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THE WHITE HOUSE

WASHINGTON

July 11, 1971

Dear Dave:

At the last meeting of the NRP Executive Committee I expressed my judgment that the EOI system could benefit by at least a year and preferably two of continued technology development prior to going into system procurement. That judgment is based on my view that today the film readout system being less exotic is more immediately feasible and available, but that the trend of progress of solid state techniques guarantees that costs will decrease and performance increase rapidly in the application of EOI technologies.

I have sought to test my judgment by having my staff complete at least to some degree the efforts undertaken as a result of Carl Duckett's suggestions earlier this year that we attempt to find measures of effectiveness for the various photographic systems which we have been probing as an answer to the NRT and crisis capability needs. I am attaching a copy of their memorandum relating to "Satellite Photographic Systems Comparisons." An examination of Figures 4 and 5 indicates that the Z systems and all film systems today fit the same trend line but that the Z systems cost about twice as much as the film systems for the same performance. I expect that Z systems can be made to offer photographic capabilities different in dimension from what is attainable with film systems.

I conclude that, if we are interested in a well-organized program with an early result we should aim at a film system today and push the EOI toward an approach that supplies superior performance at the same or even lower cost.

Sincerely,

Ed

Edward E. David, Jr.
Science Adviser

Honorable David Packard
Deputy Secretary of Defense
The Pentagon
Washington, D.C.

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Cy to Dr. McLucas
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EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20506

July 11, 1971

MEMORANDUM

SUBJECT: Satellite Photographic Systems Comparisons

A recent effort sponsored by DDNRO at finding a basis for figures of merit for the comparison of photographic systems provided a large amount of relevant data. These data, which make possible the development of such comparisons at least in a beginning way, are the subject of this memorandum. The motivation for making such a comparison derives from the need to compare systems which display great variation in values of parameters describing them and this in turn derives in part from the variety in the operation of these systems. A second motivation is the need for finding a basis of comparison which provides a context for making assessments of systems' costs, risks and benefits.

The philosophy behind developing this basis for comparison is that commensurate parametric values of the various systems should be developed so that from these, to the degree that it is possible and useful, direct comparison of these system parameters and of associated figures of merit might be made. Some effort has been expended in assuring that numerical values used are accurate, but it is worth noting that results are not sensitive to uncertainties of 10% or 15% in the values used. Where there is potential for larger uncertainty, as for instance in assessing the relationship between ground resolution dimension (GRD) and ground sample distance (GSD) or in variable integration time, these ranges of values are shown explicitly.

Nominally the characteristics of photographic systems are stated in terms of orbit parameters, nadir GRD or GSD, swath width, mission duration, gross area coverage and the like. Because no two photographic satellites operate under similar conditions, comparisons are usually made intuitively if at all, and in any event they are not very satisfying.

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In contrast, this memorandum attempts to use fundamental descriptions of systems capabilities as a basis for comparison. From these fundamentals, figures of merit are developed and compared. Certainly there must be other figures of merit that will seemingly make more clear the value of one system with respect to another, and to the degree that these can be defined they should be developed and applied.

The systems compared in the memo are operational systems, GAMBIT (G) and HEXAGON (H); R&D systems, Electro Optical Imaging (Z) and Film Readout GAMBIT (F); and conceptual systems both modifications of CORONA, referred to as [redacted] and CORONA "Six Pack" (C). Conceptual modifications to each of the two R&D systems (F* and Z*)[1] are presented but the data relating to these have no community standing.

Table 1 presents fundamental data for the several systems treated. The data included are:

1. unit cost of a satellite and booster at a "feasible" procurement rate;

2. angular resolution in microradians -- angular resolution is nadir GRD divided by altitude, both in consistent units, e. g., 1 ft nadir GRD at 165 nm (one million feet) altitude corresponds to 1 microradian (μ rad) angular resolution;

3. total number resolution cells per mission -- which is a function of either mission film load or power constraints on imaging rate;

4. short term average solid angle (field of view) rate -- short term average (STA) solid angle rate multiplied by the square of the altitude gives a rough measure of area (square miles) coverage per unit time averaged over the framing interval for a framing system or at the sweep rate of a scanning system; this is a measure of coverage capability in a given locality.

Given the photographic system parametric values of Table 1, it is possible to develop certain figures of merit which have interest per se but which also permit order of magnitude correlations to be made among systems. The figures of merit developed in this memo and presented in Table 2 are:

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[1] Parenthetical letters are reference symbols used in the figures; systems F* and Z* are defined in footnote 1/ of Table 1.

Table 1

Photographic System Parameter Values

System	Symbol	Cost \$M	Angular Resolution 10^{-6} radians	Total Cells 10^{12}	STA Solid Angle Rate Steradians/second
HEXAGON	H	80	4.7	186	$1.1 (10)^{-1}$
CORONA "Six Pack"	C	21	10	3.8	$6.8 (10)^{-2}$
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
GAMBIT	G	33	2.05	8.3	$3. (10)^{-3}$
Film Readout GAMBIT	F	35	2.05	6.3	$8.6 (10)^{-4}$
Film Readout GAMBIT*	F*1/	65	2.05	74	$8.6 (10)^{-4}$
Electro Optical Imaging	Z2/	[redacted]	[redacted]	[redacted]	[redacted]
Electro Optical Imaging*	Z*1/2/	[redacted]	[redacted]	[redacted]	[redacted]

1/ F* and Z* are defined by these entries: F* employs a larger booster and contains two reels each of 176,000 feet of wet process film as opposed to two 15,000 ft reels in F; [redacted]

2/ Where two entries are made, the first corresponds to GRD=GSD and the second to GRD=2GSD; the author believes the correct relationship is scene-dependent and lies between these extremes, on the average. Parameters involving time (e.g., Solid Angle rate in Table 1 and Cells/sec in Table 2) assume an integration time of 1 millisecond for the targeting array; if integration time is larger by a factor of two for example, then these parameters are smaller by a factor of two.

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Photographic System Figures of Merit

System	Symbol	Total Solid Angle Per Mission Steradians	Cells/Mission Unit Cost 10^6 cells/$	Cost/Frame of $10^3 x 10^3$ cells $/frame	STA Resolution Cells Rate 10^6 cells/sec	Target Resolution Dimension at Swath Edge for 1' Nadir GRD at Altitude ft/nm	Minimum Possible Target Resolution Dimension at Swath Edge (feet)[4]
HEXAGON	H	4100	2.3	0.44	4800	[3]	13.5
CORONA	C	380	0.18	5.55	680	[3]	29
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
GAMBIT	G	35	0.25	4.00	710	6.0/82	5.9
Film Readout GAMBIT	F	26	0.18	5.55	200	6.0/82	5.9
Film Readout GAMBIT*	F*[1]	310	1.14	0.87	200	6.0/82	5.9
Electro Optical Imaging	Z[2]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Electro Optical Imaging*	Z*[1][2]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[1][2] See corresponding footnote numbers of Table 1.

[3] Altitude corresponding to 1 ft nadir GRD is sufficiently below a minimum feasible altitude (≅ 65 nm) of operation as to make this entry meaningless; 2 satellite operation assumed.

[4] This condition occurs for an operating altitude of 152 nm with a corresponding maximum look angle of obliquity of 56° in the flat earth approximation; 2 satellite operation assumed.

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1. total solid angle (field of view) per mission -- total solid angle multiplied by the square of the satellite altitude of operation is a gross measure of area (square miles) per mission;

2. resolution cells per mission unit cost; and its reciprocally related

3. cost per frame of 1000 x 1000 resolution cells;

4. short term average resolution cell rate -- which is the average data-taking rate of the system;

5. resolution dimension at swath edge -- based on a one-foot nadir GRD for a two-satellite operation and with swaths abutting at the equator; and for the same operating conditions

6. minimum resolution dimension capability at swath edge.

One measure of system cost effectiveness is gross coverage per unit cost. The measure used is mission total solid angle, which at a reference altitude corresponds to a given number of square miles at varying resolution. A comparison of total solid angle per mission vs. mission recurring (satellite and booster) cost is shown in Figure 1. The figure indicates that for targeting systems such as G, F, Z and Z*, the unit area costs (at varying resolution) form one family and surveillance systems such as H, C and [redacted] form another. It is interesting that F*, the extended version of F, is a kind of transition between surveillance and targeting systems.

Another comparison of photographic systems which gives some insight is that of unit cost of resolution cells and total number of resolution cells per mission. Figure 2 makes such a comparison in which there appears, for well-designed systems of a class, to be a good correlation between cell costs and total mission capability, i.e., an economy of scale. It appears also from Figure 2 that on this basis Z is [redacted] more expensive than film systems. If better response time were possible as with Z* or shorter resolution cell integration time, then this difference might become marginally small.

A third comparison which might give insight to photographic systems is a comparison of resolution cell costs vs. angular resolution and primary optics diameter (data not separately presented). Such a comparison is made in Figure 3. One might anticipate that in well-designed systems the number of cells per unit cost would increase with lessening angular resolution. If such a trend exists it is only marginally apparent in Figure 3 and one must conclude that (1) possibly not all of the systems treated are optically well-designed or (2) that which is obvious: optical systems contribute only negligibly to the unit cost of resolution cells. The near linear dependence between angular resolution and primary optics diameter suggests that at least as among H; F&G; and Z, all systems are equally well-designed optically after optics size was chosen.

A fourth comparison which gives insight to photographic systems is the relationship between the short term average of solid angle (field of view) rate which is a measure of target or area coverage capability on a given satellite pass in a given locality vs. system angular resolution. Such a comparison as in Figure 4 establishes some norms for good design and indicates the tradeoffs which can be made between these two parameters. Figure 4 shows a fifth power dependence between these two variables, implying that for both film and solid state sensor systems, solid angle rate may be doubled by trading with resolution, the resolution being degraded by 15%, i. e., less than 2 inches per foot. Under the present level and exploitation of film and sensor technologies, there are only marginal differences in the resolution and coverage attainable between these two photographic means. Shown also is the system relative area rate capability at fixed nadir GRD as a function of angular resolution in which a cubic relationship is exhibited. Finally, a parametric overplot is shown in Figure 4 of short term average resolution cells per second which is proportional to image data rate in a readout system which had about one frame of storage capability. It appears therefore that changes in technology should aim at points above the trend line, i. e., such changes should offer improving angular resolution and at the same time increasing solid angle rate (area rate).

Because of the correlations demonstrated in Figures 2 and 4, it is possible as in Figure 5A to summarize system capabilities in a single display. Figure 5A gives these various parametric values to a factor of 40% or better, with two qualifications. They are: (1) the cost of Z is reduced by 50% and (2) for C the short term average solid angle rate and the corresponding cells per second are lower by a factor of ten than shown. The import of Figure 5A is shown in Figure 5B. Given one chooses any pair of orthogonal parameters on the chart, e. g., angular resolution and a total solid angle or area coverage, then all other parameters -- total number of resolution cells per mission, the unit cost of resolution cells, the average solid angle and area rates and the data transmission rate (moderately buffered) -- are fixed within the present applications of technology.

A final measure of system capability is the resolution which it can offer under various operating constraints. Figure 6 indicates target resolution dimension[1] for several systems at swath edge (at the equator and at 45° latitude) for a [redacted] operation and for a 1 ft nadir GRD. Shown also is the altitude at which the various systems must operate so as to give the specified nadir resolution; in some cases altitudes given are clearly infeasible. Given that there is approximately [redacted] increase in diameter of primary optics between H on the one hand and F, F* and G on the other hand, and again a factor of [redacted] these three systems and Z and Z*, it is clear that swath edge resolution is a direct function of optics diameter and operating conditions and that sensor technologies presently contribute little or nothing.

Another system target resolution capability worth noting is the swath edge minimum resolution capability such as shown in Figure 7. As best resolution dimension along a swath edge is a function only of altitude and look angle of obliquity, it is possible to determine an altitude and look angle at which that resolution dimension is as good as can be obtained. This best resolution dimension depends only on the angular dependence law chosen and not on satellite optics. Figure 7 shows for this optimum operating altitude (152 nm) and look angle (66°) swath edge minimum resolution at the equator and at 45° latitude. Again, not surprisingly, the fact of improving minimum swath edge resolution with improving angular resolution and in turn increasing optic size is demonstrated and Figure 7 shows also for the minimum swath edge resolution the corresponding nadir GRD. Both Figures 6 and 7 show as appropriate search and targeting resolution requirements.

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[1] Target resolution dimension is defined (in the ordinate of Figure 6) as the geometric mean of resolution capabilities in both the vertical and horizontal planes. It is determined in a way consistent with the analysis that leads to a $\sec^{3/2}\theta$ dependence of ground resolution distance in which θ is the look angle of obliquity. At large angle of obliquity this definition gives a $\sec^{5/4}\theta$ variation with θ which is the geometric mean of $\sec\theta$ and $\sec^{3/2}\theta$ used by different project offices.

Some generalizations ought to be drawn from the foregoing. One can draw, as in Figure 8, a three dimensional plot of average solid angle rate, angular resolution and system size (total cells) or unit cost of resolution cells and find within those three dimensions a "current design plane" which describes with the accuracies stated the present capabilities of both film and solid state sensor systems. Perhaps there is, within this three dimensional space, a new optical and senor technology plane made available by coupling image intensifiers to solid state arrays and through different circuit design choices, reducing switching and amplification noise, decreasing integration time, improving resolution, broadening spectral response and so forth. That is certainly one direction to pursue. Possibly there are film system improvements, but this is not so clear.

However, one need not be restricted by the three dimensions of Figure 8 and at least conceptually, fourth dimensions incommensurate with those shown might be found to give a new "hyperplane" of photographic satellite capability. Some possibilities for these additional dimensions are some or all of [redacted] satellite on-board data storage capability, and imaging surfaces of multi-spectral sensitivity. It would appear that the possibility of attaining even a few of these additional dimensions is worth the expenditure of significant amounts of technology funds.