TECHNICAL ADVISEMENT MEMORANDUM NO. 106-13

GEOS COMMAND ASSIGNMENT

PRC D-1190

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LIST OF EXHIBITS

TECHNICAL ADVISEMENT MEMORANDUM NO. 106-13

To: Program Manager, Geodetic Satellite Physics and Astronomy Programs, Office of Space Science and Applications, NASA Headquarters

From: PRC GEOS Reliability Assessment Team

Subject: GEOS Command Assignment

1. Introduction

The purpose of this memorandum is to develop a methodology for assigning command functions to the relay matrix positions of the GEOS command subsystem in a manner best suited to enhance overall satellite operational reliability.

This effort is undertaken with the presumption that not all possible command assignments are equally desirable from the reliability viewpoint. If this is true, then the best assignment may be defined as the one that results in the least degradation of system reliability. It is recognized that the maximum gain in reliability to be realized solely through command assignment is small. However, the particular command assignment actually used in a given satellite is more or less arbitrary; therefore, use of the most reliable assignment should involve no added increment of cost beyond the application of this memorandum.

The approach taken is first to examine in detail the command subsystem, the command function, and the assignment criteria. Then, on the basis of this analysis, a generalized assignment methodology will be presented and evaluated. The GEOS A satellite will be used for illustrative purposes throughout the memorandum.

2. Analysis

A reliability assessment for the GEOS A command subsystem, including a complete first-order failure mode and effects analysis, has been completed and the results reported in Reference 1. Although not essential for an understanding of this TAM, some results presented have been derived in detail in Reference 1. It also will provide additional background information for those unfamiliar with the GEOS A command subsystem.

The objective of Reference 1 was to assess the reliability of the GEOS A command subsystem. The results of this assessment were quite favorable. However, two assumptions inherent in that assessment were that all 64 commands were of equal value and that value lost was an additive function of commands lost. Thus, similar failure effects could be grouped; this simplified the analysis considerably. The presence of extra or wrong commands was essentially ignored to further simplify that analysis. The objective of this TAM is to remove these assumptions and then to derive a method for assigning the command functions to the matrix intersections in an optimal manner.

a. The Command Subsystem

Exhibit 1 will serve to define the major elements of the GEOS A command subsystem. The logic units and matrix are of primary interest in this analysis since only these units give rise to degraded subsystem states.[1] It is clear that command assignment offers improvement only in the face of partial subsystem loss, for no assignment offers any advantage over another if the command subsystem is perfectly operable or totally failed.

Exhibit 2 presents a detailed summary of the first-order failure effects for a single logic unit; Exhibit 3 does the same for the matrix unit. The probability of observing each distinguishable effect is also presented in these exhibits. Each effect is given a state number, or index, for ease in manipulation. Similar effects are grouped according to the state index. Exhibits 1, 2, and 3 are derived directly from Reference 1.

[1] The matrix unit is defined as extending to, but not including, the relays that a particular intersection actuates.

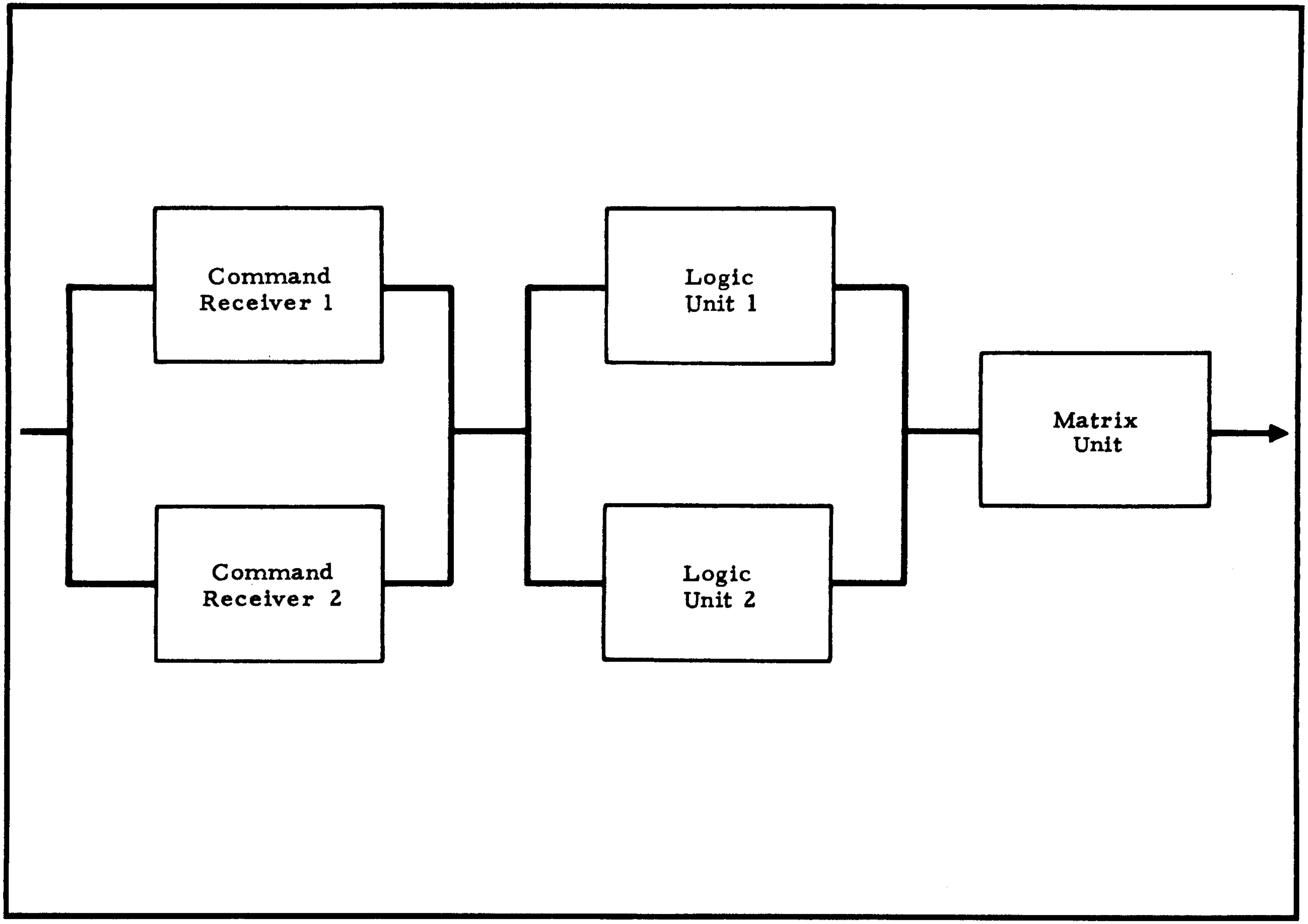

EXHIBIT 1 - COMMAND SUBSYSTEM BLOCK DIAGRAM

EXHIBIT 2 - LOGIC UNIT STATES, FAILURE EFFECTS AND STATE PROBABILITIES

State	Failure Effect	Individual State Probability
1	Perfect operation	0.4781
2	Lose logic unit 1	0.1284
3	Lose entire subsystem	0.0178
4	Lose logic unit 2[1]	0.0083
5-8	Lose C1-C7 C2-C8 F1-F7 F2-F8	0.0075
9-16	Lose one column	0.0041
17-24	Lose one row	0.0041
25-28	Lose C1-C3 and C5-C7 C3-C8 F1-F3 and F5-F7	0.0038
29-32	Lose C1-C4 C5-C8 F1-F4 F5-F8	0.0038
33-36	Lose one command tone	0.0037
37-62	Execute wrong or extra commands[2]	0.0576
63	Higher order failures[3]	0.1690

EXHIBIT 2 (Continued)

Notes: (1) This failure effect is such that, if any other logic unit in the vicinity is addressed, the failed logic unit will treat the first message tone as its address and will then accumulate successive message tone until it executes a command. If a message tone is used to address the failed logic unit, it will perform satisfactorily as long as the other logic unit in the satellite (or any others in the vicinity) is not addressed.

(2) Within the 26 states included in this entry are 5 classes of failure effects. They are as follows:

(a) State 37, which occurs if the charge line power fails true and causes up to three extra commands to be executed; the precise number and position is a function of the command sent. This is only a column-type effect, and the extra command(s) will always be executed at the intersection of the selected row. The possibilities are as shown in the following table.

Correct Column	C1	C2	C3	C4	C5	C6	C7	C8
Extra Column(s)	None	C1	C1, C2	C1, C2	C1, C2, C3	C1, C2, C3	C1, C2, C4	C1, C2, C4

(b) State 38, which occurs if the No. 2 flip-flop of the divide-by-4 counter fails true. One extra command is executed on receipt of the first message tone. The extra command will always be one of the four in the upper left corner of Exhibit 4; each occurs with essentially equal probability.

(c) States 39-46 are associated with the charge decoding gates and charge line drivers and are a column effect in that the extra command (one only) will always be executed from the intersection associated with the failed column and selected row. If the failed column is addressed, the system functions normally.

(d) States 47-54 are associated with the fire decoding gates and are a row effect in that one extra command will always be executed from from the failed row and selected column. If the failed row is addressed, the system functions normally.

(e) States 55-62 are associated with failures in the fire and charge control element gates and result in a wrong command being executed in considerably less than half

EXHIBIT 2 (Continued)

the time, on the average. The actual proportion of commands, and which commands, that will be executed erroneously in the face of this failure effect is a highly complex function of the command sent. The probability of occurrence of each of these individual states is

State	Individual State Probability
37	0.0038
38	0.0038
39-46	0.0041
47-54	0.0019
55-62	0.00027

(3) This entry includes all failure conditions not specifically treated in the rest of the exhibit. The effects of failures of this type range from none at all to complete loss of the command subsystem.

EXHIBIT 3- MATRIX UNIT STATES, FAILURE EFFECTS AND STATE PROBABILITIES

State	Failure Effect	State Probability
1	Perfect operation	0.8231
2	Marginal operation$^{(1)}$	0.0848
3	Lose entire subsystem	0.0075
4-67	Lose one command	0.00047
68-75	Lose one row	0.0022
76-83	Lose one column	0.00065
84-147	Execute extra commands$^{(2)}$	0.00047
148	Higher order failures$^{(3)}$	0.0063

Notes: (1) Includes effects such as slightly reduced power and increased noise sensitivity.

(2) These states associated with the intersection diodes and the effect are as follows. If a failure occurs at row i and column j and a command is sent to row k, column l, then commands are executed at row i, column l; row k, column j; row k, column l; and possibly at row i, column j.

(3) See note (3), Exhibit 2.

The matrix of the GEOS A command subsystem distributes signals from the command receivers and logic units to the various experiments and basic subsystems, to institute certain changes in internal satellite configurations, or to initiate or terminate the performance of certain functions. The configurations and functions, derived from Reference 2, for GEOS A are as indicated in Exhibit 4. The upper line in each matrix cell gives the tone sequence required to execute that command; in parentheses is the number of relays actuated by the command. The second and third lines of each matrix cell give the command designation and word description of the command function, respectively. Half the matrix positions represent the "ON" half of the command functions, signified by "a" in the command designations. The "OFF" half of the command function is signified by "b." The dot in the upper left corner represents the command position assumed most likely to exist at a random time t during the mission. The margins give three common designations of the matrix rows and columns.

As is evident from the preceding discussion, there are essentially three classes of failure effects:

- Those that cause all (or no) commands to be lost
- Those that cause some commands to be lost
- Those that result in the execution of erroneous commands or unwanted additional commands

Only the last two classes offer any opportunity for improving operational reliability by means of command assignment. To make this concept more definite, Exhibit 5 tabulates all possible command subsystem states arising from the two logic units and the matrix. Since there are well over half a million such states, some further notation is required. All those failure effects within a single logic unit which are associated with partial command losses are denoted L_1; all those which result in extraneous commands are denoted L_2. For the matrix, all those failure effects that result in a partial loss are denoted M_1, and those that result in extraneous commands are denoted M_2. Note that losses of single commands do not result from logic unit failures. Other effects are carried as indicated in Exhibits 2 and 3.

	C1 CA 000	C2 CB 100	C3 CC 010	C4 CD 110	C5 CE 001	C6 CF 101	C7 CG 011	C8 CH 111
F1 FA 000	BBB (5) 7b Tlm Sys OFF	DBB (5) 13b Memory 2 ON	• BDB (1) 30b Mem Conv 1	DDB (1) 1b Osc 2 Sel	• BBD (5) 7a Tim Sys ON	• DBD (5) 13a Memory 1 ON	BDD (1) 30a Mem Conv 2	• DDD (1) 1a Osc 1 Sel
F2 FB 100	• CBB (2) 26b RRR Norm	EBB (3) 196 162 φ Mod OFF	CDB (3) 20b 324 φ Mod OFF	• EDB (2) 14b Squib Enable ON	CBD (2) 26a RRR Man	• EBD (3) 19a 162 φ Mod ON	• CDD (3) 20a 324 φ Mod ON	EDD (2) 14a Squib Enable OFF
F3 FC 010	BCB (1) 32b Time Mark OFF	• DCB (2) 11b Comm 1 OFF	• BEB (4) 31b VSCO OFF	DEB (2) 9b Vect Mag OFF	• BCD (1) 32a Time Mark ON	DCD (2) 11a Comm 1 ON	BED (4) 31a VSCO ON	• DED (2) 9a Vect Mag ON
F4 FD 110	CCB (1) 5b 324 mc OFF	ECB (1) 17b Boom In	CEB (1) 22b Trans Pwr Dmp ON	EEB (1) 3b Main Conv 2	• CCD (1) 5a 324 mc ON	ECD (1) 17a Boom Out	• CED (1) 22a Trans Pwr Dmp OFF	• EED (1) 3a Main Conv 1
F5 FE 001	• BBC (4) 8b FM/PM OFF	• DBC (2) 16b Boom Bypass	• BDC (1) 15b Safe + 4.7 V	DDC (1) 2b Osc 2 Sel	BBE (4) 8a FM/PM ON	DBE (2) 16a Boom Bypass ON	BDE (1) 15a Fire + 3.9 V	• DDE (1) 2a Oven 1 Sel
F6 FF 101	CBC (4) 23b SECOR OFF	• EBC (1) 29b Mem TT Reset	CDC (1) 21b Opt Pwr Dmp ON	• EDC (3) 25b RRR OFF	• CBE (4) 23a SECOR ON	EBE (1) 29a Memory Load	• CDE (1) 21a Opt Pwr Dmp OFF	• EDE (3) 25a RRR ON
F7 FG 101	• BCC (1) 28b AOL 2 OFF	• DCC (2) 12b Comm 2 OFF	• BEC (6) 27b AOL 1 OFF	DEC (3) 10b Solar Only OFF	BCE (1) 28a AOL 2 Flash	DCE (2) 12a Comm 2 ON	BEE (6) 27a AOL 1 Flash	DEE (3) 10a Solar Only ON
F8 FH 111	CCC (1) 6b 972 mc OFF	• ECC (3) 18b B Motor OFF	• CEC (3) 24b SECOR Norm	EEC (1) 4b 162 mc OFF	• CCE (1) 6a 972 mc ON	ECE (3) 18a B Motor ON	CEE (3) 24a SECOR Man	• EEE (1) 4a 162 mc ON

Dot represents "normal" position.

EXHIBIT 4 - GEOS A COMMAND MATRIX

EXHIBIT 5 - COMMAND SUBSYSTEM STATES WITH STATE PROBABILITY AND STATE VALUE INDICATIONS

Unit State Indication			Number of System States	Probability Indication	Value Indication(1)
Matrix	L. U. 1	L. U. 2			
1	1	1	1	0.1881	1
		2	1	0.0505	1
		3	1	0.0070	0
		4	1	0.0033	g
		L_1(2)	32	0.0554	1
		L_2(3)	26	0.0227	1
		63	1	0.0665	x
	2	1	1	0.0505	1
		2	1	0.0136	0
		3	1	0.0019	0
		4	1	0.00088	g
		L_1	32	0.0149	ℓ
		L_2	26	0.0061	e
		63	1	0.0179	x
	3	1	1	0.0070	0
		2	1	0.0019	0
		3	1	0.00026	0
		4	1	0.00012	0
		L_1	32	0.0021	0
		L_2	26	0.00084	0
		63	1	0.0025	0
	4	1	1	0.0033	g
		2	1	0.00088	g
		3	1	0.00012	0
		4	1	0.000057	g^2
		L_1	32	0.00096	$g\ell$
		L_2	26	0.00039	eg
		63	1	0.0012	x
	L_1	1	32	0.0554	1
		2	32	0.0149	ℓ
		3	32	0.0021	0
		4	32	0.00096	$g\ell$
		L_1	1,024	0.0163	ℓ^2
		L_2	832	0.0067	$e\ell$
		63	32	0.0196	x
	L_2	1	26	0.0227	1
		2	26	0.0061	e
		3	26	0.00084	0
		4	26	0.00039	eg
		L_1	832	0.0067	$e\ell$
		L_2	676	0.0027	e^2
		63	26	0.0080	x

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L. U. 1	L. U. 2			
	63	1	1	0.0665	x
		2	1	0.0179	x
		3	1	0.0025	0
		4	1	0.0012	x
		L_1	32	0.0196	x
		L_2	26	0.0080	x
		63	1	0.0231	x
2	1	1	1	0.0194	v
		2	1	0.0052	v
		3	1	0.00072	0
		4	1	0.00034	gv
		L_1	32	0.0057	v
		L_2	26	0.0023	v
		63	1	0.0068	x
	2	1	1	0.0052	v
		2	1	0.0014	0
		3	1	0.00019	0
		4	1	0.000090	gv
		L_1	32	0.0015	ℓv
		L_2	26	0.00063	ev
		63	1	0.0018	x
	3	1	1	0.00072	0
		2	1	0.00019	0
		3	1	0.000027	0
		4	1	0.000013	0
		L_1	32	0.00021	0
		L_2	26	0.000087	0
		63	1	0.00026	0
	4	1	1	0.00034	gv
		2	1	0.000090	gv
		3	1	0.000013	0
		4	1	0.0000058	g^2v
		L_1	32	0.000099	$g\ell v$
		L_2	26	0.000040	egv
		63	1	0.00012	x
	L_1	1	32	0.0057	v
		2	32	0.0015	ℓv
		3	32	0.00021	0
		4	32	0.000099	$g\ell v$
		L_1	1,024	0.0017	$\ell^2 v$
		L_2	832	0.00069	$e\ell v$
		63	32	0.0020	x

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L. U. 1	L. U. 2			
	L_2	1	26	0.0023	v
		2	26	0.00063	ev
		3	26	0.000087	0
		4	26	0.000040	egv
		L_1	832	0.00069	$e\ell v$
		L_2	676	0.00028	e^2v
		63	26	0.00082	x
	63	1	1	0.0068	x
		2	1	0.0018	x
		3	1	0.00026	0
		4	1	0.00012	x
		L_1	32	0.0020	x
		L_2	26	0.00082	x
		63	1	0.0024	x
3	1	1	1	0.0017	0
		2	1	0.00046	0
		3	1	0.000064	0
		4	1	0.000030	0
		L_1	32	0.00050	0
		L_2	26	0.00021	0
		63	1	0.00060	0
	2	1	1	0.00046	0
		2	1	0.00012	0
		3	1	0.000017	0
		4	1	0.0000080	0
		L_1	32	0.00014	0
		L_2	26	0.000055	0
		63	1	0.00016	0
	3	1	1	0.000064	0
		2	1	0.000017	0
		3	1	0.0000024	0
		4	1	0.0000011	0
		L_1	32	0.000019	0
		L_2	26	0.0000077	0
		63	1	0.000023	0
	4	1	1	0.000030	0
		2	1	0.0000080	0
		3	1	0.0000011	0
		4	1	0.00000052	0
		L_1	32	0.0000088	0
		L_2	26	0.0000036	0
		63	1	0.000011	0

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L.U. 1	L.U. 2			
	L_1	1	32	0.00050	0
		2	32	0.00014	0
		3	32	0.000019	0
		4	32	0.0000088	0
		L_1	1,024	0.00015	0
		L_2	832	0.00061	0
		63	32	0.00018	0
	L_2	1	26	0.00021	0
		2	26	0.000055	0
		3	26	0.0000077	0
		4	26	0.0000036	0
		L_1	832	0.000061	0
		L_2	676	0.000025	0
		63	26	0.000073	0
	63	1	1	0.00060	0
		2	1	0.00016	0
		3	1	0.000023	0
		4	1	0.000011	0
		L_1	32	0.00018	0
		L_2	26	0.000073	0
		63	1	0.00021	0
$m_1^{(4)}$	1	1	80	0.0110	m
		2	80	0.0030	m
		3	80	0.00041	0
		4	80	0.00019	gm
		L_1	2,560	0.0032	m
		L_2	2,080	0.0013	m
		63	80	0.0039	x
	2	1	80	0.0030	m
		2	80	0.00079	0
		3	80	0.00011	0
		4	80	0.000051	gm
		L_1	2,560	0.00087	ℓm
		L_2	2,080	0.00036	em
		63	80	0.0010	x
	3	1	80	0.00041	0
		2	80	0.00011	0
		3	80	0.000015	0
		4	80	0.0000071	0
		L_1	2,560	0.00012	0
		L_2	2,080	0.000049	0
		63	80	0.00014	0

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L. U. 1	L. U. 2			
	4	1	80	0.00019	gm
		2	80	0.000051	gm
		3	80	0.0000071	0
		4	80	0.0000033	g^2m
		L_1	2,560	0.000056	$gm\ell$
		L_2	2,080	0.000023	egm
		63	80	0.000068	x
	L_1	1	2,560	0.0032	m
		2	2,560	0.00087	$m\ell$
		3	2,560	0.00012	0
		4	2,560	0.000056	gm
		L_1	81,920	0.00095	$m\ell^2$
		L_2	66,560	0.00039	$e\ell m$
		63	2,560	0.0011	x
	L_2	1	2,080	0.0013	m
		2	2,080	0.00036	em
		3	2,080	0.000049	0
		4	2,080	0.000023	gm
		L_1	66,560	0.00039	$e\ell m$
		L_2	54,080	0.00016	me^2
		63	2,080	0.00047	x
	63	1	80	0.0039	x
		2	80	0.0010	x
		3	80	0.00014	0
		4	80	0.000068	x
		L_1	2,560	0.0011	x
		L_2	2,080	0.00047	x
		63	80	0.0014	x
$m_2^{(5)}$	1	1	64	0.0069	f
		2	64	0.0018	f
		3	64	0.00026	0
		4	64	0.00012	fg
		L_1	2,048	0.0020	f
		L_2	1,664	0.00083	f
		63	64	0.0024	x
	2	1	64	0.0018	f
		2	64	0.00050	0
		3	64	0.000069	0
		4	64	0.000032	fg
		L_1	2,048	0.00054	$f\ell$
		L_2	1,664	0.00022	ef
		63	64	0.00065	x

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L. U. 1	L. U. 2			
	3	1	64	0.00026	0
		2	64	0.000069	0
		3	64	0.0000095	0
		4	64	0.0000044	0
		L_1	2,048	0.000075	0
		L_2	1,664	0.000031	0
		63	64	0.000090	0
	4	1	64	0.00012	fg
		2	64	0.000032	fg
		3	64	0.0000044	0
		4	64	0.0000021	fg^2
		L_1	2,048	0.000035	$f\ell g$
		L_2	1,664	0.000014	efg
		63	64	0.000042	x
	L_1	1	2,048	0.0020	f
		2	2,048	0.00054	$f\ell$
		3	2,048	0.000075	0
		4	2,048	0.000035	$fg\ell$
		L_1	65,536	0.00060	$f\ell^2$
		L_2	53,248	0.00024	$ef\ell$
		63	2,048	0.00072	x
	L_2	1	1,664	0.0083	f
		2	1,664	0.00022	ef
		3	1,664	0.000031	0
		4	1,664	0.000014	efg
		L_1	53,248	0.00024	$ef\ell$
		L_2	43,264	0.00010	e^2f
		63	1,664	0.00029	x
	63	1	64	0.0024	x
		2	64	0.00065	x
		3	64	0.000090	0
		4	64	0.000042	x
		L_1	2,048	0.00072	x
		L_2	1,664	0.00029	x
		63	64	0.00086	x
148	1	1	1	0.0014	x
		2	1	0.00039	x
		3	1	0.000054	0
		4	1	0.000025	x
		L_1	32	0.00042	x
		L_2	26	0.00017	x
		63	1	0.00051	x

EXHIBIT 5 (Continued)

Unit State Indication			Number of System States	Probability Indication	Value Indication
Matrix	L. U. 1	L. U. 2			
	2	1	1	0.00039	x
		2	1	0.00010	x
		3	1	0.000014	0
		4	1	0.0000067	x
		L_1	32	0.00011	x
		L_2	26	0.000046	x
		63	1	0.00014	x
	3	1	1	0.000054	0
		2	1	0.000014	0
		3	1	0.0000020	0
		4	1	0.0000010	0
		L_1	32	0.000016	0
		L_2	26	0.0000064	0
		63	1	0.000019	0
	4	1	1	0.000025	x
		2	1	0.0000067	x
		3	1	0.0000010	0
		4	1	0.00000043	x
		L_1	32	0.0000074	x
		L_2	26	0.0000030	x
		63	1	0.0000089	x
	L_1	1	32	0.0042	x
		2	32	0.00011	x
		3	32	0.000016	0
		4	32	0.0000074	x
		L_1	1,024	0.00012	x
		L_2	832	0.000051	x
		63	32	0.00015	x
	L_2	1	26	0.00017	x
		2	26	0.000046	x
		3	26	0.0000064	0
		4	26	0.0000030	x
		L_1	832	0.000051	x
		L_2	676	0.000021	x
		63	26	0.000061	x
	63	1	1	0.00051	x
		2	1	0.00014	x
		3	1	0.000019	0
		4	1	0.000089	x
		L_1	32	0.00015	x
		L_2	26	0.000061	x
		63	1	0.00018	x

EXHIBIT 5 (Continued)

Notes: (1) Value Indication Key:

1	Full value (no degradation in command subsystem capability)
0	No value (no command subsystem capability)
x	Indeterminate (some (unpredictable) command-related degradation)
v	Indeterminate (some (unpredictable noncommand-related degradation)
g	Indeterminate (some probabilistic command-related degradation)
ℓ	Partial (some (predictable) command loss from one logic unit)
e	Partial (some (predictable) extraneous commands from one logic unit)
m	Partial (some (predictable) command loss from the matrix unit)
f	Partial (some (predictable) extraneous commands from the matrix unit

Indications written as products are self-explanatory.

(2) L_1 includes all logic unit states resulting in a partial loss of command capability from the indicated unit.

(3) L_2 includes all logic unit states resulting in extraneous commands from the indicated unit.

(4) M_1 includes all matrix unit states resulting in a partial loss of command capability.

(5) M_2 includes all matrix unit states resulting in extraneous commands.

A recombination is then effected in Exhibit 6, which relates groups of subsystem states, their total probabilities, and their possibilities for improved reliability through command assignment. This exhibit indicates that, 50 percent of the time, assignment will have no effect whatever, since the command subsystem will be either fully operable or completely failed. In addition, 35 percent of the time, the subsystem state will be such that assignment would have no effect unless performed under more complete information (second-order effects, marginal effects, etc.). Thus, in only 15 percent of the possible outcomes can assignment have any effect on reliability as measured by the figure-of-merit (FOM) model.[1]

These results indicate that for GEOS A, at least, command assignment can have, at most, minimal effect on reliability as measured by the familiar FOM. However, since the FOM of a subsystem is not the only criterion to be considered in command assignment, the command function will be analyzed as well.

b. The Command Function

From the preceding section, it may be readily appreciated that a large number of different failure effects are possible. The two most obvious classes of failure effects are those that cause certain commands to be lost and those that cause the execution of unwanted commands (extra or wrong command execution). Within each group are other groups of failure effects that might be called similar: these are such effects as loss of one row of commands or loss of one command tone. However, in order to improve operational reliability through command assignment, one must look more closely at the actual command functions being performed and their relative value to the overall mission.

The mission value lost for a given failure effect depends on whether the failure results in an inability to execute a command or in a particular command being executed extraneously. Value lost also varies with mission time and with the precise function of the command. Finally, certain

[1] See subsection 2. c. (1) for a definition of the FOM model.

EXHIBIT 6 - COMBINED SUBSYSTEM STATE PROBABILITIES

Value Indication	Probability	Value Indication	Probability
l	0.4453	m	0.0260
0	0.0588	gm	0.00056
g	0.0084	lm	0.0017
x	0.3046	em	0.00072
v	0.0458	g^2m	0.0000033
g^2	0.000057	glm	0.000056
l	0.0298	egm	0.000023
e	0.0122	l^2m	0.00095
l^2	0.0163	elm	0.00078
el	0.0134	e^2m	0.00016
gl	0.0019	f	0.0162
eg	0.00078	fg	0.00030
e^2	0.0027	fg^2	0.0000021
gv	0.00090	fgl	0.000070
lv	0.0030	efg	0.000028
ev	0.0013	fl	0.0011
g^2v	0.0000058	fl^2	0.00060
glv	0.00020	efl	0.00048
egv	0.000080	ef	0.00044
l^2v	0.0017	e^2f	0.00010
elv	0.0014		
e^2v	0.00028		

groups of commands may be such that multiple losses within the group would be more severe than a simple addition of losses, determined independently, would indicate. One possible grouping of commands--by gross function, frequency of execution, and time of execution--is shown in Exhibit 7.

The SECOR, R/RR, telemetry, and Doppler would present a particularly severe power problem if the associated power-on commands were to be lost or executed extraneously. The attitude control (boom manipulation) could present a problem after successful acquisition, primarily as a result of extraneous commands. The commands associated with the power-dump circuits, if lost or extraneously executed, could render power-supply control exceedingly difficult.

If half of a command "ON-OFF" pair is lost, that command designation may be executed only once. Therefore, in ranking the relative values of individual commands, when considering each to be either operable or lost, the "a" and "b" portions are considered together. The 32 command pairs are listed below in order of decreasing value to the mission. For example, the value of command 29 is ≥ the value of command 27, etc. This ranking is based on Exhibit 1, the preceding group discussion, and general familiarity with the GEOS satellite and is, in spite of all precautions, highly subjective. The order, however, is not critically important for the development of this TAM and is presented primarily as an example.

Rank	Command	Rank	Command	Rank	Command	Rank	Command
1	29	9	9	17	7	25	19
2	27	10	14	18	8	26	20
3	28	11	15	19	4	27	24
4	13	12	16	20	5	28	26
5	30	13	17	21	6	29	31
6	3	14	18	22	10	30	11
7	1	15	23	23	21	31	12
8	2	16	25	24	22	32	32

EXHIBIT 7 - POSSIBLE GROUPING OF COMMANDS

Group 1: Boom manipulation--low-frequency execution--primarily early time period

14a	Boom squib enable OFF	EDD
14b	ON	EOB
15a	Boom squib fire and 3.9V Zener In	BDE
15b	Safe and 4.7	BDC
16a	Boom bypass ON	DBE
16b	OFF	DBC
17a	Boom Out	ECD
17b	In	ECB
18a	Boom motor ON	ECF
18b	OFF	ECC
9a	Vector magnetometer ON	DEP
9b	OFF	DEB

Group 2: Redundancy capability--low-frequency execution--random time period

1a	Osc 1 select	DDP
1b	2	DDB
2a	Oven 1	DDE
2b	2	DDC
3a	Main conv 1 select	EED
3b	2	EEB
13a	Memory 1 select	DBD
13b	2	DBB
30a	Memory conv 1 select	DDP
30b	2	BDB

Group 3: Experiment commands--moderate frequency--throughout the mission

A. Doppler

4a	162-mc XMIT	ON	EEE
4b		OFF	EEC
5a	324	ON	CCD
5b		OFF	CCB
6a	972	ON	CCE
6b		OFF	CCC
19a	162 Phase mod	ON	EBD
19b		OFF	EBB
20a	324	ON	CDD
20b		OFF	CDB

EXHIBIT 7 (Continued)

B. Optical Beacon

			Frequency	Time
27a	AOL 1 start flash	BEE	High	Random
27b	flash OFF	BEC	High	Random
28a	2 start flash	BCE	High	Random
28b	flash OFF	BCC	High	Random
29a	Memory load start	EBE	High	Throughout the mission
29b	Memory load reset	EBC	High	Throughout the mission

C. SECOR--moderate frequency--throughout the mission

23a	ON and voltage sensing switch reset	CBE
23b	OFF	CBC
24a	Manual	CEE
24b	Normal	CEC

D. R and RR--moderate frequency--throughout the mission

25a	ON and voltage sensing reset	EDE
25b	OFF	EDC
26a	Manual	CBD
26b	Normal	CBB

Group 4: Power supply--low-frequency--random

10a	Solar only ON	DEE
10b	OFF	DEC
21a	Power optical dump	CDE
21b		CDC
22a	Transponder	CED
22b	Power dump	CEB
31a	Voltage sensing cutoff override ON	BED
31b	OFF	BEB

Group 5: Telemetry

			Frequency	Time
7a	ON	BBD	Low	Early and random
7b	OFF	BBB	Low	Random
8a	FM/PM ON	BDE	High	Throughout the mission
8b	OFF	DBC	High	Throughout the mission
11a	Comm 1 Hold ON	DCD	Medium	Random
11b	OFF	DCB	Medium	Random

EXHIBIT 7 (Continued)

Group 5: (Continued)

				Frequency	Time
12a	2	ON	DCE	Medium	Random
12b		OFF	DCC	Medium	Random
32a	Time marker	ON	BCD	Low	Early and random
32b		OFF	BCB	Low	Random

In general, the values of a command seem to be quite independent of the operability of other commands. Three exceptions might be

- o Commands 27 and 28
- o Commands 23 and 25
- o Commands 4, 5, 6, 7, and 8.

That is, loss of both commands 27 and 28 would be more than twice as severe as the loss of either considered singly, and loss of commands 4 and 5 would be more than twice as severe as the loss of either considered singly, etc. As regards extra commands, those which it is least desirable to execute falsely are 29a, 21b, 22b, 10a, 27a, 28a, and 18a, in that order. The remaining commands, in general, cause no particularly severe effects, and all rank essentially equally. As for groups, the execution of 17b and 18a would be particularly severe. Other criteria to be used in optimizing include the following:

- o It is more desirable to lose both halves of a particular command function than half of two command functions. This is because in the latter case twice as many commands are ultimately lost.
- o Extraneous commands would be the least deleterious if they occurred at intersections whose corresponding relays were already in the state represented by the command.
- o Extra commands would be, in general, most deleterious if they occurred in the other half of the desired command, since it is assumed that no change could occur under this condition.

c. Command Assignment Criteria

In the previous two sections many criteria were mentioned that might be used in evaluating a given command assignment. The purpose of this section is to examine these criteria and others in a more systematic manner.

The first point that probably should be made is that any assignment that exists could be proclaimed the best assignment simply by arguing that any alteration would confuse the associated paper work too much to be worth the effort. This might be true. If, however, improvement in operational reliability can be assumed to outweigh paper shuffling, or if no assignment at all has been made, then assignment in a systematic fashion according to preselected criteria would seem to be desirable.

A second preliminary point should be raised regarding GEOS A. The present assignment of command functions to matrix intersections as reflected in Exhibit 4 and Reference 2 seems rather clearly to have been made using some set of criteria. For example, all the "b" portions of the 32 command designations occur in the left half of the matrix, and the "a" and "b" portions of each command designation occur in the same row separated by three generally unrelated command functions. The fact that PRC is unaware of the precise criteria used in this assignment neither invalidates the effort reported nor means that these criteria, as far as they are not included, are unimportant. In fact, the introduction of some new, unrelated criterion always carries with it the possibility that a given assignment would have to be completely rejected. These two points should be kept in mind in the following examination of the possible assignment criteria.

Three generalized criteria are assumed to be sufficient for assigning the GEOS command functions to the relay matrix. These may be rather simply enumerated as

- o Minimum expected loss for each subsystem failure state
- o Equal expected loss for similar failure effects
- o Minimum loss of group commands.

Each of these criteria will be discussed in the following subsections.

(1) <u>Maximum Expected Value for the Command Subsystem</u>

This criterion is directly associated with the PRC measure of system reliability which is defined in more detail in Reference 1, but for the purpose of this section may be stated simply as

$$FOM = \sum_{\text{all } i} P(S_i)\, V(S_i)$$

where S_i = ith subsystem state

$P(S_i)$ = probability of the ith subystem state

$V(S_i)$ = relative value of the ith subsystem state

Now, under the assumption of unequal valued commands, the relative value of a particular failure state will, in general, vary with the particular command assignment used, whereas the probabilities will remain constant. Thus, that assignment will be best, from the point of view of this criterion, which results in the maximum $V(S_i)$ to occur with the maximum $P(S_i)$. A simple example will serve to illustrate assignment according to this criteria. Assume a two-by-two matrix to which four command functions are to be assigned. This can be done in 4! ways. Assume further that there are exactly six failure states defined as follows with the given probabilities:

States S_i	Failure Effect	State Probability $P(S_i)$
S_1	No loss	0.50
S_2	Lose row 1	0.20
S_3	Lose row 2	0.10
S_4	Lose column 1	0.10
S_5	Lose column 2	0.05
S_6	Lose everything	0.05

The relative values of the four command functions will be assumed to be 0.1, 0.2, 0.3, and 0.4. Exhibit 8 shows all possible assignments, where the individual command values are used to indicate the permutations and each permutation is labeled with its figure of merit. From the exhibit it can be seen that the FOM ranges from 0.70 to 0.75, depending on the assignment used. The assignment of the upper left matrix of Exhibit 8 is the best assignment using this criteria. Note that the actual values assigned to each command would not change the result as long as their relative order were not changed thereby. The application of this criterion will be considered in more detail in Section 3.

EXHIBIT 8 - FOM DERIVATION FOR SAMPLE TWO-BY-TWO MATRIX

0.750		0.745		0.735		0.720	
0.1	0.2	0.2	0.1	0.3	0.1	0.4	0.1
0.3	0.4	0.3	0.4	0.2	0.4	0.2	0.3
0.745		0.740		0.725		0.715	
0.1	0.2	0.2	0.1	0.3	0.1	0.4	0.1
0.4	0.3	0.4	0.3	0.4	0.2	0.3	0.2
0.745		0.735		0.730		0.715	
0.1	0.3	0.2	0.3	0.3	0.2	0.4	0.2
0.2	0.4	0.1	0.4	0.1	0.4	0.1	0.3
0.735		0.720		0.715		0.705	
0.1	0.3	0.2	0.3	0.3	0.2	0.4	0.2
0.4	0.2	0.4	0.1	0.4	0.1	0.3	0.1
0.735		0.725		0.730		0.705	
0.1	0.4	0.2	0.4	0.3	0.4	0.4	0.3
0.2	0.3	0.1	0.3	0.1	0.2	0.1	0.2
0.730		0.715		0.705		0.700	
0.1	0.4	0.2	0.4	0.3	0.4	0.4	0.3
0.3	0.2	0.3	0.1	0.2	0.1	0.2	0.1

(2) Equal Expected Loss for Similar Failure Effects

This criterion is mathematically unrelated to the FOM defined above. As such, it is somewhat more difficult to measure improvement. The intuitive idea is this: a single failure effect of a given kind should be no more detrimental to proper operation of the spacecraft than any other failure of the same kind. In terms of the previous two-by-two matrix example, all partial failure effects are similar; i.e., each causes the loss of two commands in either a row or a column. This criterion would be completely satisfied if the sums of the row and column losses were identical. Due to the integral nature of assigned values in this case (and in general), exact equality is not possible. The criterion could also be satisfied, however, by minimizing the sum of squared deviations from the theoretical mean loss of similar failure effects. In the simple example the theoretical mean loss per failure is 0.5, since half the matrix is lost in any event. The sum of squared deviations of the upper left matrix assignment of Exhibit 8, for example, is : $(0.1 + 0.2 - 0.5)^2 + (0.3 + 0.4 - 0.5)^2 + (0.1 + 0.3 - 0.5)^2 + (0.2 + 0.4 - 0.5)^2 = 0.10$. The assignment represented by the matrix in the last row and first column of Exhibit 8 has a similar sum of only 0.02, which can be shown to be a minimum for this example. A general assignment method to satisfy this criterion under the assumption of row or column losses only has been developed in Reference 3 for $m \times n$ matrices. Where other failure effects are prevalent, as in the GEOS A "tone loss" failure effect, the criterion is the same; i.e., that assignment which most nearly equalizes the losses due to similar failure effects is best. Section 3 will consider the problems unique to the GEOS A regarding the application of this criterion.

(3) Minimum Loss of Group Commands

This last of the three general criteria is probably the most difficult to implement or even to define adequately. It arises from the following considerations. Some command functions are related in such a way that the failure to execute one of the commands significantly changes the relative values of other commands. The case in which two command functions provide redundancy is an obvious example. The five groups of subsection 2.b provide another possible example, although the grouping in this section was not done for this purpose. The best assignment under this criterion would have essentially two characteristics. First, if a critical satellite function could be initiated by either of two commands, loss of both commands would be much more severe than the loss of either individually. Hence, that assignment is best which separates such command functions with respect to failure effect. Second, a command that would be of sharply reduced utility upon the loss of a related command (the on/off pairs provide an immediate example) should be combined with respect to failure effects. This minimizes the number of command functions that will be degraded, given a particular loss.

To revert to the simple example above, assume first that the commands valued 0.1 and 0.3 are such that loss of both would be catastrophic to the mission, whereas the other two commands are independent of each other and of this pair. Then this criterion would necessitate that the related command be assigned on a diagonal of the matrix so that both command functions would not be lost upon the occurrence of a single failure. Next, assume that the commands valued 0.2 and 0.4 are such that, if one is lost, the value of the other is essentially zero. Then the criteria would require that, wherever command 0.2 is located, command 0.4 should be in the same row or column. Again, the application of this criterion to GEOS A will be discussed in Section 3.

(4) Combination of Criteria

It should be quite evident at this point that individual application of the three criteria discussed above would not, in general, lead to the same resultant command assignment. This brings up the necessity of some priority scheme for the assignment criteria. Again, this would appear to be more a matter for sound engineering judgment than for theoretical analysis. In order to clarify the problem, however, consider once more the example above. Designate the four commands and the associated values as a(0.1), b(0.2), c(0.3), and d(0.4), and let the example of subsections 2.c.(1) and 2.c.(2) describe the basic situation. In addition, assume that commands a and c should not be lost together, that commands b and c should be lost together, and that command d is entirely independent of the other three in a relative value sense. What is the best assignment? Exhibit 9 shows the assignments that would be made under the various criteria, considered singly. For the first criterion the results of subsection 2.c.(1) clearly hold. For the second criterion there are eight possibilities, all yielding the minimum squared deviation of 0.02. There are also eight ways of satisfying the third criterion, in which commands a and c never occur in the same row or column. The added stipulation above is, in this case, redundant. No 2 of these 17 possible assignments are the same. Therefore, some additional method must be used to arrive at a single best assignment.

This can be done most easily by ranking the weighting criteria in the order judged most important. Assume, for the moment, that this judgment indicates that the third criterion is most important and that the first is least important. Then, one would reevaluate the problem, using, instead of Exhibit 8, Exhibit 9, and finding that assignment of the eight possible assignments which has the least summation of squared deviations. If there are more than one with the same minimum, the one with the highest FOM is selected. It turns out that, for the situations under consideration, all eight assignments of Exhibit 9 have the same sum of squared deviations--0.08--and of these eight, the two at the top of the left column have the same FOM. Thus, the choice has been narrowed from 24 assignments to 2, and the choice between these 2, according to the framework of the problem, is arbitrary. The general methods are similar for any priority of criteria, although the results, of course, might well be different and, for many situations, a tradeoff might be required regarding two or more criteria. Reference 3 contains a unified treatment of the second and third criteria for command subsystems, in which only rows or columns are assumed to be lost and such losses occur with equal probabilities. Since, however, the GEOS situation is considerably more complex, the development of an appropriate methodology suitable to this case will be undertaken independently in Section 3.

EXHIBIT 9 - POSSIBLE COMMAND ASSIGNMENTS SATISFYING THE THREE CRITERIA

a	b
c	d

a	c
d	b

a	d
c	b

a	b
d	c

a	d
b	c

b	c
d	a

b	d
c	a

b	a
c	d

d	a
c	b

c	a
b	d

c	b
a	d

c	b
d	a

c	d
b	a

d	a
b	c

d	b
a	c

b	c
a	d

d	c
a	b

a. Criterion 1 (maximum FOM)

b. Criterion 2 (minimum deviations)

c. Criterion 3 (minimum group loss)

3. GEOS A Assignment Methodology

The preceding sections have delineated the failure states on effects of the command subsystem hardware; have delineated the functions to be performed by the hardware, and the relative value and relationships of these functions; and have suggested possible criteria by which a rational and, it is hoped, near-optimal assignment of the command functions to the command-relay matrix of GEOS A might be made. The purpose of this section is to combine these three analyses into a methodology.

There are, in theory, 64! (1.3×10^{89}) ways to assign the 64 command functions to the command matrix intersection of the GEOS A command subsystem. Thus, it is manifest that a simple tabulation and comparison, as done in the previous example, cannot be applied as a workable methodology. For this reason, great care must be taken in selecting and ordering the criteria to be used in the assignment task.

The three criteria discussed previously are assumed to be adequate for making an optimal command assignment where the overall goal is to increase operational reliability. After prolonged consideration of the GEOS mission, the inherent reliability and function of the GEOS command subsystem, and the possible failure consequences, the order of importance of these criteria is judged to be in the inverse order in which they were presented in the previous section. That is, that minimum loss result from group failure is considered most important, that the subsystem FOM be improved is considered least important. Providing for most nearly equivalent losses is, therefore, ranked as second in importance.

a. Minimum Group Loss

In GEOS A there are, in essence, two types of groups. First, there are those groups formed by the on/off or a/b nature of the command functions. Each such pair of functions forms one group, since the value of the group (or pair) is greater than the sum of the individual command functions. This is because, in general, the ability to issue an "off" command is of low utility unless the ability to issue the "on" command is also present, and vice versa. The other class of groups includes those command functions such as 27 and 28 (AOL Nos. 1 and 2 flash commands, since the value of this group is less valuable than the sum of the values of the individual commands. This is because commands of this type perform essentially redundant functions.

The first class of groups includes all command functions in the matrix whereas the second class is assumed to consist of only four groups: (1) 27, 28; (2) 23, 25; (3) 4, 5, 6, 7, 8; and (4) 17b, 18a, as specified in subsection 2.b. The first group appears because it flashes alternative lamps in the optical beacon, if required. The second and third groups arise from power considerations, and the final group is associated with unwanted gravity-gradient boom manipulation. Another evaluation might have derived an entirely different set of groups, but these will, at least, serve as an example.

Let us denote the first class of groups as the class of command pairs. The loss due to these command pairs will be at a minimum when their assignment is such that loss of both halves of the pair is more likely than the loss of half of two different pairs, and if extraneous commands are most likely to occur in that half of the command which is normally on. The requirement that both halves be in the same failure effect ensures that the fewest total commands will be degraded. In other words, it is better to lose both halves of one command than one half of two commands. The requirement that extraneous commands occur at the normal half of the command position tends to ensure that there will be no change in the spacecraft condition and, hence, no degradation.

The question now is: how is the assignment to be made to fulfill these requirements? This will require further consideration of the command subsystem failure effects. Examination of Exhibits 2 through 6 indicates that the most probable partial command loss type of failure results in losing complete rows or columns from the command matrix and, because of the matrix failure effects, loss of rows is slightly more probable than loss of columns. Therefore, command pairs should be located in the same rows of the matrix. In addition to strict row/column losses in the matrix, there are those losses resulting from tone loss, loss of a single command, and multiple failures among the three primary command subsystem units. Since many of the latter are row/column losses and the remainder are of very low probability, these will be considered no further. Single command losses offer no basis for pair assignment, since each is equally likely. Finally, the tone-loss effect would require that the halves of each command pair differ by, at most, one tone. This requirement can also be readily satisfied by assigning pairs to the same row in a rather large number of ways. Exhibit 4 shows one way they can be assigned.

From a consideration of Exhibits 2 and 3, it can be seen that extraneous commands are more likely to occur in the left half of the matrix than in the right half. Therefore, the optimal assignment not only would assign command pairs to the same row and to tone sequences differing by only one tone, but also would assign them such that the normally "on" portion of the command would be assigned to the left half of the matrix. If the "b" portion of the commands was the normally "on" portion of the commands, the present assignment (shown in Exhibit 4) is admirably suited to assigning commands under the minimum-loss criteria of command-pair groups. Otherwise, the assignment should be altered so that the command half in which the dot appears in Exhibit 4 also occurs in the left half of the matrix.

The second class of grouped commands will now be discussed. The criterion here requires an assignment such that the command functions 27 and 28 or 23 and 25 should not both be lost due to a single failure. A single failure should cause the fewest command functions from the 4, 5, 6, 7, and 8 groups to be lost. Finally, a single failure effect should not extraneously execute both commands 17b and 18a. Consider first those groups of commands whose simultaneous loss is to be avoided. Because of the previous requirement that both halves of a command pair appear in the same row, there are effectively four columns and eight rows to which a given complete command function may be assigned. Reference to Exhibits 2 through 6 indicates that appearance of the grouped command functions in the same rows or columns should be avoided, since a single matrix loss, for example, could cause both (all) such functions to be lost.

Command losses other than individual row/column losses with reasonable probabilities of occurrence are essentially those shown in Exhibit 2. States 5 through 8 of this exhibit put the further constraint on the assignment that pairs of command functions should be assigned to the first and last rows of the matrix to avoid simultaneous loss of two command functions. States 25 through 28 place the added requirement of putting the command pairs in columns 1 and 4. Finally, states 33 through 36 imply use of different tones. By placing commands 27 and 28 in matrix positions C1, F1 and C4, F8, respectively, and commands 23 and 25 in positions C1, F8 and C4, F1, respectively, this criterion has been met for these command groups. The 4, 5, 6, 7, and 8 groups present a slightly more difficult problem. First, it is manifest that two of the command functions must fall in the same column. States 5 through 8 suggest one command function in the first row, F1, and one in F8. States 25 through 28 suggest use of rows 1, 2, 4, and 8 and columns 1, 2, and 4. States 29 through 32 imply a maximum division between the first four and last four rows. Finally, states 29 through 32 imply maximum separation of command tones. Positions C1, F2; C2, F1; C3, F8; C4, F7; and C1, F6 are one possible assignment.

A perusal of note 2, Exhibit 2, indicates that, to prevent the simultaneous execution of commands 17 and 18 from one failure effect, the commands should not be placed in the same row. Placing these commands in C2, F4 and C2, F8 as shown in Exhibit 4 is satisfactory from the point of view of this criterion.

b. Equal Expected Loss

Assignment under this criterion can be reduced to a typical "magic-squares" problem. That is, the problem is essentially one of assigning the consecutive integers (1 to mn) to an m x n matrix such that the column sums are identical and the row sums are identical. If there are no other constraints on the problem, this can be done in a very large number of ways for a matrix of the size considered here.[1]

[1] See, for example, the chapter on magic squares in W. W. Rouse Ball, Mathematical Recreations and Essays, New York: MacMillan, 1962.

If the command pairs are treated as shown in Exhibit 4; i.e., if both halves of each command appear in the same row separated by three other command functions, the problem is to assign the first 32 integers to an 8 x 4 matrix such that the row sums are equal and the column sums are equal.[1] This solution will hold for all failure effects that are reflected in the loss of rows or columns. Row/column failure effects include all single failures except loss of a tone and extraneous commands. The treatment of command halves (or pairs) very nearly optimizes the assignment with respect to extraneous commands so they will not be considered further. The expected loss could be equalized in the four tone losses, but since the procedure is rather tedious and the event of relatively low probability, this will not be attempted herein.

Exhibit 10a shows one possible assignment that gives equal loss under row/column failure effects. Exhibit 10b is an evaluation of the present assignment under this criterion. Exhibit 11 shows a near optimal assignment considering both classes of groups from the previous subsection. Exhibit 11 was derived by fixing the assignment of the group commands as discussed in the previous section and then juggling the assignment of Exhibit 10 until a near-optimal solution was obtained. A more systematic manner of obtaining a near-optimal assignment is given in the appendix. While this method will not, in general, yield results as good as shown here, it has the advantage of simplicity and routine application. The method of the appendix is only applicable to single row or column failures and, hence, does not treat such failure effects as loss of multirows when considering groups. As suggested in the appendix, however, small post mortem adjustments in the assignment should minimize this undesirable aspect of the solution. This appendix is abstracted from Reference 3, which may be consulted for further details.

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[1] Ignore for the moment the second class of groups discussed in the preceding subsection.

EXHIBIT 10 - COMMAND ASSIGNMENTS AND EXPECTED ROW/ COLUMN LOSSES(1)

a. Equal Loss Assignment

					Row Sums
	17 (7)	25 (19)	8 (2)	16 (25)	66
	31 (12)	18 (8)	7 (1)	10 (14)	66
	30 (11)	27 (24)	6 (3)	3 (28)	66
	20 (5)	28 (26)	13 (17)	5 (30)	66
	1 (29)	9 (9)	24 (22)	32 (32)	66
	15 (23)	2 (27)	23 (21)	26 (20)	66
	14 (18)	11 (15)	22 (10)	19 (4)	66
	4 (13)	12 (16)	29 (31)	21 (6)	66
Column Sums	132	132	132	132	

b. Present Assignment

					Row Sums
	17 (7)	4 (13)	5 (30)	7 (1)	33
	28 (26)	25 (19)	26 (20)	10 (14)	89
	32 (32)	30 (11)	29 (31)	9 (9)	100
	20 (5)	13 (17)	24 (22)	6 (3)	63
	18 (8)	12 (16)	11 (15)	8 (2)	49
	15 (23)	1 (29)	23 (21)	16 (25)	55
	3 (28)	31 (12)	2 (27)	22 (10)	58
	21 (6)	14 (18)	27 (24)	19 (4)	81
Column Sums	154	130	147	97	

Note: (1) Bottom entry is command designation; upper entry is command rank.

EXHIBIT 11 - NEAR-OPTIMAL ASSIGNMENT UNDER CRITERIA 1 AND 2

					Row Sums
	2 (27)	20 (5)	28 (26)	16 (25)	66
	19 (4)	7 (1)	10 (14)	30 (11)	66
	13 (17)	1 (29)	22 (10)	29 (31)	65
	26 (20)	23 (21)	12 (16)	6 (3)	67
	8 (2)	9 (9)	24 (22)	25 (19)	66
	18 (8)	32 (32)	11 (15)	5 (30)	66
	31 (12)	14 (18)	4 (13)	17 (7)	66
	15 (23)	27 (24)	21 (6)	3 (28)	66
Column Sums	132	133	132	131	

c. <u>Maximum Figure of Merit</u>

The objective of this portion of the assignment methodology is to maximize the expression

$$\text{FOM} = \sum_{i} P(S_i)\ V(S_i)$$

The states (S_i) and the state probabilities $P(S_i)$ are fixed entities. Therefore, the FOM can be altered only by changing the $V(S_i)$ terms. Since the $V(S_i)$ are directly related to the command values lost in the particular state, they are a direct function of the assignment used. It should be noted, however, that the FOM varies only if the $P(S_i)$ are not all identical. In other words, matching the maximum $V(S_i)$ with the maximum $P(S_i)$ yields the maximum FOM, and the $V(S_i)$ associated with large $P(S_i)$ can be increased by appropriate command assignment.

The reason that this assignment criterion has been relegated to the position of least importance herein can be seen by considering Exhibits 5 and 6. Those states which are grouped under value indicators of 1, 0, and v offer no opportunity for changing the $V(S_i)$ because these failure effects affect all commands. In addition, the x-valued commands cannot be optimally assigned without a number of further (perhaps unrealistic) assumptions. The probability associated with these states is approximately 0.85. Therefore, even if every partially degraded state had a value of unity (not true by definition) the FOM would be increased by only 15 percent.

In assigning command functions to matrix intersections according to the criterion, it will be assumed initially that all the commands are independent in the value sense and the investigation will be restricted to loss of commands only. Under these conditions, it can be shown that

$$\text{FOM} = \sum_{i=1}^{32} p_i\ v_i$$

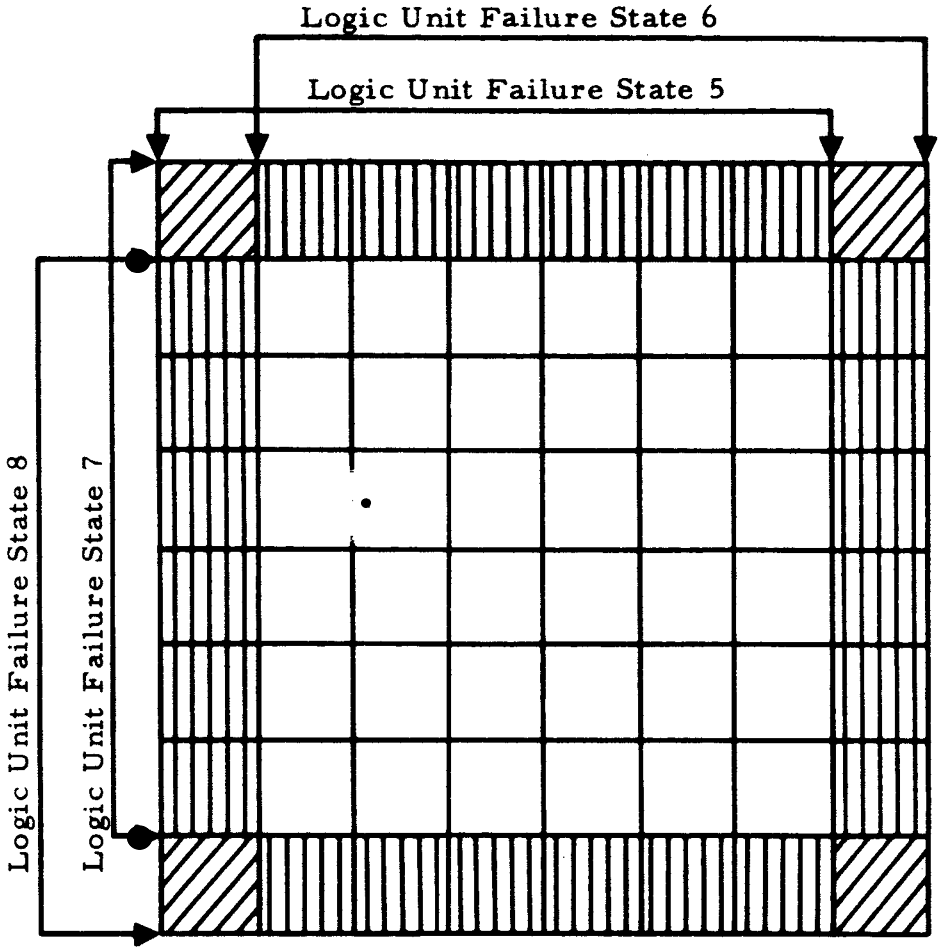
where p_i = the probability of not losing command function i

v_i = the value of command function i

and the summation extends over all command functions, taken to be 32 in this case. Because of the rather strange nature of the degraded failure states, the p_i are not equal, and it is clear from what has preceded that the v_i are not equal. Again, the problem is to match maximum p_i with maximum v_i. Consider first the disparity in the p_i.

From Exhibit 2 the logic unit states which cause partial loss of commands only are (a) 5-8, (b) 9-16, (c) 17-24, (d) 33-36, (e) 37-40, and (f) 43-46. Each of these groups represents a similar type of loss as indicated in Exhibit 2. From Exhibit 3, the matrix unit states leading to partial command losses are (g) 4-11, (h) 12-75, and (i) 140-147.

Examination of state groups (b), (c), (e), (g), (h), and (i) shows immediately that any given intersection of the matrix is as likely to fail as any other due to these failure state groups. This is not true, however, for groups (a), (d), and (f). This is indicated in Exhibits 12, 13, and 14, where, for each of these failure groups, a "propensity to fail" is indicated for each intersection. Referring to Exhibit 12 (and Exhibit 2), for example, we know that logic unit failure state 5 causes loss of the first seven columns of commands in the matrix and that state 6 causes loss of the last seven columns. Since these two effects overlap, the middle six columns of commands are twice as likely to fail, given logic unit failure states 5 or 6, as are the two end columns. Continuing this logic, it is readily apparent that, given a failure from group (a), each corner of the matrix may be lost in exactly two ways, the remaining marginal positions lost in exactly three ways, and the remaining positions in all four ways. The propensities to fail of the other two failure groups are derived in precisely the same fashion. The overall relative propensity to fail, considering one logic unit and the matrix, is as shown in Exhibit 15, obtained by summing the propensities of Exhibit 12, 13, and 14. The only utility of Exhibit 15 is in indicating relative propensities, since absolute propensities are a function of the different failure probabilities for each state group. Each entry implicitly includes a constant term for equally likely failure effects.



Failure Group a. (Lose 56 Commands)

Propensity to Fail Key:

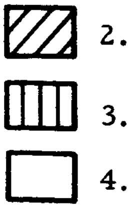
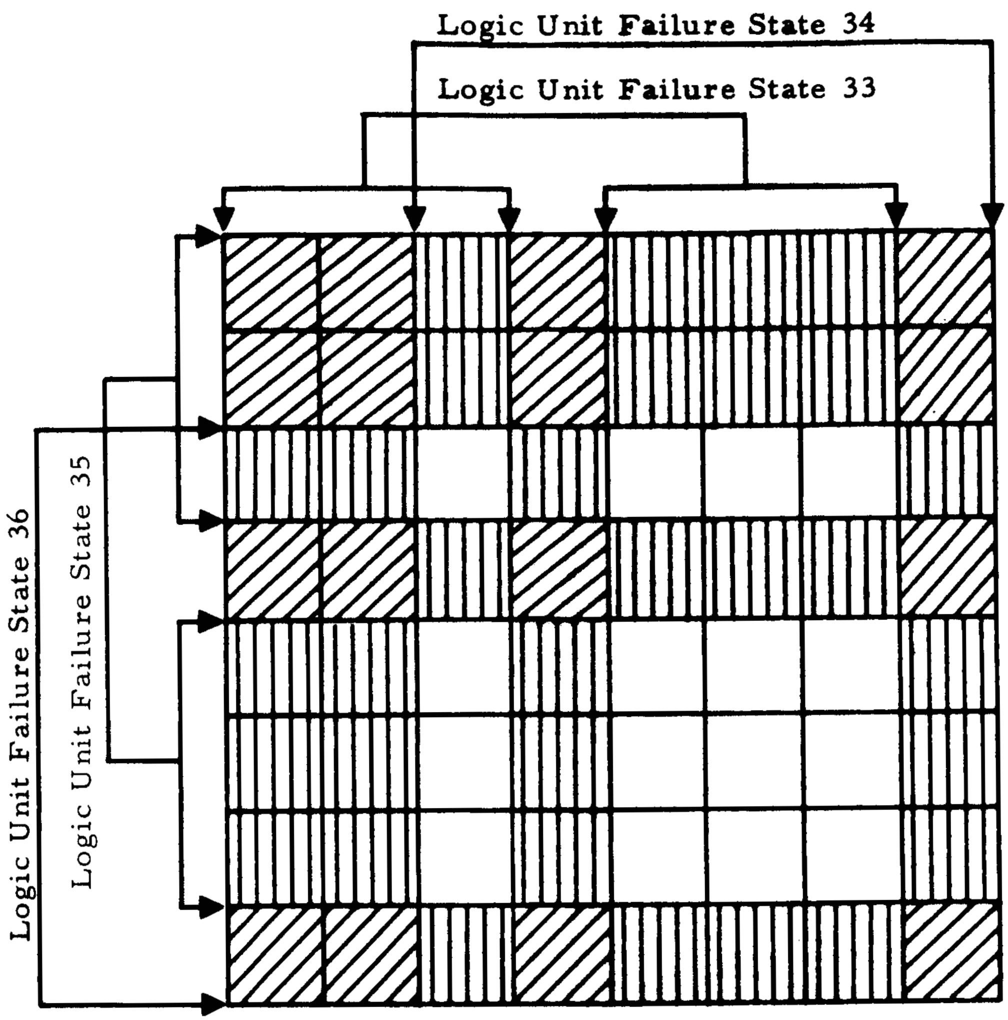


EXHIBIT 12 - FAILURE PROPENSITY--GROUP a



Failure Group d. (Lose 48 Commands)

Propensity to Fail Key:

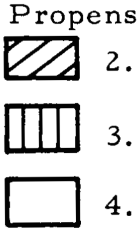
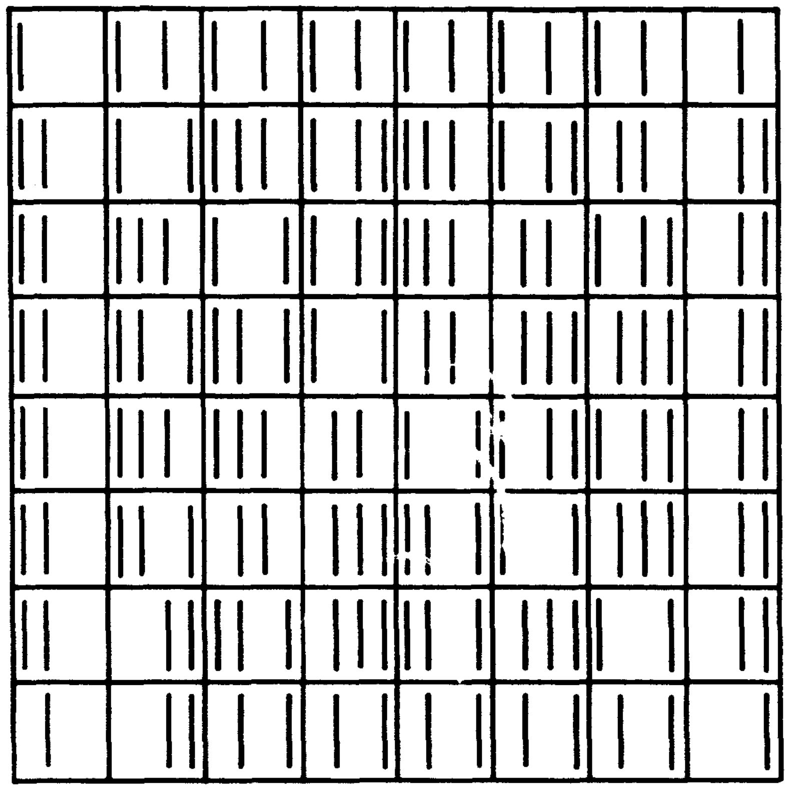


EXHIBIT 13 - FAILURE PROPENSITY - GROUP d



Failure Group f. ("Loss of Tone"; 37 Commands.)

Propensity to Fail

1 - |

2 - ||

3 - |||

EXHIBIT 14 - FAILURE PROPENSITY--GROUP f

EXHIBIT 15 - LOSS OF INTERSECTION FAILURE PROPENSITY

5	7	8	7	8	8	8	5
7	8	10	9	10	10	9	7
8	10	10	10	11	10	11	8
7	9	10	8	9	10	10	7
8	10	11	9	10	11	11	8
8	10	10	10	11	10	11	8
8	9	11	10	11	11	10	8
5	7	8	7	8	8	8	5

The relative propensities to fail for the various intersections are unchanged when partial losses of commands from both logic units are taken into account. For, consider the following: all states that cause equiprobable loss of an intersection merely add another constant term to each cell of Exhibit 15, considered together or in conjunction with a partial loss of unequal probability from one logic unit. Thus, only the three previously mentioned groups of logic unit failure states, from each logic unit, must be considered in more detail. If group (a) occurs in both logic units, the propensity of a cell to fail is simply the square of the propensity in a single logic unit. If a failure of group (a) occurs in logic unit 2, then the propensity for both logic units in the product of the propensities of each. Since this can also occur in the obverse, the total propensity from different group failures is twice the product of propensities. In more mathematical terms, the propensities of Exhibit 15 are of the form $x_1 + x_2 + x_3$, where x_1 represents the propensity to fail from failure group (a), x_2 the propensity to fail from failure group (d), and x_3 the propensity to fail from failure group (f). When both logic units are considered, the total relative propensity to fail for a given intersection is simply $(x_1 + x_2 + x_3)^2$. Since, if $a > b$ then $a^2 > b^2$, the squares are in the same relationship to each other on an ordering basis as the single logic unit propensities; hence, from the probability-of-loss view only, the most desirable command intersections are those represented in Exhibit 15 by the lowest number.

Recall that the 64 intersections represented in Exhibit 15 actually operate in pairs. Assume that the pairs are assigned as recommended in subsection 3.a. Then if Exhibit 15 were folded over from right to left and the overlapping propensities summed, the result would be more in accord with the actual situation. This has been done in Exhibit 16.

Now, to accomplish the assignment according to this criterion is simply a matter of placing the highest ranked commands (see subsection

EXHIBIT 16 - FAILURE PROPENSITY--COMMAND FUNCTION/ INTERSECTION

13	15	16	12
17	18	19	16
19	20	21	18
16	19	20	15
18	21	22	17
19	20	21	18
19	20	21	18
13	15	16	12

2.b) in those intersections with the least propensity to fail. The following tabulation indicates an assignment that satisfies this criterion.

Failure Propensity	Number of Cells	Command Function Assignment	
		By Rank	By Designation
12	2	1, 2	29, 27
13	2	3, 4	28, 13
15	3	5, 6, 7	30, 3, 1
16	4	8, 9, 10, 11	2, 9, 14, 15
17	2	12, 13	16, 17
18	5	14, 15, 16, 17, 18	18, 23, 25, 7, 8
19	5	19, 20, 21, 22, 23	4, 5, 6, 10, 21
20	4	24, 25, 26, 27	22, 19, 20, 24
21	4	28, 29, 20, 21	26, 31, 11, 12
22	1	32	32

Using the above tabulation still allows considerable freedom of assignment. For example, it is immaterial which of the two lowest failure propensity intersections the first- and second-ranked command functions are assigned to using this criterion only.

Extraneous commands will now be briefly considered. Reference to Exhibits 2 and 3 indicates that extraneous commands are a function of logic unit state groups (a) 25-32, (b) 41, (c) 42, (d) 47-54, and (e) 55-62 and matrix state groups (f) 76-139.

These six failure modes have three characteristics in common:

- o The "extra" command is a function of the desired command
- o An "extra" command sent to a position already "in effect" will cause no status change
- o A function simultaneously commanded on and off will cause no status change

Survey of the actual failure effects shows that propensities to execute extra commands are essentially equal for groups (a), (d), (e), and (f). The propensities of groups (b) and (c) are shown in Exhibits 17 and 18 for one logic unit and the matrix. These are summed in Exhibit 19 for a total relative propensity to fail for one logic unit and the matrix unit. The propensity for execution of extraneous commands is essentially

EXHIBIT 17 - FAILURE PROPENSITY (LOGIC UNIT STATE 41)

7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				

EXHIBIT 18 - FAILURE PROPENSITY (LOGIC UNIT STATE 42)

15	16						
16	16						

EXHIBIT 19 - EXTRANEOUS INTERSECTION FAILURE PROPENSITY

22	22	2	2				
23	22	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				
7	6	2	2				

unchanged from Exhibit 19 when considering the redundant set of logic units. One can (possibly) remove the extraneous commands from the "failed" logic unit and almost certainly from the redundant unit, unless, of course, it is too late. Thus, commands that it is highly desirable not to execute extraneously should be placed first in columns 5-8, then in columns 2 and 3, and never in C1, F1; C1, F2; C2, F1; or C2, F2. This criterion is essentially satisfied by the command-pair assignment of subsection 3. a.

Combining this criterion with the preceding two, while possible, would appear to be extremely tedious, particularly if, as assumed here, this criterion is of least importance. The difficulty lies in determining the number of assignments that do not violate the first and second criteria, and hence can be used in applying this criterion. The problem is not quite as difficult under reverse ordering of the criterion; but, in any event, the methodology can only be described as trial and error. Therefore, it is recommended that one (or at most two) criteria be selected for evaluating assignments and that these be adhered to even though a "better" assignment may be possible.

4. Summary and Conclusions

This TAM has investigated in some detail the command-assignment problem for the GEOS A spacecraft. It was initially expected that the final results would be somewhat more definitive than is actually the case. Be that as it may, there are some results that do appear to be reasonably sound. First, the present assignment of two command intersections per command function has been treated admirably and goes a long way toward an optimal assigment, particularly if the normally on commands are placed in the first four columns of the matrix. Second, additional consideration should be given by those responsible for command assignment to the existence of other groups of related commands and the resulting possibility of better assignment.

The failure mode and effects analysis given herein is considered to be quite reliable, as are the relative state probabilities. No effort has been made to assign values to commands in any other but a relative sense, and even this was done more for use as an example than as the result of a detailed study. Thus, if a different ordering is felt to be desirable, the methods presented can be used by changing only the order of command values.

The primary purpose of developing the methodology presented herein was to assist in the allocation of commands for the GEOS B spacecraft. The basic decision to be made is whether to use the same assignments in GEOS B as were used in GEOS A or to make certain modifications. To the best of PRC's knowledge, the design of the GEOS B command subsystem, as well as the entire spacecraft, is essentially the same as for GEOS A. Thus, the results of this TAM should be applicable to GEOS B.

The differences between the assignments of Exhibit 11 and those actually used on GEOS A (Exhibit 4) are sufficiently small to preclude a firm recommendation to modify the GEOS B assignments to those of Exhibit 11. Rather, PRC feels that the small improvements to be gained in operational reliability by making the modifications have to be weighed against the cost of making the modifications and associated schedule alterations.

APPENDIX

Consider an $n \times m$ matrix array to which nm command functions are to be assigned. Assume that the functions fall naturally into related groups. (If this is not the case, one may consider nm groups of one function each.) Also, suppose that values can be assigned to the functions and groups of functions. An allocation scheme with the following characteristics is desired:

1. "Separates" the functions in each group into different rows and columns to the extent possible
2. Makes the values of the rows as nearly the same as possible
3. Makes the values of the columns as nearly the same as possible

It should be recognized that goal (1) may sometimes conflict with goals (2) and (3). The proposed allocation scheme in a sense ignores this problem. A relatively easy systematic device has been used that inherently makes long strides toward the satisfaction of all three goals.

Once the symbolic approach is appreciated, the discussion may proceed. For ease of terminology, the conventional row-column matrix terms will be augmented by consideration of matrix <u>lines</u>. For our $n \times m$ matrix, the $n + m$ matrix lines correspond to the n rows and m columns in the following manner:

column 1 = line 1
column 2 = line 2

. . . .

column m = line m
row 1 = line m+1
row 2 = line m+2

. . . .

row n = line m+n

The following notation is adopted:

v_{ij} = value of function in ith row and jth column, where $i = 1, 2, \cdots, n$; $j = 1, 2, \cdots, m$; or, equivalently, at the intersection of lines j and $m + i$

V_k = value of kth matrix line, where $k = 1, 2, \cdots, m + n$

The following formulas are straightforward:

$$V = \sum_{i,j} v_{ij}$$

$$V_k = \begin{cases} \displaystyle\sum_{i=1}^{n} v_{ij}, & k = j = 1, 2, \cdots, m \\ \displaystyle\sum_{j=1}^{m} v_{ij}, & k = i + m = m + 1, \cdots, m + n \end{cases}$$

Average row value = V/n

Average column value = V/m

Goals (2) and (3) then become

$$(2') \quad V_k \cong V/n, \qquad k = m + 1, \cdots, m + n$$

$$(3') \quad V_k \cong V/m, \qquad k = 1, 2, \cdots, m$$

A. The Allocation Scheme

There are three basic steps to be performed in allocating a collection of functions to an $n \times m$ matrix array under the present conditions. These steps are

(1) Grouping of functions and assignment of group and function values

(2) Ordering the functions and/or groups

(3) Allocating the ordered collection of functions to the matrix array

Once an effective allocation scheme is developed, difficult but necessary decisions remain in step (1) each time the user applies the scheme. The choices between the various alternatives in steps (2) and (3) will be made in the development of an effective scheme, as will be seen in subsections D and E. The nature of these choices will be outlined, and a recommendation of the most desirable course of action at each point will be made. The various steps will be discussed in turn.

B. Grouping the Functions

There are many factors to consider when grouping the functions to be assigned. In some cases, it is extremely important that specific functions be in the same group. In other cases, the grouping may be of little importance, and the decision to group or not to group certain functions is immaterial to effective allocation. It should be noted first that all functions in a specified group must have the same value. The converse of this is not true! In other words, two functions do not have to be placed in the same group just because they seem to have the same value. However, there is one instance in which it is of great importance to place functions in the same group: if two or more functions are so related that the loss of all the functions is considerably more damaging than the loss of just one, they must be placed in the same group. The purpose of placing functions in the same group is to maximize the probability that they fall in distinct rows and columns. Such functions should be placed in the same group even if the user must "fudge" a little to proclaim that they have the same value. It would generally appear that functions that must be separated will, in fact, have the same value. Once the functions of the above type have been properly grouped, the remainder of the grouping task is relatively simple, primarily because the effectiveness of the allocation will not be noticeably affected by the nature of the grouping. Keeping firmly in mind that the functions in a group must have the same value, this latter portion of the grouping task should be done in such a way that the bookkeeping is as simple as possible. The remainder of the allocation scheme will be simplified somewhat if the number of groups is kept reasonably small. On the other hand, there is no real point in grouping a collection of functions if they have nothing in common except the same value.

C. Assignment of Group and Element Values

The problem of assigning values to the groups and elements is more complex. The valuation problem is in no way unique to this device for allocation, but is a question that would have to be resolved in order to evaluate the effectiveness of any proposed assignment of functions to the command matrix. In a larger sense, the valuation problem is encountered in many situations when one needs to assign a numeric value to the contribution of a given object (component, subsystem, etc.) to the total mission.

It would be desirable if an objective method to assign the group and element values could be described. Unfortunately, in nearly all interesting examples of valuation problems, no straightforward approach is feasible. The best that can be done is to permit a subjective assignment of values by a person who is intimately familiar with the system and its uses. It is sometimes useful to combine the <u>independently</u> assigned values of two or more knowledgeable individuals. Value assignment by committee is usually unsuccessful due to conflicts and parochial interests on the part of committee members.

With these ideas in mind, some practical approaches that a knowledgeable individual might take to a valuation problem will be discussed. It must be emphasized in the beginning that only <u>relative</u> values are important. For example, if object "A" is thought to be twice as valuable as object "B," "A" could be assigned a value of 2 and "B" a value of 1. On the other hand, assigning 10 to "A" and 5 to "B" would be equally good. This example concerns itself, of course, only with a comparison between "A" and "B." The proper valuation to compare "A" and "B" would ultimately depend on other comparisons as well.

One possible approach to the valuation problem is to assign a point value (e. g., 1,000) to the total mission. Then each object is inspected, and an estimate is made of the percentage contribution of the object to the total mission. The value of the object is then assigned accordingly. This method of value assignment is effective only when the number of objects to be evaluated is quite small. If the number of objects is large, it is not feasible to decide whether an object contributes 1, 2, or 3 percent to the total mission. Remember that the sum of these percentages must be 100 percent.

A second approach is to write the name of each object on a separate piece of paper. The papers are then placed in ascending (or descending) order of importance. Note that this is a considerably easier task than assignment of numeric values. If ascending order (the better approach) is selected, one may assign a value of 1 to the least important object. Proceeding through the stack of papers, values are assigned with subjective value increases as required. Of course, objects may be assigned the same value if desired. This method is most efficient when there are several objects (though not a great number) whose values have a wide variation.

Many assignment problems involve a large number of distinct objects with a somewhat limited range of values (e. g., 1-50). In this case, a third approach is frequently the most efficient. A complete list of the objects is made. Some attempt at priority ordering may be made, although this is not essential and is usually impractical for a large number of objects. The list is then considered line by line. The first item is assigned a value in an almost arbitrary fashion. If the item is thought to be of great importance, a relatively high value is assigned; if it is considered to be of little importance, it is given a relatively low value. One then continues through the list, attempting to assign to each object values that are consistent with those already assigned. As one proceeds through the list, the value assignment generally becomes easier, for there is a more complete distribution of assigned values available as a basis for comparison. This procedure will normally lead to a "reasonable" set of values.

The most that one can hope to obtain is such a reasonable set of values. There are far too many intangibles to talk in terms of a right or wrong set of values. Furthermore, one should not attempt excessive refinements of values. For example, if the total value of the objects is 1,000, it is foolish to quibble about whether a particular object should have a value of 18 or 20.

D. Ordering the Groups

The collection of elements is to be ordered in some fashion, three different approaches are possible:

- o Ignore the groupings, and order the elements as desired
- o Order the groups, and then order the elements within each group
- o Order the groups placing the elements within the groups in an arbitrary fashion

The first of these is of no value in this case. For allocation purposes the elements within a group do not have to be in any special order, so that the second alternative is discarded unless some internal ordering is desired for bookkeeping purposes.

After the decision has been made to order the groups only, proper criteria to obtain a useful order of elements must be specified. Again, three possible methods are encountered.

- o Order on decreasing (increasing) total group value
- o Order on decreasing (increasing) number of functions in the group
- o Order on decreasing (increasing) prorated value of the functions in the group

To achieve the goal of obtaining approximately equal row and column sums, the third of these orderings is the most efficient. Observe that, in any of the cases, either decreasing or increasing orderings might be chosen without affecting our allocation. The third scheme above, ordering on decreasing function value, is finally chosen.

E. Allocation of the Ordered Functions to the Matrix Array

When the tasks of grouping, valuing, and ordering the functions to be assigned, have been completed, the actual allocation is reasonably straightforward. However, the procedure is a little difficult to describe verbally. The nature of the scheme, as applied to a 16 x 16 array and a 16 x 8 array, is described in Exhibits 20 and 21. To describe the procedure verbally, note first that the matrix should be thought of as extending to the right; i. e., that a carbon copy of the matrix is written to the right of the given matrix. In the 16 x 16 case, this superficially creates a 16 x 32 matrix, with column 17 the same as column 1, column 18 like column 2, etc. (For these familiar with determinants, this device is analogous to recopying columns 1 and 2 to the right of a third-order determinant for evaluation purposes.) Now proceed down the list of ordered functions, allocating each function as it is encountered. Begin in the upper left-hand corner and proceed down the diagonal; i. e., the first function at the (1, 1) intersection, the second at the (2, 2) intersection, and so on, with the sixteenth at the (16, 16) intersection. (Note: In general, by the (i, j) intersection the intersection of the ith row and the jth column will be indicated.) The bottom of the matrix has now been reached, and the critical question is where to go from here. To this end, the following rule is adopted:

> When reaching the bottom or top of the matrix, move one column to the <u>right</u> and proceed along that diagonal.

At the present position this would mean that the next (seventeenth) function should be assigned at the intersection (16, 17). But column 17 is imaginary; it is really column 1 rewritten. Thus, intersection (16, 17) is <u>actually</u> intersection (16, 1), and the seventeenth function is so allocated. The next intersection <u>up</u> this diagonal is (15, 16), so that the eighteenth function is assigned to (15, 16). Proceeding up this diagonal, assign functions 16 through 32 with the thirty-second function allocated at intersection (1, 2). The top of our matrix has now been reached. Applying the rule above, move one column to the right, assigning function 33 to intersection (1, 3), and proceed down this diagonal.

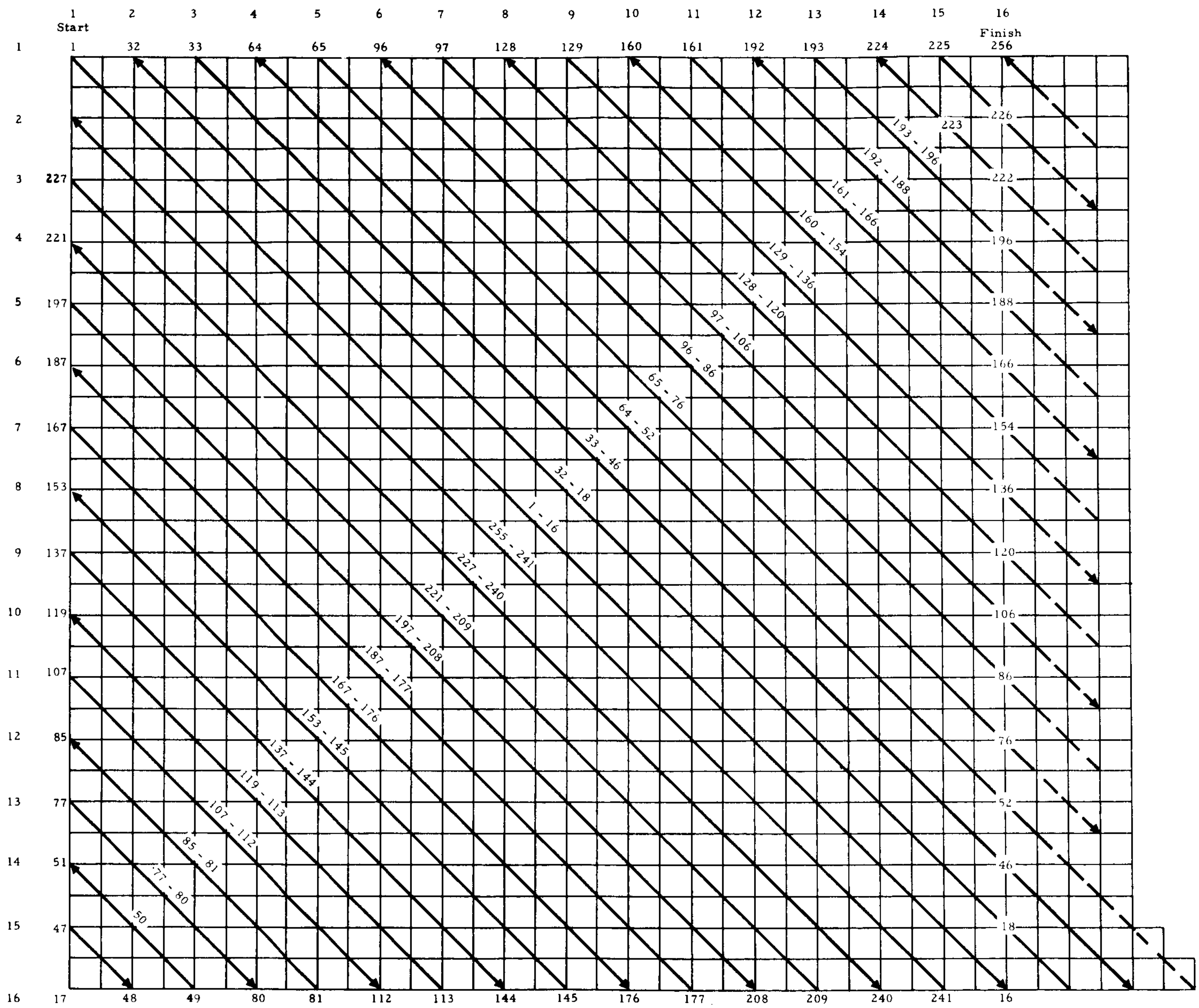


EXHIBIT 20 - ALLOCATION SCHEME (16 x 16 ARRAY)

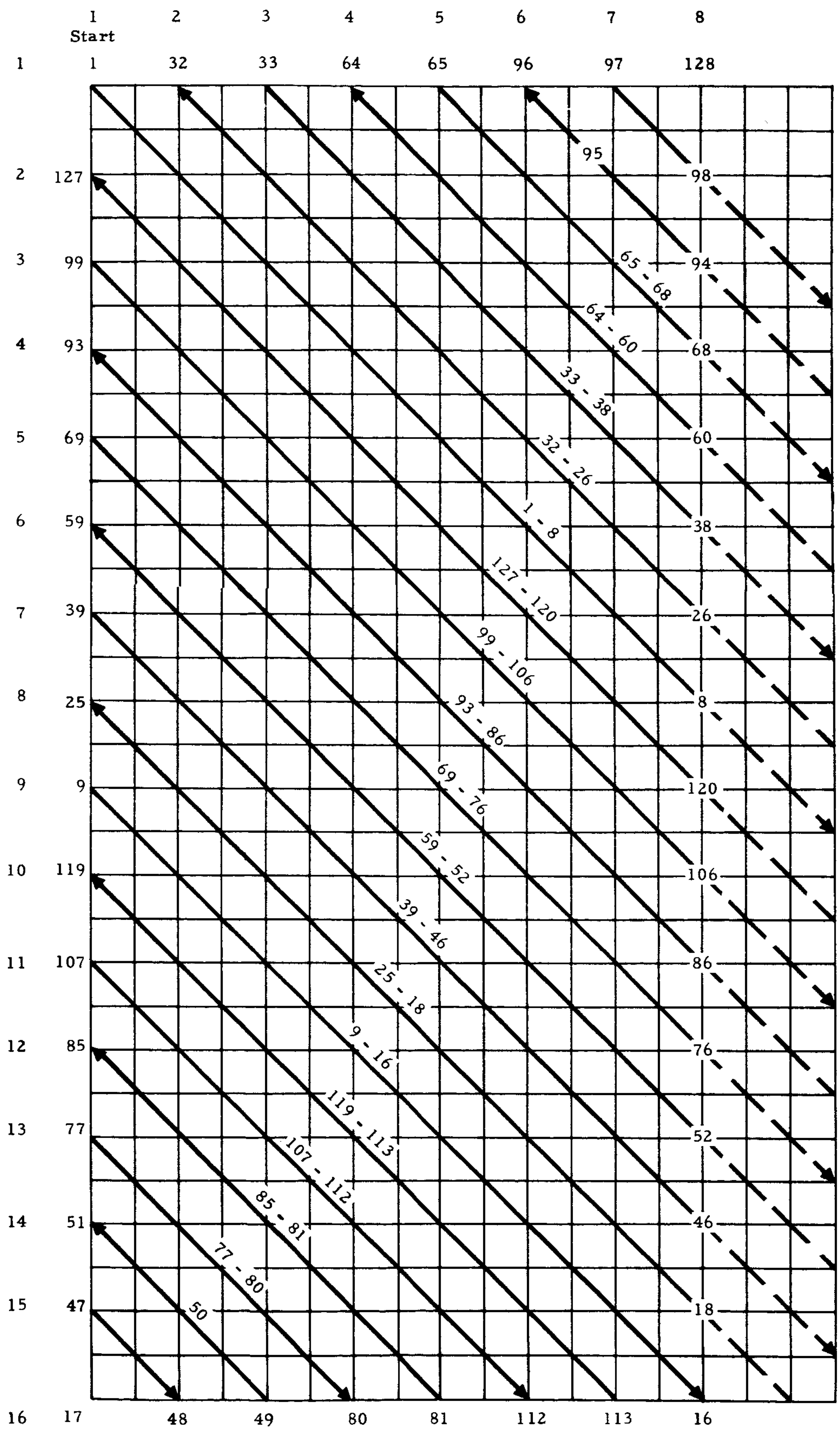


EXHIBIT 21 - ALLOCATION SCHEME (16 x 8 ARRAY)

Continue in this manner until all functions are assigned. The basic idea of the procedure is to separate adjacent functions to a great extent, while assigning functions in a "continuous" fashion to maximize the possibility of obtaining proper row-column sums. The major flaw in the scheme is that adjacent functions are placed in the same row each time "the corner is turned" at the top or bottom of the matrix. Some minor post mortem adjustments can frequently overcome this flaw if it is thought necessary. The scheme is essentially the same for the 16 x 8 array, except that now one may wish to think of the matrix as reproduced to the right twice before proceeding with the allocation. Other matrix dimensions are hand ed in a similar manner.

REFERENCES

1. Planning Research Corporation, D-1022, GEOS Command Subsystem (U), 8 June 1965

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3. Planning Research Corporation, D-708, Methods for Optimizing the Assignment of Functions Within a Matrix, With Applications to the OGO Command Relay Matrix (U), 1 September 1963