A METHOD FOR EVALUATING ENVIRONMENTAL EFFECTS ON MILITARY OPERATIONS

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RM-2080

ASTIA Document Number AD 144309

December 21, 1957

Assigned to ____________________________

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SUMMARY

Assessing the effect of environment on a complex military operation is frequently difficult, and military planners must generally rely on "minimum weather conditions." Information on the effects of gradations in weather, however, can be valuable, particularly if the information can be applied at an early planning stage. The effects of environment on elemental activities of a complex operation may be determined individually, and then combined to produce a numerical factor expressing the effects on the entire operation. The military planner may employ this factor with other quantitative factors in his final calculations. This report presents a method of accomplishing the breakdown and recombination of effects.
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I. INTRODUCTION

The environment* is one of many factors that may materially affect military operations, but the effects of the environment on a complex operation are frequently difficult to assess. Military climatological studies generally attempt, therefore, to establish a set of minimum weather conditions, above which an operation is assumed to be completely successful. The war games played at The RAND Corporation, however, have demonstrated the need for considering the effects of gradations in the weather by indicating that information regarding the degrading effect of weather on the operation of military gear can be of considerable value to a military planner, particularly if this information can be applied at an early stage of the planning.

The effects of gradations in the weather on the environmentally sensitive, elemental activities of a complex operation may be considered separately, and a numerical factor expressing each effect may be obtained. These factors may then be combined, in a manner dictated by the particular operation, to obtain a factor representing the overall effect of the environment on the entire operation. When a military planner has received this information, he may then combine it with other quantitative information when he makes his final calculations.

This report presents a method of accomplishing the breakdown and recombination of environmental effects, and it demonstrates, by means of an example, the value of the results of this procedure to a military planner.

*See Section II for definitions of environment, effectiveness, efficiency, and operation as used in this paper.
The plan for the quantitative evaluation of the environmental effects on military operations encompasses three areas of investigation:

1. The graduated effect of environmental factors on each of the elemental actions that make up military operations.

2. The analytical incorporation of environmental effects on elemental actions into an evaluation of the effect on the entire operation.

3. The development of a procedure for presummarizing environmental data that may be directly introduced into the analytical formulation.

The effects of environment on the elemental activities must be obtained from field tests, and this study attempts, in part, to demonstrate the need for acquiring and publishing these data. Some specific data do exist, but generally performance and environmental data have not been correlated.*

The second area of investigation, that of analytically introducing the effect of various gradations of the environment into the planning of an operation, is the main concern of the present study. The third area, presummarizing environmental data, is briefly discussed, and some suggestions based on the illustrative problem and on earlier studies are made.

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*The Army has recognized the need for performance data. Their extensive ENVANAL tests (1) are intended to provide quantitative information on the performance of personnel and equipment under varying environmental conditions.
II. ANALYTICAL FORMULATION

This section describes a general method for analytically determining the effect of the environment on individual elements of an operation and for combining these effects. The result to be obtained is a single number which expresses the most probable efficiency or effectiveness of an operation performed under a set of given circumstances.

DEFINITIONS:

The environment is the scene of the activity. In order to properly characterize the scene it is necessary to describe the surface or space, the modification of the surface or space due to weather, and the weather itself.

The effectiveness of an operation or any of its components is the rate of accomplishment or the amount accomplished by the military instruments and actions involved.

The efficiency of an operation or any of its components is the ratio of its effectiveness under given conditions to its effectiveness under optimum conditions, with effectiveness formulated in such a way that the efficiency remains less than or equal to unity.

An activity is as an elemental action with a single military instrument or array of identical instruments, for which the effectiveness of action is constant for unvarying environmental conditions. According to this definition the effectiveness of an activity changes only when the environment changes.

An operation may be defined more explicitly as the combination of any number of component activities, in sequence and/or in parallel,
necessary to accomplish a military mission.

METHODS

The character of an operation determines the manner in which the individual activities combine to form the operation. The choice of the significant environmental parameters is determined by the manner in which the activities are affected by gradations of the environmental factors.

The effectiveness of an activity may be expressed in terms of the time required for successful accomplishment, the probability of success, the attrition rate, the delivery rate, the distance covered, the width of reconnaissance channel, etc. The effectiveness of an operation may be expressed in the same terms or by combinations of them.

1. Efficiency of an Activity

The efficiency of an activity is a function of the surface or space as affected by the weather and the direct effect of the weather on the activity. For example, consider the activity of man walking over different surfaces in various kinds of weather. The weather affects the conditions of the surfaces: rain will cause a grass surface to become slick (reducing the man's walking efficiency), a sandy surface to become packed (increasing his efficiency), and a dirt road to become impassable mud; heat, cold, snow, etc., will all produce different effects on the surface. But the weather also has a direct effect on the man himself and therefore on his walking efficiency. When it rains his clothes become heavier and he may become chilled and uncomfortable, or the gloomy weather may dampen his spirits and produce mental depression, all acting to reduce his efficiency. Analogous examples can be found for surface equipment, aircraft,
ships, electromagnetic propagation, missiles, etc.

The effect of any one gradation of the weather on the efficiency of a single activity performed over several surfaces or regions of space in sequence may be expressed analytically as the harmonic sum of the efficiencies of the activity over each surface or region. Since an activity may be conducted for longer times, or for greater distances over one surface, or through one region of space rather than another, each term of the harmonic sum must be fractionally weighted according to its relative importance. Finally, the harmonic sum is multiplied by the efficiency of the activity due to the direct effect of the weather. Thus the efficiency of an activity over all surfaces in one gradation or type of weather \( (w_1) \) is:

\[
E_a(s, w_1) = \frac{E_a(w_1)}{\sum_{s=1}^{s_k} \frac{f_a}{E(s, w_1)}}
\]

(1)

In this expression and in those to follow, "F" refers to efficiency, "a" to activity, "o" to operation, "f" to the fraction of the activity performed in each space, and the letter within the parentheses indicates the dependence of "F" on the variation of the quantity inside ("s" for environment, "s" for surface or space, and "w" for weather).

To obtain the efficiency of an activity in all kinds of weather (climatic efficiency), Eq. (1) is weighted by the fractional occurrence of each gradation of the weather and summed over all weather. The overall probable efficiency of an activity at a given time and place is:

\[
E_a(s, w) = \sum_{w=1}^{w_k} \frac{P_w \, E_a(w)}{\sum_{s=1}^{s_k} \frac{f_s}{E_a(s, w)}}
\]

(2)
where $P_w$ is the decimal probability of the occurrence of the $w$ gradation of weather.

Equation (1) is used in connection with a specific forecast or the analysis of a particular kind of weather, and Eq. (2) for climatological surveys and planning purposes.

2. Efficiency of an Operation

The following paragraphs demonstrate the ways in which the activity efficiencies may combine to form an operation efficiency. Wherever the activity efficiency is mentioned, it may assume any of the forms discussed in the previous section.

Activities Performed in Sequence. If the efficiency of each activity is independent of any other activity, but the ability to accomplish the mission requires some degree of completion of all activities, then the efficiency of an operation may be written

$$E_o = \prod_{a=a_1}^{a_n} E_a(e)$$

Activities Performed in Parallel. Independent activities may be employed simultaneously to accomplish the same objective or mission. The activity efficiencies may be considered probabilities of success. Therefore, according to Sokalnikoff, the probability of all the activities failing simultaneously is

$$\prod_{a=a_1}^{a_n} [1 - E_a]$$
It follows then that the efficiency (probability of success) of the operation combining the activities in this manner is

\[ E_0 = 1 - \prod_{a=1}^{a_n} \left[ 1 - F_a \right] \]  \hspace{1cm} (4)

**Mutually Exclusive Activities.** When the activities are mutually exclusive events, e.g., when the weather determines the form of the activity, the efficiency of the operation is:

\[ E_0 = \sum_{a=1}^{a_n} f_a E_a(e) \]  \hspace{1cm} (5)

where \( f_a \) is the fractional contribution of each activity to the operation as a whole, and \( \sum_{a=1}^{a_n} f_a = 1 \).

**Complex Combination of Activities.** The operation may be a combination of the basic ways of combining activities. For example, subsequent environmental conditions may depend on the initial environmental conditions. This is true when the weather is correlated for activities performed in sequence or in parallel. Subsequent activities then become mutually exclusive events categorized by the classes of the weather entering into the first activity. In these cases the operation efficiency is:

\[ E_0 = \sum_{e=1}^{e_n} f_a E_a(e) \prod_{a=2}^{a_n} E_a(e) \]  \hspace{1cm} (6)
Conceivably an operation could consist of such sums and products in an alternating fashion.

3. Obtaining the Effectiveness from the Efficiency

Where the efficiency of an operation is the product of the activity efficiencies, the effectiveness of an operation will be the product of the efficiency of the operation and the maximum effectiveness figures of all the component activities. If $E_a$ and $E_o$ represent activity effectiveness and operation effectiveness, respectively, then

$$E_o = E_o \prod_{a=a_1}^{a_n} E_{a(max)}$$ (7)

For operations where the activities combine as a sum, the efficiencies of all the activities have a common maximum effectiveness as a base and

$$E_o = E_o \sum a(max)$$ (8)
III. THE APPLICATION OF THE METHOD TO A RECONNAISSANCE OPERATION

In this section the method already outlined is applied to the problem of quantitatively evaluating the effect of the weather on three types of aerial reconnaissance operations against vertical-take-off-or-landing (VTOL) sites in two adjacent areas of contrasting weather. The results may be used to determine the most effective altitude for each type of reconnaissance in either area for any month of the year.

A particular problem was chosen primarily because operational performance data is available for each of the important activities involved. The effectiveness numbers are based on estimates of performance figures. The following example clearly illustrates the value obtained by using such data at an early planning stage.

The three types of operations are visual, photographic, and radar reconnaissance against VTOL sites in two areas hypothetically controlled by an enemy. Reconnaissance of Area I is made from Air Base No. 1; that of Area II from Air Base No. 2. Actual weather data were used for both areas and both bases.

ANALYTICAL FORMULATION OF THE OPERATIONS OF THE EXAMPLE

The analytical formulation for all three operations is the same. Individual activities are "take-off," "flight," "reconnaissance," and "land." The efficiency of "take-off" and "land" is assumed to depend on three types of weather, but surface environment (runway condition, etc.) is assumed to be always at its optimum. In order to simplify the illustration, the weather for the "land" activity is taken as the same for that of "take-off." The activity of "flight" is a function of space (altitude), but the
effect of the en-route weather is slight and therefore neglected.

The environmental efficiency of the "reconnaissance" activity is a function of both space (altitude) and weather (clouds and precipitation). The weather conditions are correlated with the take-off weather. The operations will be evaluated for feasible altitudes separately, so that the most efficient altitude may be determined. The assumptions and the analytical formulations are discussed in greater detail in the Appendix.

Incorporating the above assumptions and considerations, the analytical formulation of the example is:

\[ E_0 = \sum_{w=W_1}^{W_3} P_w E_{T/L}(w) \cdot E_{F}(s) \cdot E_{R}(s) \cdot E_{R}(w) \]

where the symbolism has its previously defined meaning and the subscripts T/L, F, and R refer to "take-off and land," "flight," and "reconnaissance," respectively.

Tables of the various efficiencies and the form of \( E_R(w) \) are given in the Appendix.

**RESULTS OF THE RECONNAISSANCE EXAMPLE**

The complete results form a series of three charts for each of the areas considered. Each chart contains information for all possible altitudes for each month of the year. The results are presented in terms of operation effectiveness in Fig. 1, which gives a quantitative measure of the overall usefulness or productivity of the operation, so that different techniques, altitudes, and seasons may be compared directly. Each chart of Fig. 1 represents the quantitative trade-off of three factors:
Fig. 1 — Effectiveness of reconnaissance
1. Flight distance with maximum fuel as a function of altitude.

2. Efficiency of the reconnaissance technique as a function of altitude.

3. Degradation due to weather as a function of altitude, season, and terminal weather conditions.

The charts of Fig. 1 provide quantitative solutions to the many questions that might be asked about the effect of the environment on an operation. Information pertaining to specific questions may be extracted from Fig. 1 and presented in a clearer manner isolated from the rest of the data. For example, the military planner may need to know the maximum effectiveness and the optimum altitude for each of the three types of reconnaissance in both areas. This information is isolated in Figs. 2 and 3. Figure 2 presents the data for reconnaissance over Area I when take-off is made from Base No. 1 at 0300 GMT. Figure 3 presents similar information for Area II when take-off is made from Base No. 2 at 0300 GMT. The maximum effectiveness of photographic reconnaissance over Area II is superior to the other types during all months. Over Area I, however, the maximum effectiveness of photographic reconnaissance drops below that of radar during the months of June, July and August.

It is these crossovers that are likely to be of major importance to the military planner. Since the evaluation is quantitative, he can introduce estimates of other non-environmental considerations to assist his decision of the type of reconnaissance to use at any particular season. For example, the attrition rate may be slightly higher at 15,000 ft (the altitude of maximum effectiveness of radar) than at 20,000 ft (the altitude of maximum effectiveness of photographic reconnaissance). If the attrition rate is
Fig. 2 — Maximum effectiveness of area I reconnaissance (all types) 0300 GMT
Fig. 3—Maximum effectiveness of area II reconnaissance (all types) 0300 GMT
sufficiently critical, he may wish to choose photographic reconnaissance. On the other hand, the military planner may feel that the attrition rate at 20,000 ft is too high and wish to know how much effectiveness he would lose by flying at even higher altitudes. This information is also available from the basic charts, or it may be extracted and presented to him in the form illustrated in Fig. 4, where the optimum (no weather degradation) effectiveness, the effectiveness during the best month, and that for the worst month are shown for photographic and radar reconnaissance as a function of altitude over Area I. From this information the planner may decide that he can accept a loss in effectiveness to an altitude of 30,000 ft in December, but in July he will desire radar reconnaissance and will plan to fly at the lowest possible altitude where the effectiveness of radar is higher than that of photographic reconnaissance and where the attrition rate is again small.

Over Area I and Area II the altitude of maximum effectiveness remains the same throughout the entire year. This is not true in general. Data on the maximum effectiveness of photographic reconnaissance for the same type of operation is given in Fig. 5 for Areas III and IV as well as for Areas I and II. The numbers in the breaks of the graphs refer to the altitudes of the maximum effectiveness. Here we see that the altitude of maximum effectiveness of photographic reconnaissance over Areas III and IV markedly changes with season. For maximum effectiveness in these areas, flight should be conducted at low altitudes in summer and at higher altitudes in winter and spring.

**DISCUSSION OF THE EXAMPLE**

Charts, like those of the example, represent a graphical presentation of the solution of the general analytical formulation and method that are
Fig. 4—Effectiveness of radar and photo 24 in. reconnaissance over area I for best and worst periods of 0300 GMT
Fig. 5—Maximum effectiveness of photo reconnaissance 0300 GMT
the subject of this report. The procedure is designed to be comprehensive in its treatment of the environmental effects on military operations.

How well it succeeds depends to some extent on the availability of weather information. In general however, the availability of weather information is much greater than that of operational information on the effect of the weather. The available weather data can usually be considered adequate in the light of the paucity of information on the quantitative effect of the weather in degrading an operation. It is hoped that this presentation has demonstrated the practibility and considerable value which can be attained by introducing environmental parameters into military planning at an early stage.
IV. PRESUMMARIZATION OF CLIMATIC DATA

The huge volume of unorganized and unclassified data and the prodigious effort required to analyze these data makes it highly desirable to seek some way of at least partially presummarizing climatic records for use in military problems, but the problem of summarizing the data for ready inclusion into an evaluation of military operations is complicated by the requirement for widely varied criteria demanded by the very large number of operational questions to be answered. A breakdown of weather parameters essential for one activity may be quite useless for another. An argument could also be made against the breakdown of the weather into any classification dictated by any specific operation, on the basis that this would be a completely arbitrary procedure. The weather data must be examined then, to see if they offer some natural criteria for classifying. The inherent uncertainty of certain weather parameters (e.g., the militarily important visibility, ceiling, and sky cover observations) provides such a natural breakdown. The significant observed values may sometimes be obtained by an inspection of the frequency distribution plot of continuously increasing values of the parameter in question.

The frequency distribution diagram often indicates certain preferred values by high frequencies and certain other intermediate non-preferred or non-distinguishable values by much lower frequencies. The intervals between high frequency peaks may be taken as the range of observational certainty. The data may be summarized using these intervals as classes. Smaller intervals should not be used since the reliability of the intermediate data is questionable. However, if the intervals appear too small, larger intervals which are combinations of the natural intervals may be chosen.
When the frequency distribution is fairly regular in shape, the intervals will be chosen in the usual manner, so that the shape of the distribution is reasonably reproduced by the summarized data.

Simultaneous frequencies for a single station should also be summarized around the natural intervals. A satisfactory method does not exist for pre-summarizing the simultaneous frequencies between stations. When simultaneous frequencies between stations are required, they will usually have to be prepared as needed. The intervals around which the simultaneous summaries are made should not be less than those of the station with the largest natural interval.

The correlations between the different meteorological elements in climatologically homogeneous regions throughout the world would be a very valuable pre-summarization procedure. In this case the knowledge of a lack of correlation is just as valuable as that of a strong correlation. This is in distinction to the usual meteorological study where a strong correlation is desired for use in forecasting. Either can be used in place of simultaneous or combined frequencies (universally or regionally) according to the area of validity.

A survey of military operations for types of meteorological information not presently observed which, without severe hardship, could be introduced into the observational routine and should be the subject of a special investigation. Other types of information could be scheduled for special data gathering programs of an investigative nature.
V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The value of a quantitative foreknowledge of the degradation of the weather and environment on a military operation would be invaluable to the military planner. An analytical method for providing such information using presently available meteorological data is possible. The method may also be used by weather forecasters to provide the operational personnel with a forecast suited to their needs. The immediate usefulness of the method is limited by the scarcity of data on the effect of weather and operational environment on the various individual activities making up an operation.

The usefulness of meteorological data can be extended by presummarization as well as by other techniques of utilization. Some first steps have been suggested; other procedures are the subjects for research studies and may depend on the results of the initial steps.

RECOMMENDATIONS

Sources of information on the quantitative effect of different gradations in the weather and environmental parameters should be investigated, and the desired data accumulated. Where important deficiencies exist, programs for obtaining or measuring the data should be initiated.

Samples of meteorological data can be analyzed for the natural intervals of observational uncertainty and for the types of correlations of interest in planning military operations.

The quantitative method could be applied to a practical operational forecast problem and the usefulness of characterizing the effect of the weather on an operation in terms of efficiency and effectiveness studied.
Appendix

DETAILED PRESENTATION OF THE ILLUSTRATIVE PROBLEM

Efficiency of Take-off and Land Activities. No instrument landing facilities are available at the forward bases used in these operations. Instrument take-offs (ceiling ≥ 500 ft but < 1000 ft, and visibility ≥ 1 mi but < 3 mi) can be made, but landings must be made at an alternate air base. No take-offs will be made in less than instrument conditions. Take-offs and landings can be made at the home base when ceiling ≥ 1000 ft and visibility ≥ 3 mi (visual conditions). The weather does not affect the efficiency of take-off in instrument and visual conditions but does affect the efficiencies of flight since an additional thirty minutes flight time is required when the weather is "instrument" so that the home base aircraft can land at another base. Efficiencies of taking off and landing are given in Table 1.

Table 1

EFFICIENCIES OF TAKING OFF AND LANDING

<table>
<thead>
<tr>
<th>Weather</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>0</td>
</tr>
<tr>
<td>(Ceiling &lt; 500 ft, visibility &lt; 1 mi)</td>
<td></td>
</tr>
<tr>
<td>Instrument</td>
<td>1.0</td>
</tr>
<tr>
<td>(Ceiling ≥ 500 ft but &lt; 1000 ft)</td>
<td></td>
</tr>
<tr>
<td>(Visibility ≥ 1 mi but &lt; 3 mi)</td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>1.0</td>
</tr>
<tr>
<td>(Ceiling ≥ 1000 ft, visibility ≥ 3 mi)</td>
<td></td>
</tr>
</tbody>
</table>

Efficiency of Flight. The reconnaissance aircraft chosen was a jet fighter-bomber. An instrument landing requires an additional thirty minutes
flying time over friendly territory and thus cuts the productive reconnaissance flying time. The following table gives the efficiency of flight based on the productive range of the fighter-bomber with maximum fuel. These efficiencies are unmodified by weather.

Table 2

EFFICIENCY OF FLIGHT
(Productive Range for Fighter-Bomber with Maximum Fuel)

<table>
<thead>
<tr>
<th>Flight Altitude (1000's ft)</th>
<th>Visual Landing $F_v(s)$</th>
<th>Instrument Landing $F_i(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.595</td>
<td>.318</td>
</tr>
<tr>
<td>2</td>
<td>.611</td>
<td>.333</td>
</tr>
<tr>
<td>3</td>
<td>.627</td>
<td>.354</td>
</tr>
<tr>
<td>5</td>
<td>.656</td>
<td>.383</td>
</tr>
<tr>
<td>6.5</td>
<td>.682</td>
<td>.409</td>
</tr>
<tr>
<td>8</td>
<td>.705</td>
<td>.432</td>
</tr>
<tr>
<td>10</td>
<td>.736</td>
<td>.464</td>
</tr>
<tr>
<td>15</td>
<td>.817</td>
<td>.545</td>
</tr>
<tr>
<td>20</td>
<td>.890</td>
<td>.648</td>
</tr>
<tr>
<td>25</td>
<td>.964</td>
<td>.690</td>
</tr>
<tr>
<td>30</td>
<td>1.000</td>
<td>.728</td>
</tr>
<tr>
<td>40</td>
<td>1.000</td>
<td>.728</td>
</tr>
</tbody>
</table>

BASE (maximum flight range) = 1100 n.mil.
(Effectiveness = Base x Efficiency)

Efficiency of Reconnaissance. The three types of reconnaissance considered, visual, photographic and radar, are all affected by changes in altitude and weather. The efficiencies are based on the maximum width of reconnaissance channel that gives satisfactory resolution for a VTOL site as a function of altitude. Visual and photographic reconnaissance are affected by the number of tenths of cloud cover below flight altitude; radar reconnaissance is affected by the amount and thickness of cloud cover below flight altitude and by the intensity of precipitation between the
aerial and the ground. Table 3 lists the efficiency of each type of reconnaissance [represented by \( E_R(s) \)] in the analytical formulation as a function of altitude alone.

<table>
<thead>
<tr>
<th>Altitude (1000 ft)</th>
<th>Visual ( E_R(s)_v )</th>
<th>Radar ( E_R(s)_r )</th>
<th>Photo ( E_R(s)_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.429</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>0.571</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>0.714</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>5</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>6.5</td>
<td>1.000</td>
<td>1.000</td>
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<td>8</td>
<td>1.000</td>
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<td>10</td>
<td>1.000</td>
<td>1.000</td>
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<tr>
<td>15</td>
<td>0.143</td>
<td>1.000</td>
<td>.938</td>
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<td></td>
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<td>.875</td>
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<td></td>
<td></td>
<td>.718</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>.688</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td>.375</td>
</tr>
</tbody>
</table>

**BASE**

7.0 n.mi. 12.0 n.mi. 16.0 n.mi.

(Effectiveness = Base x Efficiency)

**EFFECT OF WEATHER ON RECONNAISSANCE ACTIVITY**

There is the problem of determining the effect of the weather on reconnaissance in terms of the surface weather observations, which are limited by what the observer can see from the ground. This is seldom the information needed to assess the weather's effect on an activity.

**Effect of Weather on Visual and Photographic Reconnaissance.** In the case of visual or photographic reconnaissance an observer in an aircraft can sight a point of interest on the ground only when the observer at the ground point can theoretically see the aircraft. Thus the probability of an
aircraft observer or photo interpreter sighting a given small target is

\[ (1 - H_c) \]

where \( H_c \) is the fraction of the sky covered by cloud from the
surface to aircraft altitude. This probability represents the maximum.
Because of fixed-look angles and non-randomness of flight headings, the
probability will likely be some lesser figure. This point and many others
raised by this example could be discussed at greater length. They form
areas of research which would be profitable to the Air Force. For our
purposes we will consistently, in the example, select the more optimistic
figure. In this way, when the results show significant difference from
one reconnaissance type to another or from one environment to another, we
can be assured that the differences are real, and what is probably more
important, we can be certain that low operational efficiencies represent
serious degradations due to environmental and weather condition.

An evaluation of the effect of restricted visibility on the width of
the reconnaissance channel was made using information contained in the Air
Force Surveys of Geophysics, No. 21, on "Slant Visibility."(3) This report
contains charts of slant range from different altitudes versus meteorologi-
cal visibility. A study of these charts in light of the problem at hand
shows that, except for extremely low visibilities, the effectiveness of
each of the types of reconnaissance is insensitive to visibility. The
weather data indicate that extremely low visibilities are usually accompa-
nied by a low overcast or observed sky condition. Thus, a slight degree of
optimism, if there is any departure from the assumption at all, is intro-
duced when the visibility is omitted as a factor in degrading the reconna-
issances.

**Effect of Weather on Radar Reconnaissance.** A K-Band side-lookig radar
is assumed for this type of reconnaissance. The thickness and amount of cloud and the depth and intensity of precipitation are effective in reducing the range of this radar. Average attenuation rates are assumed for cloud and for four intensities or precipitation: light, moderate, heavy, and thunderstorm. Precipitation is assumed to exist from flight altitude to the ground and the accompanying cloud from flight altitude to cloud base. In order to obtain a measure of the cloud thickness in the absence of precipitation it was assumed that, where cloud exists, it fills one-half of the volume between cloud base and flight altitude.

The weather efficiencies for the three types of reconnaissance are given in Table 4. These efficiencies are modified by the appropriate frequency ratios of the respective cloud amount or precipitation intensity. The computational form of the climatic weather efficiency for visual and photographic reconnaissance becomes

\[ E_R (W) = \sum_{N_c = 0}^{10} f_c (1 - \frac{N_c}{10}) \]

where \( f_c \) is the fraction of the time the cloud amount below flight altitude is \( N_c \), and \( N_c \) is the tenths of cloud cover below flight altitude.

The climatic weather efficiency for radar reconnaissance for any given altitude is computed from the following equations:
\[
\begin{align*}
\text{when } & \frac{1}{2} \sum_{N=0}^{10} f_c \left( \frac{N \delta}{10} \right) \geq f_p:
\Xi_R(W)_r &= \Xi_R(W_0)_r \left[ 1 - \frac{1}{2} \sum_{N=0}^{10} f_c \left( \frac{N \delta}{10} \right) \right] + \left[ \frac{1}{2} \sum_{N=0}^{10} f_c \left( \frac{N \delta}{10} - f_p \right) \right] \Xi_R(W_i)_r \\
& + \left[ 1 - f_R \right] \left[ f_L \Xi_R(W_L)_r + f_m \Xi_R(W_m)_r + f_H \Xi_R(W_H)_r \right] + f_{R_u} \Xi_R(W_u)_r \\
\text{when } & f_p > \frac{1}{2} \sum_{N=0}^{10} f_c \left( \frac{N \delta}{10} \right):
\Xi_R(W)_r &= (1 - f_p) \Xi_R(W_0)_r + \left[ 1 - f_R \right] \left[ f_L \Xi_R(W_L)_r + f_m \Xi_R(W_m)_r + f_H \Xi_R(W_H)_r \right] \\
& + f_{R_u} \Xi_R(W_u)_r \\
\end{align*}
\]

where the subscript of \( W \) refers to the type of weather: "0" for optimum or no clouds, "c" for clouds, "L" for light rain, "M" for moderate rain, "H" for heavy rain and "u" for thunderstorm rain, and where \( f_c, f_L, f_m, f_H, f_{R_u} \) refer respectively to the fractional frequency of clouds, light rain, moderate rain, heavy rain, thunderstorm rain, and \( f_p = f_L + f_m + f_H \).
Table 4

WEATHER EFFICIENCY OF RECONNAISSANCE
(Based on Width of Recon Channel)

<table>
<thead>
<tr>
<th>Altitude (1,000 ft)</th>
<th>Visual and Photo</th>
<th>Radar</th>
<th>Radar</th>
<th>Radar</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Cloud</td>
<td>No Cloud</td>
<td>Cloud</td>
<td>Light</td>
<td>Rain</td>
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<td>1.000</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>0</td>
<td>1.000</td>
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</tbody>
</table>

BASE, visual and photo: BASE for radar 12 n.mi.
see Table 3.

GRAPHIC RESULTS OF RECONNAISSANCE EXAMPLE

The complete results form a series of three charts containing information for all possible altitudes for all months of the year for each of the areas considered. The final data may be presented in terms of either the efficiency or the effectiveness. The efficiency offers a better basis for comparing the same system at different altitudes or over different areas. The effectiveness gives a quantitative measure of the overall usefulness or productivity of the operation and may be used to compare different operations in different locations or seasons. The efficiency of the operations of our example is illustrated in Fig. 6. Figure 1 of the text is obtained by multiplying each efficiency in Fig. 6 by the product of the optimum effectiveness of flight and the optimum effectiveness of the appropriate reconnaissance.
Fig. 6 — Efficiency of reconnaissance
systems. Both series of charts represent the quantitative trade off among the following three factors:

1. Flight distance with maximum fuel as a function of altitude.

2. Efficiency of the reconnaissance technique as a function of altitude.

3. Degradation due to the weather as a function of altitude, season, and terminal weather conditions.

The trade off is further modified by the probability of being able to take-off as determined by terminal weather conditions. This trade off is illustrated schematically in Fig. 7. The numbers in Fig. 7 correspond to those factors enumerated above. The resulting operation efficiency curve is the product of the others and the terminal weather probabilities.

Presentations in the forms of Figs. 1 and 6 are designed for their flexibility in providing quantitative solutions to the many questions which might be asked about the effect of the environment on an operation. They can serve as working charts for the staff meteorologist.
Fig. 7 — Schematic design of operation efficiency illustrating quantitative trade-off of the several factors.
REFERENCES


