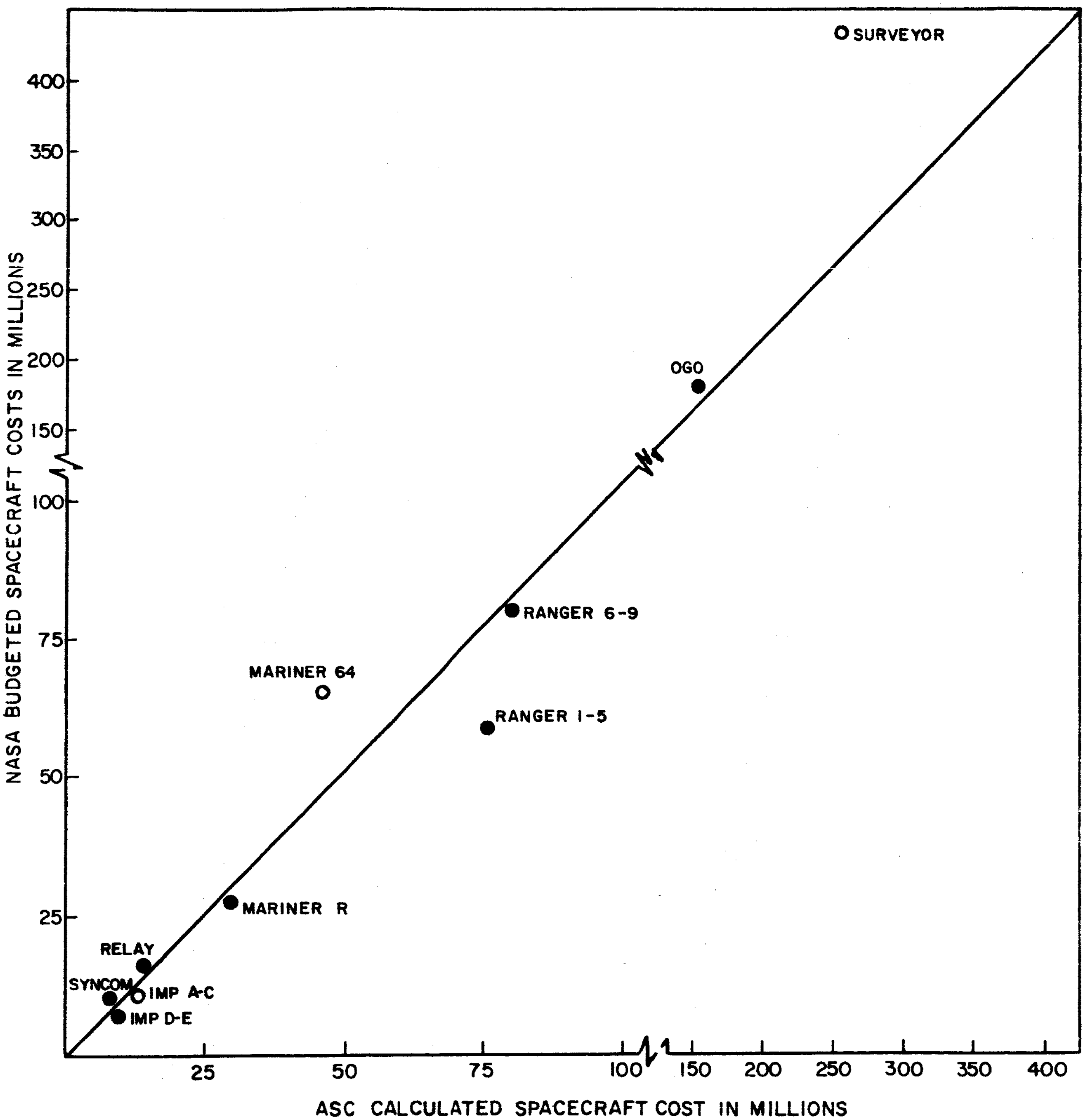
$$C_{S/C} = \frac{N\,W_T}{W_{S/C}}\ 0.038\ (W_S + W_{TD}) + 0.023\ (W_P)$$

	Programs	$W_{Str} + W_{TD}$ Contribution to Calculated Cost C_1		W_{Prop} Contribution to Calculated Cost C_2		Total Calculated Spacecraft Cost $C_1+C_2 = C_{S/C}$	NASA** Budgeted Spacecraft Cost C_B		Percentage Error $100(C_B-C_{S/C})/C_B$
1.	Ranger 6-9*	$ 77.3	+	2.4	=	79.7	80.1		- 0%
2.	Ranger 1-5*	74.3	+	2.1	=	76.4	59.8		+ 28%
3.	Mariner R*	27.7	+	1.3	=	29.0	28.2		+ 3%
4.	Syncom*	7.9	+	0.9	=	8.8	11.1		- 21%
5.	OGO A-E*	156.0	+	0	=	156.0	178.6		- 13%
6.	IMP D-E*	4.5	+	4.4	=	8.9	8.7		+ 2%
7.	Relay*	14.6	+	0	=	14.6	14.9		- 2%
						RMSPE	7 Programs	=	± 14%
1.	Mariner 64	41.3	+	2.4	=	43.7	64.8		- 33%
2.	Surveyor 1-7	177.8	+	70.8	=	248.5	436.5		- 43%
3.	IMP A-C	11.8	+	0	=	11.8	12.1		- 2%
						RMSPE	3 Programs	=	± 31%

* Programs used to calculate the coefficients.

**Budget figures are based on NASA's "Fiscal Year 1967 - President's Budget to Congress". The budgeted figures used have been adjusted to exclude the costs of ground operation equipment.

FIGURE I. COMPARSION OF CALCULATED SPACECRAFT COSTS WITH NASA BUDGETED SPACECRAFT COSTS



IITRI/ASC

● PROGRAMS USED TO ESTABLISH COEFFICIENTS
O PROGRAMS PREDICTED

6. SUBSYSTEM DATA REQUIREMENTS

The results discussed in the previous sections were obtained using subsystem weights derived from detailed weight and balance charts and a reasonably uniform set of functional definitions as mentioned in Section 2.

Detailed weights will in general not be available for missions in the early stages of advanced planning. Currently such information is often obtained only with difficulty. Also, an unambiguous description of subsystem functions would be difficult to write, very long and probably would not be widely accepted.

We therefore applied a nominal set of definitions to the summary type of weight data currently contained in Program Development Plans (PDPs) to obtain weights more closely corresponding to those available for long range planning. These definitions are contained in Appendix A together with illustrative PDP data and the derived subsystem weights for a typical program. Weights obtained in this fashion were utilized in a recalculation of the coefficients based on the same 7 programs. The gross weight data used are given in Table 6.

Estimated costs for the three programs were calculated using these coefficients and the gross weights. The results are summarized in Table 7 and are compared to the results derived using detailed weights.

Table 6

GROSS SPACECRAFT WEIGHT DATA
(in pounds)

Program	W_T	$W_{S/C}$	Telecommunication and Data	Structure	Dry Propulsion	Guidance and Control	Power	Experiments
Ranger 6-9*	788	698	160	197	25	100	216	90
Ranger 1-5*	612	487	66	193	13	54	161	125
Surveyor 1-7	787	723	43	269	229	128	54	64
Mariner R*	437	388	65	132	23	64	104	49
Mariner 64	555	502	143	83	29	78	170	52
Syncom*	84	84	32	20	10	9	13	0
OGO A-E*	1038	848	160	345	0	135	208	190
IMP D-E*	204	183	19	35	86	2	41	21
IMP A-C	135	99	19	38	0	2	40	36
Relay*	184	172	45	45	0	4	78	12

* Most heterogeneous group of 7 programs.

Table 7

COMPARISON OF CALCULATED COST

DETAILED WEIGHTS VS GROSS WEIGHTS

	Program	NASA* Budgeted S/C Cost C_B	Calculated S/C Cost (detailed weights) C_P	Calculated S/C Cost (gross weights) C_P	% Error Detailed Weights $100(C_B-C_P)/C_B$	% Error Gross Weights $100(C_B-C_P)/C_B$
1.	Ranger 6-9	$ 80.1	$ 79.7	$ 79.8	- 0%	+ 0%
2.	Ranger 1-5	59.8	76.4	76.5	+ 28%	+ 28%
3.	Mariner R	28.2	29.0	27.1	+ 3%	- 4%
4.	Syncom	11.1	8.8	8.8	- 21%	- 21%
5.	OGO A-E	178.6	156.0	144.7	- 13%	- 19%
6.	IMP D-E	8.7	8.9	8.5	+ 2%	+ 2%
7.	Relay	14.9	14.6	14.6	- 2%	+ 2%
				RMSPE 7 programs =	± 14%	± 15%
1.	Mariner 64	64.8	43.7	40.9	- 33%	- 37%
2.	Surveyor 1-7	436.5	248.6	242.3	- 43%	- 44%
3.	IMP A-C	12.1	11.8	11.8	- 2%	- 2%
				RMSPE 3 programs =	± 31%	± 33%

* Budget figures are based on NASA's "Fiscal Year 1967 - President's Budget to Congress". The budgeted figures used have been adjusted to exclude the costs of ground operation equipment.

7. CONCLUSIONS

The relative cost significance of the spacecraft subsystems in a linear regression model has been established. Telecommunications and Data Handling is the most important single factor as previously determined but structure and propulsion are also significant. Based on this analysis, an improved cost estimation equation has been developed.

$$C_{S/C} = \frac{N\ W_T}{W_{S/C}}\ 0.038\ (W_S + W_{TD}) + 0.023\ (W_P)\ .$$

The number of space programs on which the model is based is very limited. However, the diversity of these programs, the span of time over which these programs were pursued and the RMSPE for three programs "predicted" indicate that one should expect errors of 50 percent or less with 90 percent probability and errors of 25 percent or less with 60 percent probability.

This model can easily provide cost estimates for long range planning purposes using program level information and can also serve as a check on more detailed estimates.

The data available and the adequacy of the model developed do not appear to justify additional effort to alter or further refine this approach for at least a year or more. However, it will be instructive to apply the method to the several programs which will reach or closely approach completion in the next year or so. Use of the model on such programs as the Lunar Orbiter, Pioneer and OAO should provide additional data on the spread of predictions and hopefully, further increase confidence in the model.

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Appendix A

<u>SUBSYSTEM WEIGHT - DEFINITION, APPLICATION AND EFFECTS OF VARIATION IN APPLICATION</u>

Appendix A

SUBSYSTEM WEIGHT - DEFINITION, APPLICATION AND EFFECTS OF VARIATION IN APPLICATION

The purpose of this appendix is to present the definitions by which we arrived at the input weight data to the equation. To illustrate the application of the definitions we have chosen the program Mariner R (Program Development Plan 1961). The data in the table have been allocated to each subsystem in accordance with the definitions with the results shown in Table A-2, Subsystem Weights Derived from Input Data and Definitions. It should be noted that the illustration does not truly represent many of the subtleties involved in properly determining the allocation of all spacecraft components. For example the Ranger 3-9 spacecraft weight distribution chart listed the entire 383 lb RCA TV system as the experimental payload. This is an erroneous experiment weight and we therefore obtained a detailed breakdown of the system from RCA. From the breakdown we were able to properly allocate the TV system to four subsystems.

Table A-1

SAMPLE PROGRAM LEVEL INPUT DATA

Mariner R Weight Listing*

Subsystem	Weight Allocation (pounds)
Transponder	20.20
Antenna	19.81
Command	9.50
Central computer and sequencer	10.95
Data encoder	15.29
Attitude control	55.81
Structure	83.00
Actuators	3.40
Pyrotechnics	3.75
Motion sensors	1.33
Spacecraft wiring	33.00
Propulsion (dry)	23.00
Thermal control	14.30
Contingency	1.59

* Chart extracted from Mariner R program Development Plan 12/31/61, Jet Propulsion Laboratory.

Table A-2

SUBSYSTEM WEIGHTS DERIVED FROM INPUT DATA AND DEFINITIONS

Mariner R Subsystem Weights

		Weights (lbs)
Structure Subsystem		
Structure		83.00
Actuators		3.40
Pyrotechnics		3.75
Spacecraft wiring		33.00
Thermal control		14.30
Contingency		1.59
	Total	139.04
Telemetry and Data Handling Subsystem		
Transponder		20.20
Antenna		19.81
Central computer and sequencer		10.95
Command		9.50
Data encoder		15.29
	Total	75.75
Propulsion Subsystem		
Propulsion (dry)	Total	23.0
Guidance and Control Subsystem		
Attitude control		55.81
Motion sensors		1.33
	Total	57.14
Power Subsystem		
Power	Total	99.89
Experiment Subsystem		
Space Science	Total	42.10
	Grand Total	436.92 lb

To further illustrate the influence of variations in weight data or allocation on the accuracy of estimating spacecraft cost we arbitrarily introduced a 5, 10 and 15 percent change in selected subsystems using Mariner R data. The effects of these changes are shown in Figure A-1.

SPACECRAFT SUBSYSTEM DEFINITIONS

To arrive at the weights included in the equation, the total weight of a spacecraft should be allocated to the six spacecraft subsystems in accordance with the definitions that follow. Gross estimates made bearing these definitions in mind can be used for highly conceptual designs with attendant loss in confidence levels.

Structure Subsystem (W_S)

Includes basic structure, temperature and thermal control, harnesses, cabling mounting, hardware, pyrotechnics, wiring, etc. Many of these items are rarely distinct in the weight information most commonly available. Therefore, whenever possible, detailed weight information should be obtained in order that these items can be separated from subassemblies that are assigned to one of the other five subsystems.

Propulsion Subsystem (W_P)

Includes motors and thrusters with their mechanical arrangements, valves, tanks and pipelines which maneuver or stabilize the spacecraft. It excludes propellant, ordinary mounting provisions and electronic sensing and control equipment.

Guidance and Control Subsystems (W_{GC})

Consists of equipment necessary for attitude sensing, scanning, selection of flight path and determination of correction of position error. Specifically includes stabilization and attitude subsystem, sensors, flight control, pneumatic and detection system and altimeter. Excluded are engines used for station keeping or attitude control.

Telecommunications and Data Handling Subsystem (W_{TD})

Consists of equipment which on receiving data from the experimental payload allows perception, interpretation, recording, and two-way communication of data. Specific equipment included antenna assemblies, data encoders, decoders, central computer and sequencer, transponders, command and control systems, data automation and storage, recorders, readout systems, and receivers. Excludes radio frequency equipment used primarily as an experiment.

Power Subsystem (W_{Pwr})

Consists of equipment necessary to supply and condition power to the spacecraft subsystems. It specifically includes solar cells and panels, batteries, RTG systems, converters and inverters, regulators, transformers, and charges. It excludes mounting provisions and structures which can be identified for inclusion in the structure subsystem.

Experiment Subsystem (W_{Exp})

Consists of all experiments and equipment whose primary purpose is to provide scientific information. It excludes sources of raw power, booms, major pointing platforms, sequencing equipment, data handling equipment, mounting provisions and structure.

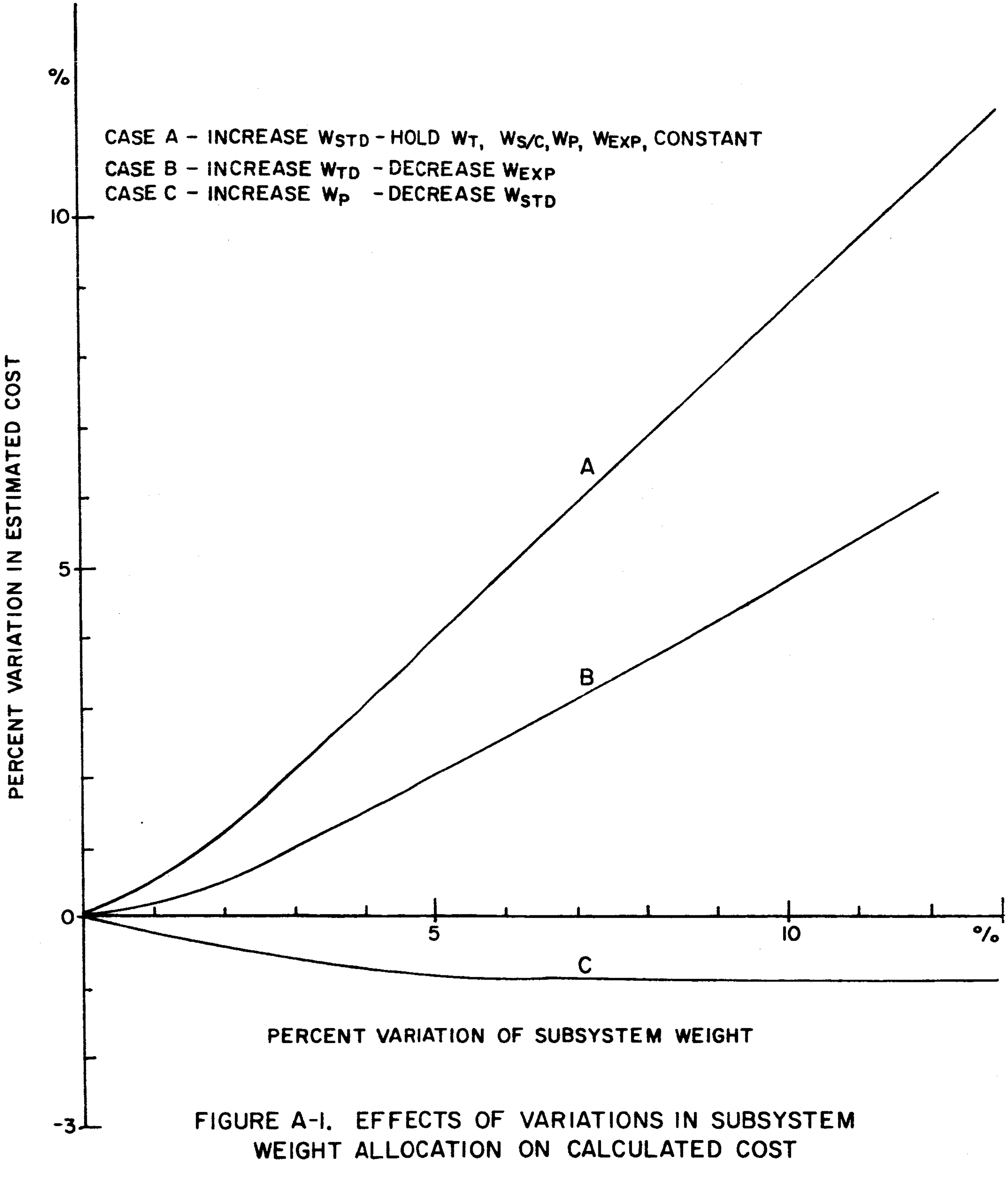

FIGURE A-1. EFFECTS OF VARIATIONS IN SUBSYSTEM WEIGHT ALLOCATION ON CALCULATED COST

Appendix B

COST ESTIMATION RELATIONSHIPS
OF EXPERIMENTS AND SPACECRAFT

Appendix B

COST ESTIMATION RELATIONSHIPS OF EXPERIMENTS AND SPACECRAFT

Early attempts to estimate costs for space programs were highly unsuccessful on an individual basis. Included in these attempts were plots of program dollars per pound versus such parameters as spacecraft weight, experiment weight, and number of flight units. The outstanding feature of these plots was their inconsistency, but these early studies led to two important conclusions. First, the non-spacecraft costs such as ground operations and data analysis which varied substantially from program to program due in part to accounting methods should be treated separately. Secondly, the spacecraft costs are controlled by the major subsystems and experiments rather than gross features such as total weight and mission distance.

With these two facts in mind plus cost data on various programs made available in 1963, the first evidence of data correlation came when the percentage of cost attributable to the spacecraft alone was tabulated together with the percentage weight invested in the spacecraft less experiments. The similarity of these two fractions indicated that on the average the cost per pound of spacecraft is essentially the same as that per pound of scientific experiment although the total spacecraft costs may differ greatly from program to program.

Table 1 summarizes the 1963 data and shows that on the average the percentage of program cost attributable to the spacecraft alone is within five percent of the percentage of the weight attributable to the spacecraft. It can be seen that most individual programs do adhere to this rather closely. Table 2 and Table 3 contain similar data compiled in 1964 and 1965 and further substantiates the correlation. Therefore it appears that for purposes of estimating total program costs, the approximation that the cost per pound of experiments is equal to the cost per pound of spacecraft can be used.

This approximation makes it possible for one to evaluate total cost on the basis of spacecraft data alone which is preferable for two reasons: (1) information on the costs and weight of experiments is much more difficult to obtain, and (2) a total cost estimate based on spacecraft data is likely to be less sensitive to such deviations as high experiment costs associated with a particular mission.

Table 1

PROGRAM COSTING DATA (1963)

Program	Total Budgeted Program Cost ($M)	Mission Support Cost (C_{MS}) ($M)	Net Cost Spacecraft plus Experiments ($M)	Spacecraft Costs ($C_{S/C}$) ($M)	$(\frac{C_{S/C}}{\text{Net cost}})100$	$(\frac{W_{S/C}}{W_T})100$
Mariner C	$ 79.5	$ 21.3	$ 58.2	$ 50.9	88%	93%
Pioneer	29.0	2.1	26.9	21.5	80	80
IMP	9.0	0.7	8.3	5.8	70	74
OSO	21.1	2.5	18.6	11.9	64	62
AOSO	78.0	1.2	76.8	56.1	73	72
OAO	117.7	2.0	115.7	90.4	78	72
OGO	121.7	4.2	117.5	72.8	62	85
Relay	40.9	16.4	24.5	15.5	63	93
Tiros	38.7	8.8	29.9	24.4	82	75
Syncom	26.7	12.2	14.5	14.5	100	100
				Average	76	81

Table 2

PROGRAM COSTING DATA (1964)

Program	Total Budgeted Program Cost ($M)	Mission Support Cost (C_{MS}) ($M)	Net Cost Spacecraft plus Experiments ($M)	Spacecraft Costs ($C_{S/C}$) ($M)	$(\frac{C_{S/C}}{\text{Net cost}})100$	$(\frac{W_{S/C}}{W_T})100$
Mariner C	$ 84.2	$ 12.4	$ 71.8	$ 59.5	83%	92%
Pioneer	29.8	1.7	28.1	21.9	78	78
IMP	8.3	0.3	8.0	6.0	75	74
OSO	7.1	2.1	5.0	2.5	50	45
OGO	113.8	3.2	110.6	79.6	72	86
Relay	41.0	25.4	15.6	15.2	97	93
Tiros	13.1	6.0	5.7	5.2	91	74
Syncom	30.6	16.8	13.8	13.8	100	100
Ranger 1-5	62.5	----	62.5	53.6	86	83
Ranger 6-9	87.0	8.7	78.3	51.7	66	89
Mariner R	25.0	3.5	21.5	17.1	80	93
Surveyor 1-7	237.7	20.5	217.2	198	91	91
				Average	81	83

Table 3

PROGRAM COSTING DATA (1965)

	Total Budgeted Program Cost ($M)	Mission Support Cost (C_{MS}) ($M)	Net Cost Spacecraft plus Experiments ($M)	Spacecraft Costs ($C_{S/C}$) ($M)	$(\frac{C_{S/C}}{\text{Net Cost}})100$	$(\frac{W_{S/C}}{W_T})100$
Ranger 6-9	$ 88.8	$ 8.7	$ 80.1	$ 43.3	54	87
Ranger 1-5	59.8	0	59.8	50.9	85	78
Surveyor 1-7	457.6	21.1	436.5	419.9	96	97
Mariner R	30.7	2.5	28.2	25.5	90	89
Mariner 64	85.5	20.7	64.8	51.9	80	92
Syncom	20.8	9.7	11.1	11.1	100	100
OGO A-E	184.9	6.3	178.6	126.3	71	82
IMP D-E	9.1	0.4	8.7	5.7	66	90
IMP A-C	11.6	0.1	11.5	7.7	67	73
Relay	35.0	20.1	14.9	14.6	97	93
					81	88