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# SWATH WIDTH STUDY

FINAL REPORT ON CONTRACT NAS8-32491 MOD 1

## *A Simulation Assessment Of Costs And Benefits Of A Sensor System For Agricultural Application*

PREPARED FOR

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
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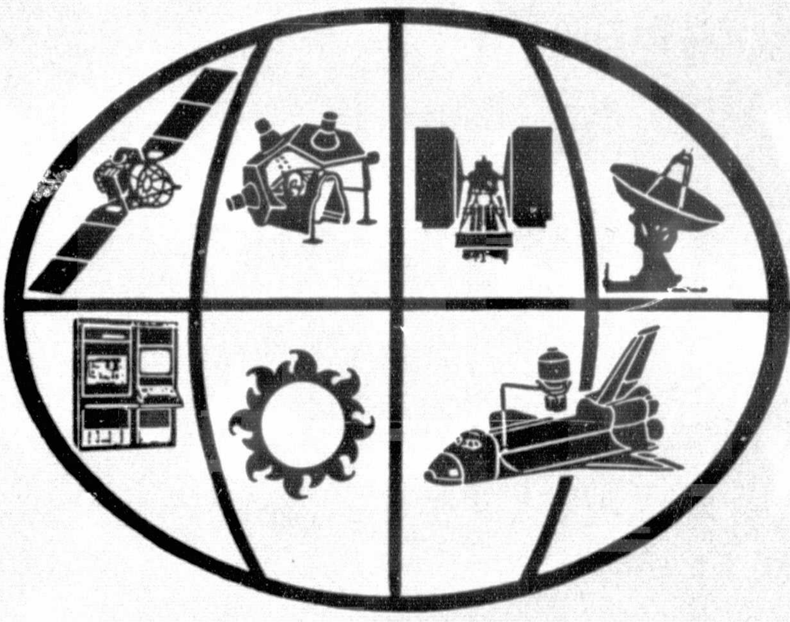

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## ABSTRACT


Satellites provide an excellent platform from which to observe crops on the scale and frequency required to provide accurate crop production estimates on a worldwide basis. Multi-spectral imaging sensors aboard these platforms are capable of providing data from which to derive acreage and production estimates. Major issues requiring resolution before an operational satellite-based system for global crop production forecasting can be specified are:

- When and how frequently must each crop in each world region be observed?
- How large an area in each region must be sampled?
- What combination of (1) number of platforms, (2) orbits of platforms, and (3) sensor swath width is most cost-effective in obtaining the required observations?

In a preceding study, these questions were addressed and partially answered. Crop observation "windows" were established, sampling strategies were developed, and the number of orbits of platforms evaluated. The potential of reducing the number of required satellites by increasing the sensor swath width was identified. In the present study, this issue of sensor swath width was examined. The quantitative trade data necessary to resolve the combined issue of sensor swath width, number of platforms, and their orbits was generated and are included in this report. Problems with different swath width sensors were analyzed and an assessment of system trade-offs of swath width versus number of satellites was made for achieving Global Crop Production Forecasting.

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# 1.0 INTRODUCTION

This report was prepared under contract to the National Aeronautics and Space Administration, George C. Marshall Space Flight Center (MSFC), as partial fulfillment of the requirements of Contract NAS8-32491, Mod 1. This report documents an investigation of the benefits and problems of using a multispectral scanning sensor having a swath width wider than the 185 km Thematic Mapper. The investigation was based upon previous analyses performed by General Electric and others on the far term, 1985 and beyond, Office of Space and Terrestrial Application's objective of applying space technology to an operational Global Crop Production Forecasting (GCPF) System (Ref. 1). From those studies (Ref. 2, 3), the use of wider swath sensors was identified as a possible cost effective way to achieve the desired observations with a minimum number of satellites. The objective of the study was to trade-off the cost of increasing sensor swath width against the cost of additional satellites to provide the data required for Global Crop Production Forecasting.

It was desired to develop a systems concept that would provide for the acquisition of at least 98 percent of the samples desired to inventory the amount of land in production for particular crops. A major constraint was to not degrade the utility of the acquired image data for non-agricultural applications.

# 2.0 SUMMARY OF RESULTS

Quantified data is presented in the form of curves of percent of targets acquired versus swath width. This data has application to both mission designers and sensor designers. This data includes the effect of agricultural windows and cloud statistics for the conditions described in this report. Swath width data extends from the nominal Thematic Mapper swath of 185 km to 350 km.

A coupling was observed between swath width and orbit in achieving successful acquisitions. While there are benefits resulting from wider sensors, there are additional benefits from altering the orbit to distribute the opportunities more evenly over the target areas. A change from a 704 km 16-day revisit orbit to a 771 km 14-day revisit orbit offers more effective use of the wider swath, especially in the cloudy regions at lower latitudes that exhibit fewer acquisitions with the planned 185 km swath and orbit. Deviations from the planned deployment of the Thematic Mapper is also suggested. The incorporation of terrain corrections during data processing and employing an off-nadir scan to take better advantage of sunlight illumination is suggested.

The benefits achievable with wider swath sensors were compared with the penalties and relative costs of obtaining the wider swaths. The study results indicate how a sacrifice in spatial resolution from 30 meters to 32.85 meters can be combined with a 14-day revisit cycle orbit to acquire 98 percent of the desired samples on a worldwide basis with two satellites. This alternate has the least relative cost of all the options considered.

Another alternate with a 315 km swath sensor is also suggested. This swath width was chosen using the data of this study to compare the performance of two satellites against three satellites. Some of the difficulties of using this wide a sensor are explored and the recommendation is--should this alternate be selected--to concentrate on a pushbroom type sensor.

## 3.0 REQUIREMENTS

The Global Crop Production Forecasting requirements for multispectral data were developed in the preceding studies (Ref. 4, 5). The driving parameter for monitoring agricultural production is revisit time between successive observations, or temporal resolution. The ability to reliably obtain cloud free images at precise time during the growing seasons determines the number of satellites required. When combined with other information called collateral data, the system will: 1) measure or inventory the amount of land in production for particular crops, 2) determine plant vigor as an indication of growth stage and potential yield, and 3) assess the extent of stress from either environmental or induced episodes as it affects yield. Each of these uses imposes constraints on the timing of data acquisition.

This study is directed toward a more indepth analyses of wider swath sensors than was explored in the "Global Crop Production Forecasting (GCPF)" Study (Ref. 4). In the previous study, an increase in the sensor swath width was identified as a potential for improving an operational GCPF system performance. That study concentrated on the performance of the inventory function. Likewise, this study will be based on the requirements as developed for the inventory functions. With the identification of different acquisition times, the results will also apply to the monitoring of plant vigor.

This study concentrated on data related problems rather than the science of using the data. Where the use of the data drives the data requirements, values from pragmatic considerations such as currently planned NASA programs were accepted as "givens." In order to properly bound the problem and provide utility of the results as precise requirements evolve, the requirements developed during the preceding study (Ref. 4) were extrapolated. The requirements pertinent to the study of swath width are listed in Tables 1 and 2.

Table 1. Selected Requirements for GCPF

| | | |
|---|---|---|
| 1 | Spectral Resolution | 5 visible & near IR + 1 thermal IR as defined for Thematic Mapper |
| 2 | Radiometric Quantization | 128 levels |
| 3 | Spatial Resolution | Approximately 30 meters |
| 4 | Temporal Resolution | Defined by crop species calendars and sensor radiometric resolution |
| 5 | Coverage | Sample segments 1 $Km^2$ |
| 6 | Number of Samples | Determined by region and crop density |
| 7 | Crops | Wheat, corn, soybeans, and rice |
| 8 | Countries | 22 major producers (36 regions) |
| 9 | Acquisition Confidence | 19 years out of 20 |
| 10 | Sample Quality | Less than 10% cloud conditions |

Table 2. Assumptions for Study

| | |
|---|---|
| **Assumptions Pertaining to the Science of GCPF and the System Concept** | |
| 1 | Visible and infrared image data requirements for GCPF can be met with three satellites of the planned Landsat-D type using sensor systems having characteristics as planned for the Thematic Mapper. |
| 2 | The spectral and radiometric resolutions of the planned Thematic Mapper are firm requirements for GCPF satellite image data. |
| 3 | The satellites providing GCPF data will and should be in helio-synchronous low earth orbits. |
| **Assumptions Pertaining to the Modeling Concept and its Validity** | |
| 4 | An operational GCPF system can be hypothesized such that the effect of sensor swath width on GCPF can be determined. |
| 5 | The percentage of targets acquired is a valid measure of GCPF system performance. |
| 6 | The results of comparisons of sensor performance based upon sample acquisitions within windows chosen for simple discrimination conditions are valid for more complex conditions. |
| 7 | One observation per window is required. |
| **Assumptions Pertaining to Technology** | |
| 8 | The planned Thematic Mapper represents the state-of-the-art in a) primary sensor element manufacture, b) optical materials manufacture, and c) mechanical whisk-broom sensor technology. |

The requirements of Table 1 constrain the permissible trade-offs of sensor system swath width. Requirements one through three impact the methods available to obtain wider swaths. Requirements four through ten impact the utility of a given swath sensor system.

While classification of crop species solely by two-class discrimination is not expected to be an operationally accepted approach, it provides a way to determine the temporal resolution needed to compare the performance of alternate sensor systems. Windows during which cloud free acquistions are required were determined based upon the twenty year crop calendars historical data for the crops and their major confusers in each region.

Several assumptions were necessary at the start of the study in order that the main objective could be investigated. They fall into three categories. The first category pertains to the basic science of Global Crop Production Forecasting. It is necessary that some sort of operational system be conceived in order that requirements can be defined. The conceived system is based upon technologies that have been tried as experiments but have not yet been put together as an operational system. The assumptions are listed in Table 2. Assumption 1 of this table provides the benchmark against which sensor system alternatives can be measured. Assumptions 2 and 3 provide some constraints on the permissible approaches to achieving wider swath widths.

The second category of assumptions, 4 through 7, pertains to the criteria of evaluating alternate sensor systems. Assumption 4 bounds the evaluation of sensor system performance to a fixed set of conditions for all alternatives. For the system hypothesized, an acquisition of 98 percent of the desired samples was set as a goal to minimize accuracy degradation because of sampling error. The development of the sample distributions used for measuring sensor system performance was based upon this goal. Changes in the science of classification and GCPF technology could conceivably have some impact on the importance of the percentage of samples acquired. No attempt was made in this study to assess either the extent or likelihood of such events. The temporal resolution requirements used were based upon assumptions 6 and 7. The present status of the science of plant specie classification is such that many data acquisitions are required, often at very precise temporal resolution. The recently completed LACIE Program (reference 6) and other studies (references 7 and 8) have identified the extreme complexity of determining the temporal resolution requirements for an operational multi-crop classification system. The determination of temporal resolution requirements is still in an R&D stage with no approved solution. For this study, the temporal resolution was assumed based upon one observation within each window. Windows were chosen for homogeneous crop growing regions, based upon the mix of the four chosen crops in the region as in reference 4.

The third category of assumptions pertains to sensor system technology. Assumption 8 constrains the permissible methods of obtaining wider swaths. It simplifies the study by removing the need to conjecture any radical improvements in the sensitivity of electro-optical materials or the development of super-light, super-rigid, super-reflective mirror materials, etc. The practical consideration of this assumption is that the time required to obtain a signal, an acceptable signal to noise ratio and radiometric quantization, is fixed to the Thematic Mapper design.

## 4.0 SWATH WIDTH, SATELLITES, AND COSTS

This study was undertaken in two parts. One part determined a quantified measure of the benefits of using wider swath sensors for obtaining GCPF data and the other part determined their costs. Costs included penalties of performance, technical limitations, and processing throughout the data acquisition system as well as relative dollar considerations. The benefits and penalties were considered jointly to obtain rankings of alternate approaches.

The benefits of different swath width sensors were measured using the approach developed during the preceding study (Ref. 3). The satellities, their movement and observation capability, world cloud conditions, and major growing regions for wheat, corn, soybeans, and rice were modeled using the MSFC Data System Dynamic Simulator (DSDS) (Ref. 9).

Sample targets were identified along with pertinent regional cloud conditions and crop mixes, statistics were collected on individual samples and regions. This permitted a measure of the effects of opportunity variations due to overlap in coverage, length of time during which observations could be obtained, and the effects of localized cloud conditions. During this study, sensors of different swath widths were modeled and the acquisition success was determined for one, two, and three satellite systems. The effect of orbit selection to maximize the benefits of using wider swath sensors was also investigated.

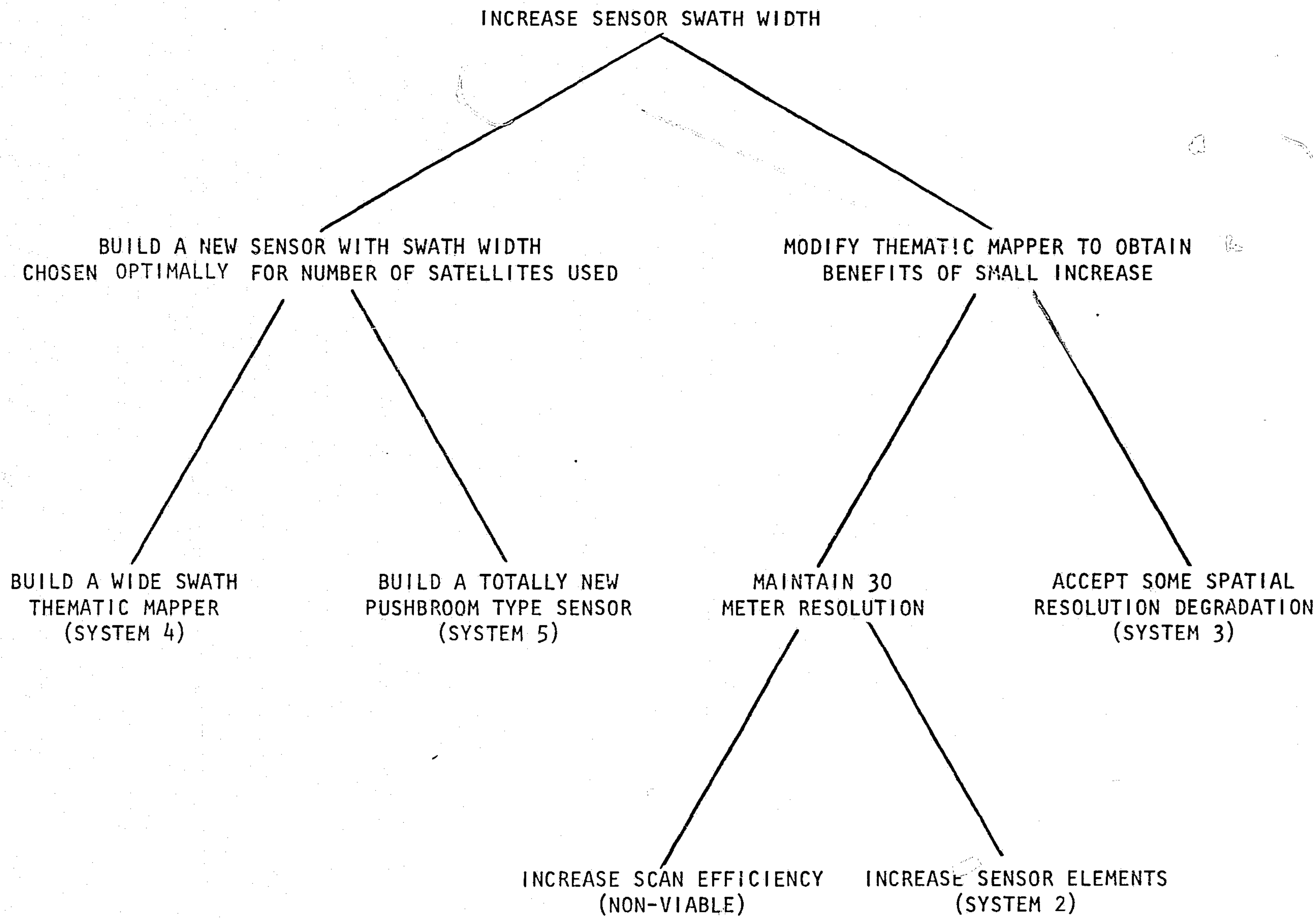
A series of issues surface when the design, implementation, and use of a wider swath sensor are considered. There are penalties incurred because of the cost of development and testing, performance degradation, and operational difficulty. The issues are not all on the same level. As choices are made between alternatives, subsequent issues arise that are a direct result of the selection made. The complete assessment of alternatives is dependent upon completing the analysis through all subsequent issues to an acceptable solution. This sequence of issues is illustrated by the decision tree of Figure 1.

This study used the Thematic Mapper design as planned for use on Landsat-D as the baseline for analyzing wider swath width penalties. Attempts were made to identify possible approaches to increasing the sensor swath width with a minimum of penalty. Technical limitations were considered and possible alternate solutions were assessed. The overall data acquistion system costs were then evaluated in conjunction with the benefits previously determined for each system.

## 4.1 APPROACH TO MEASURING BENEFITS OF WIDER SWATH

Twenty-two countries were chosen based on the criteria that each contributed two percent or more to the world harvest of one of the selected crops. The larger countries were divided into geographic regions corresponding to statistical reporting districts. The point target capability of DSDS was used to provide a statistically sound measure of variations due to geographic location and cloud conditions. A minimum number of samples in a simulation region was set at 30 for a geographic region containing only one crop. The number of samples was adjusted to a maximum of 60 when all four crops were grown in a region.

This approach resulted in 1553 samples for the world and permitted the collection of statistics on individual samples and regions. The number of samples drawn for an operation system varies for each region according to accuracy considerations and can be scaled from the simulation data. The countries chosen, along with their crops, and the number of samples allocated to each are listed in Table 3.




NOTE: SYSTEM 1 IS BASELINE

Figure 1. Decision Tree for Implementing Increased Sensor Swath

Table 3. Countries, Regions, Crops, and Number of Samples Used for Study

| Country & Region | Crops | Number of Simulation Samples | Estimate of # of Operational Sample Segments |
|---|---|---|---|
| Argentina | W,C | 45 | 1500 |
| Australia | W | 30 | 1000 |
| Bangladesh | R | 30 | 1000 |
| Brazil North | C | 30 | 1000 |
| Brazil South | C,S,R | 53 | 1767 |
| Canada | W | 30 | 1000 |
| China North | W,C,S,R | 60 | 2000 |
| China Central | W,C,S,R | 60 | 2000 |
| China South | W,C,S,R | 60 | 2000 |
| Egypt | C | 30 | 1000 |
| France | W,C | 45 | 1500 |
| India Punjab | W,C | 45 | 1500 |
| India Ganges | W,C,R | 53 | 1767 |
| India Central | W,C,R | 53 | 1767 |
| India Bilaspur | W,C,R | 53 | 1767 |
| India Coastal | R | 30 | 1000 |
| Indonesia | R | 30 | 1000 |
| Italy | W,C,R | 53 | 1767 |
| Japan | R | 30 | 1000 |
| Mexico | C | 30 | 1000 |
| Pakistan | W | 30 | 1000 |
| Romania | W,C | 45 | 1500 |
| South Africa | C | 30 | 1000 |
| Philippines | R | 30 | 1000 |
| Thailand | R | 30 | 1000 |
| Turkey | W | 30 | 1000 |
| USA -Southern Midwest | W,C,S | 53 | 1500 |
| USA -Western Great Plains | W,C | 45 | 2000 |
| USA - All Other | W,C,S,R | 60 | 2000 |
| USA - Southern | W,C,S,R | 60 | 2000 |
| USSR Latvia | W,C | 45 | 1500 |
| USSR Ukraine | W,C | 45 | 1500 |
| USSR Transvolga | W,C | 45 | 1500 |
| USSR Volga-Ural | W,C | 45 | 1500 |
| USSR Siberia | W,C | 45 | 1500 |
| Yugoslavia | W,C | 45 | 1500 |
| TOTAL | | 1553 | 51355 |

W = Wheat, C = Corn, S = Soybeans, R = Rice

The DSDS at MSFC was used to determine the following:

- o Orbital position of the satellites as a function of time and orbital parameters.
- o The sensor field of view as a function of satellite position and swath width.
- o The state of the samples within the field of view as a function of the cloud model.
- o The statistics on the target acquisitions as a function of the above, the preprocessing acceptance criteria and the processing requirements.

The DSDS combined the dynamics of satellite position, crop models, cloud models, and processing requirements. A Monte-Carlo method was used in conjunction with a cloud model to inject the realism of cloud cover in the simulation.

The simulation was segmented as illustrated in Figure 2. For economy of simulation time, the results of each successive simulation segment were saved and used for later parametric variations. For example, for a one year simulation of satellite positions repeating every 16 days, the mission ephemeris was generated for 16 days and reused. For different sensor swath widths for the same satellite positions, the same mission model data was used. The results of the Mission Model, sensor swath, and target described the data available from one satellite. Any combination of satellites desired was combined in the multi-vehicle crop model to constitute one of the candidate systems. Thus, such subtle effects as the difference in insertion time and position offset for a 3 Landsat vehicle system were included. The effects of cloud conditions were determined by a comparison of a random number against the predesignated cloud condition breakpoints for the cloud region corresponding to each sample. The acceptable cloud conditions for preprocessing was the first criterion to be met for all the samples in a scene 90 nautical miles along track and one swath width wide. A subsequent random number was compared with the scene cloud conditions to determine if each sample was clear or cloudy. A more detailed discussion of the DSDS models and the available data is presented in References 3 and 4.

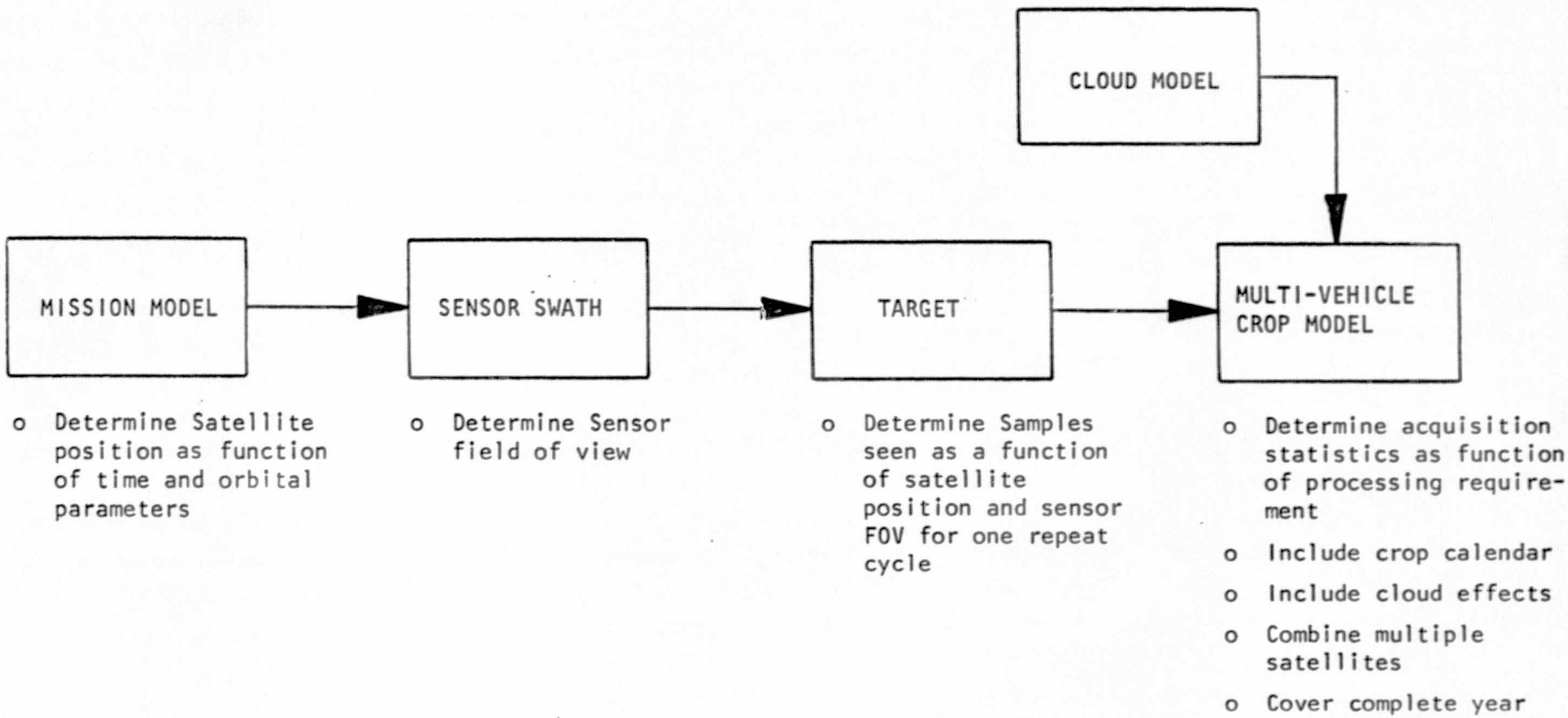



Figure 2. DSDS Model

## 4.2 TARGETS OBTAINED USING 1, 2, AND 3 LANDSAT-D SATELLITES

The first step in this study was to determine a curve of acquisition versus swath width with a standard Landsat-D orbit repeating every 16 days after 233 orbits. This curve provides information on the benefit of wider swath with no consideration as to how it may be obtained.

Simulation runs were made with 1, 2, and 3 Landsat-D satellites to determine the percent of desired target areas for which cloud free image data could be obtained with increased swath width. When 2 satellites were employed, they were spaced so that each point on the ground is covered every 8 days and when 3 satellites were employed, each point on the ground is covered every 5 1/3 days. For each combination of satellites, the swath width was increased in discrete steps from 185 km to 350 km. For each swath width, five one-year runs were made with different random number seeds in the cloud model to represent five different years of data. The results of these runs are plotted on Figure 3. For each combination of satellites and swath widths, the range of the percent of desired samples for which cloud free image data was obtained is plotted as a bar on Figure 3. Five runs do not cover the entire range of expected results for any combination of satellites and swath widths. The smooth curve fitted through the range marks represents the expected mean performance when using 1, 2, or 3 Landsat-D satellites.

As expected, there was more variation in the range for the one satellite case. This occurs because there are fewer opportunities to "see" each target area (sample) during its specified windows. The system with one satellite does not meet the goal of acquiring 98 percent of desired samples during prescribed windows. This acquisition goal was set to minimize the sampling error for crop production forecasting.

With two satellites deployed and a swath width of 222 km (a 20 percent increase in nominal swath width) the mean percent of samples acquired is at the 98 percent level. All five test cases exceeded the 98 percent goal. With 3 satellites deployed, the mean percent of samples acquired globally was 99.3 with the nominal 185 km swath width. To achieve this performance level with 2 satellites, would require increasing the swath width to 300 km.

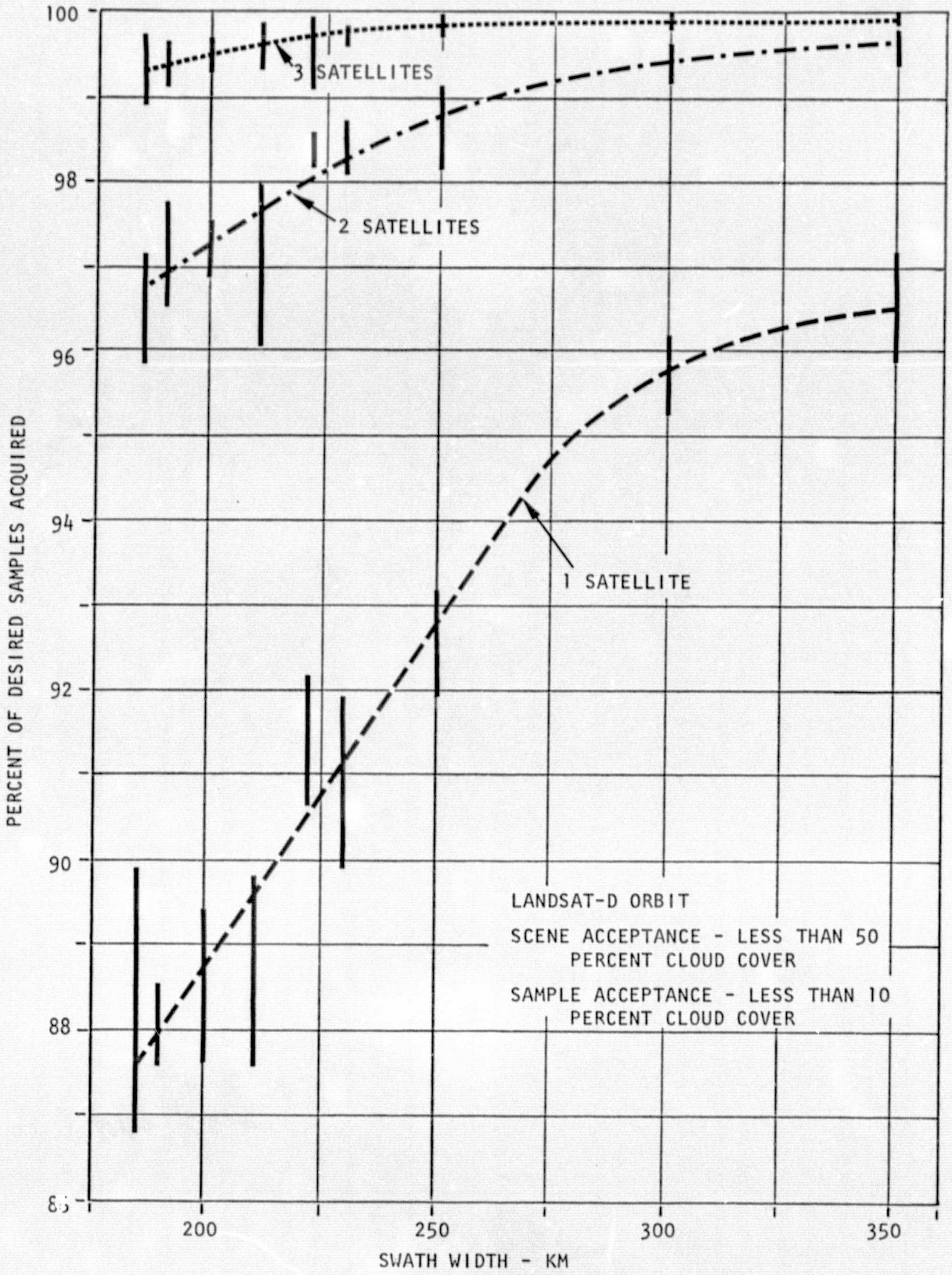



Figure 3. Percent of Samples Acquired Versus Swath Width with Landsat-D

In all three cases, the curves exhibit a knee beyond which increased swath width results in a lower rate of increase in the percent of samples acquired. The initial increase in swath width enhances the probability of acquiring missed samples in regions where acquisition is moderately difficult. Beyond this point, further increase does not appreciably enhance the probability of obtaining samples in regions which exhibit high cloud probability. The knees in the curves occur at approximately 285 km, 240 km, and 200 km swath width for 1, 2, or 3 satellites, respectively.

## 4.3 REGIONAL EFFECTS

While an operation GCPF system is concerned with regional requirements, global data is more meaningful for evaluation of most swath width trades. Regional data is pertinent for specific considerations. Additional regional studies can be performed as required. Because of the statistical variations introduced by clouds, the larger data sets available using the worldwide aggregation were chosen as the prime indicators of performances. Results from the previous studies (Ref. 3, 4) were used to the maximum extent possible. Those results for the 185 km swath for 20 simulations are reproduced in Figure 4. The targets, windows, and cloud conditions of this data correspond to the conditons required for this study. In this study, five simulations were used for each condition.

Two regions, Central China and Ganges India, were chosen for identifying regional effects. These regions represent difficult acquisition regions. Data was also analyzed for the Russian regions for comparison of effects for the easy regions. (A region is easy because of a combination of prevalent cloud conditions and overlap in coverage at polar latitudes.) The China-India two satellite data was averaged and plotted as a percent of targets acquired versus swath width.

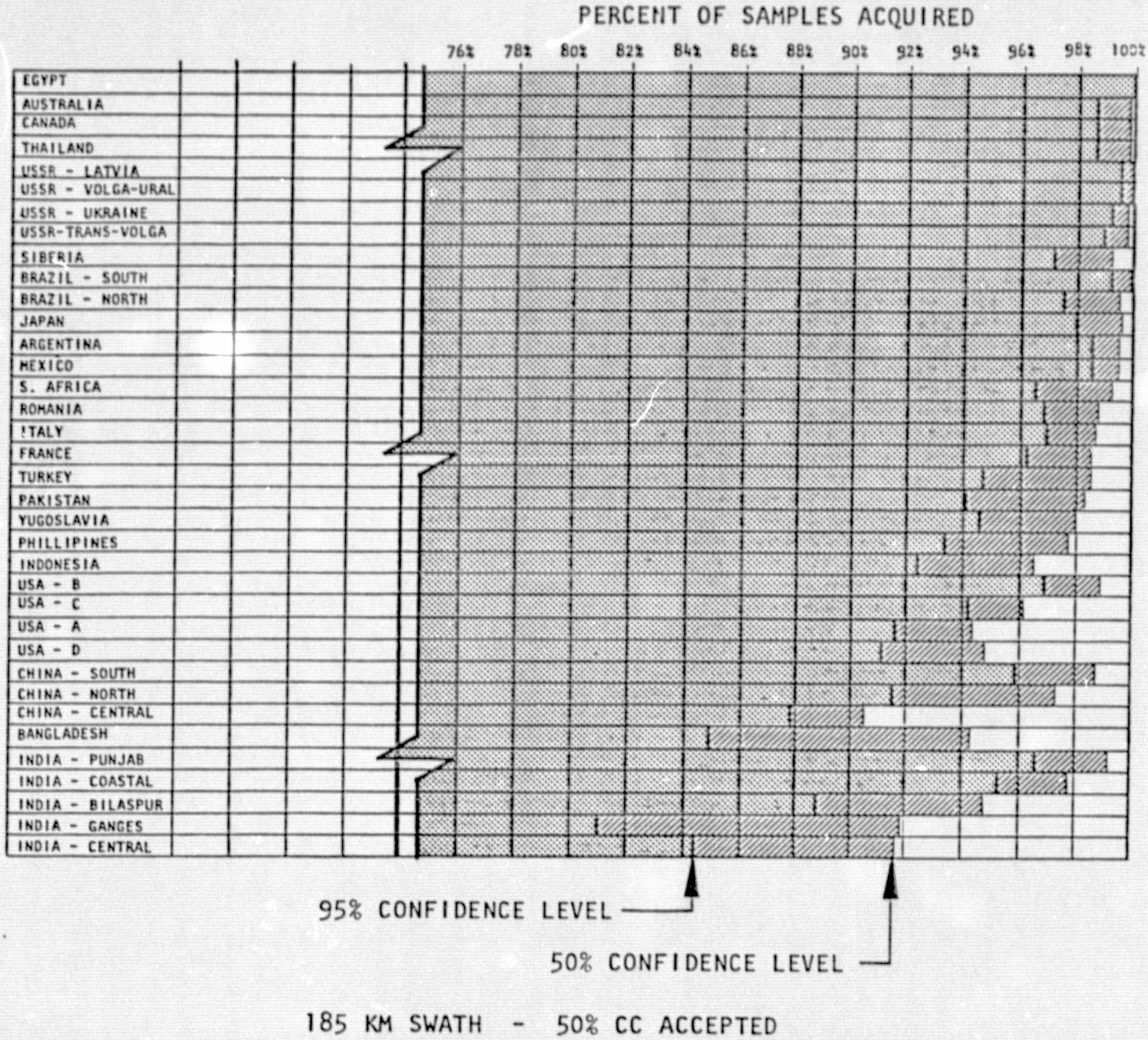



Figure 4. Percent of Samples Acquired with 2 Landsat Satellites

Note: This data reproduced from "Global Crop Production Forecasting--An Analysis of the Data Systems Problems and Their Solutions."

The data, as plotted on Figure 5, illustrates a linear relationship in the range from 185 to 250 km. This is consistent with the curves of Figure 3. A least squares curve fit of the data yields the equation below:

$$y = 72.30 + 0.1019x$$

where $y$ is the percent of targets acquired and
$x$ is the swath width in kilometers.

The realistic variations in cloud coverage causes a wide variance in the data for any particular region and swath width. This is a result of the comparatively few target windows in a region (120 for Central China, 212 for Ganges India). For the basic study of swath width effects, the use of global data with 2926 target windows is more illustrative. When an analysis of the data is performed for determining regional effects, it is necessary to perform some averaging or smoothing. To illustrate how the data of Figure 5 was obtained, the data from the individual regions is presented in Table 4. The mean of 5 runs, plus the minimum and maximum is presented. This data is plotted in Figures 6 and 7. A visual "best fit" curve is drawn that exhibits similar characteristics to the global curves of Figure 3.

Because of the frequent observations encountered at the higher latitudes due to overlap, there is little benefit from increased swath width. Two satellite data from the five Russian regions is presented in Table 5 to illustrate this phenomena.

## 4.4 EFFECT OF REDUCING THE REPEAT CYCLE

The previous sections show that increased swath width does provide a benefit in terms of the percent of target areas for which cloud free image data is obtained. It was also noted that beyond a certain point, the incremental benefit fell off. This occurred becasue further increase in swath width did not provide additional viewing opportunities for targets in the non-overlap regions at the lower latitudes. These regions also correspond with areas of high clould persistence. To maximize the probability of obtaining desired samples from all regions, it requires increasing the number of

Note: This data was plotted using the interactive capability of DSDS. The data points were truncated to permit a straight line curve fit. A flattening occurs at wider swath widths as exhibited by Figures 6 and 7.

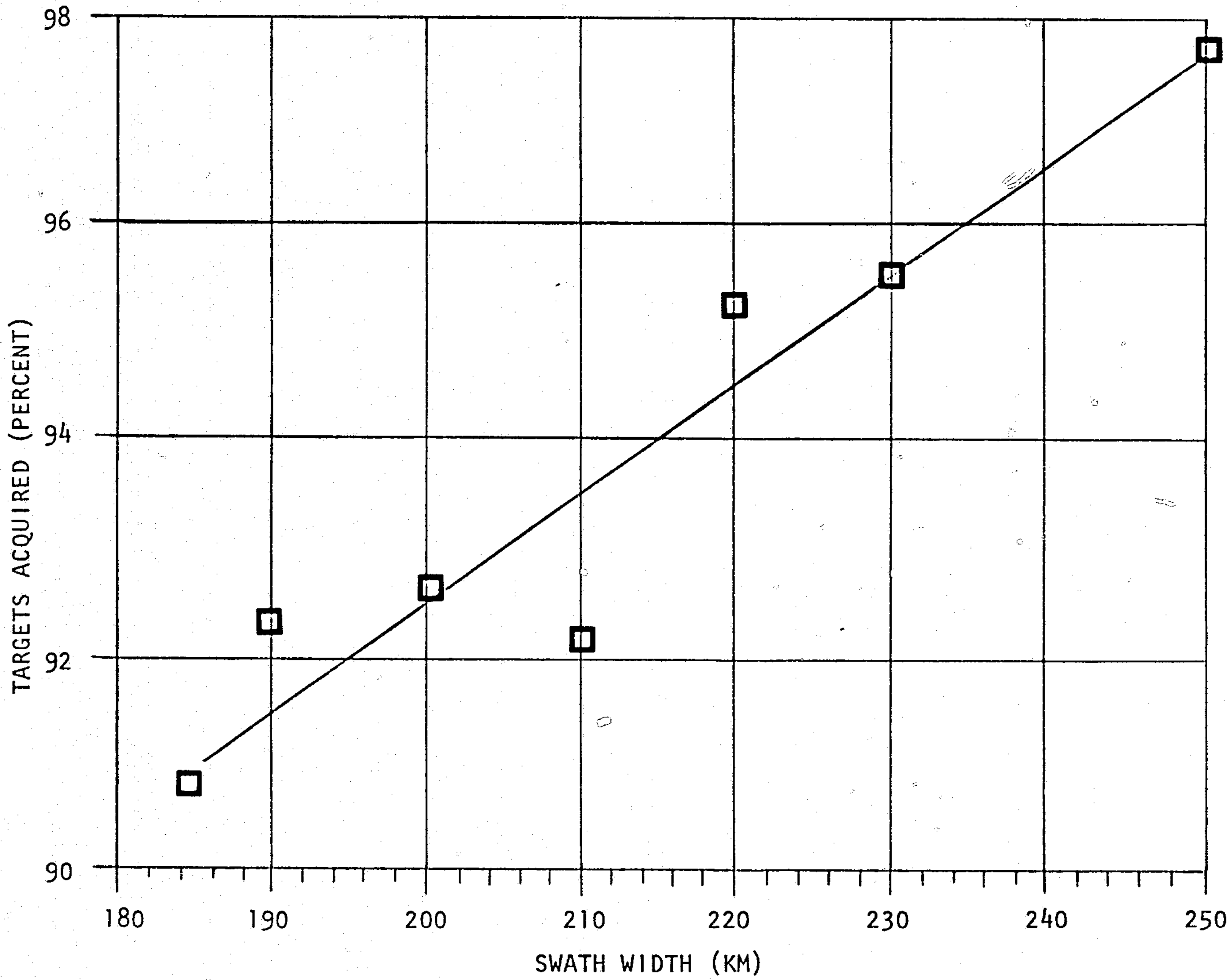



Figure 5. Mean Acquisition for Central China and Ganges India

Table 4. Unsmoothed Data for Central China and Ganges India

| SWATH WIDTH KM | PERCENT OF SAMPLES ACQUIRED | | | | | | |
|---|---|---|---|---|---|---|---|
| | CENTRAL CHINA | | | GANGES INDIA | | | AVERAGE |
| | MINIMUM | MAXIMUM | MEAN | MINIMUM | MAXIMUM | MEAN | |
| 185 | 90.8 | 95.0 | 93.0 | 83.0 | 94.3 | 88.5 | 90.75 |
| 190 | 90.0 | 94.2 | 92.3 | 84.0 | 97.2 | 92.2 | 92.25 |
| 200 | 87.5 | 95.8 | 92.3 | 87.7 | 98.6 | 92.8 | 92.55 |
| 210 | 91.7 | 95.8 | 93.7 | 76.4 | 93.9 | 90.6 | 92.15 |
| 222 | 94.2 | 96.7 | 94.8 | 94.3 | 96.7 | 95.4 | 95.10 |
| 230 | 92.5 | 96.7 | 94.6 | 93.9 | 98.1 | 96.4 | 95.50 |
| 250 | 92.1 | 99.2 | 98.2 | 91.5 | 99.1 | 97.1 | 97.65 |
| 300 | 98.3 | 100.0 | 99.2 | 95.3 | 99.5 | 97.8 | 98.00 |
| 350 | 98.3 | 100.0 | 99.3 | 97.6 | 100.0 | 99.2 | 99.25 |

Table 5. Average Acquisition for Five Runs for Russia

| SWATH WIDTH KM | LATVIA | UKRAINE | TRANSVOLGA | VOLGA-URAL | SIBERIA | AVERAGE |
|---|---|---|---|---|---|---|
| 185 | 100.0 | 99.8 | 99.3 | 99.8 | 99.1 | 99.65 |
| 190 | 99.6 | 100.0 | 99.6 | 100.0 | 98.7 | 99.65 |
| 200 | 100.0 | 100.0 | 99.8 | 100.0 | 98.7 | 99.80 |
| 210 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.00 |
| 222 | 100.0 | 100.0 | 99.8 | 99.8 | 99.6 | 99.85 |
| 230 | 100.0 | 100.0 | 100.0 | 100.0 | 99.6 | 99.85 |

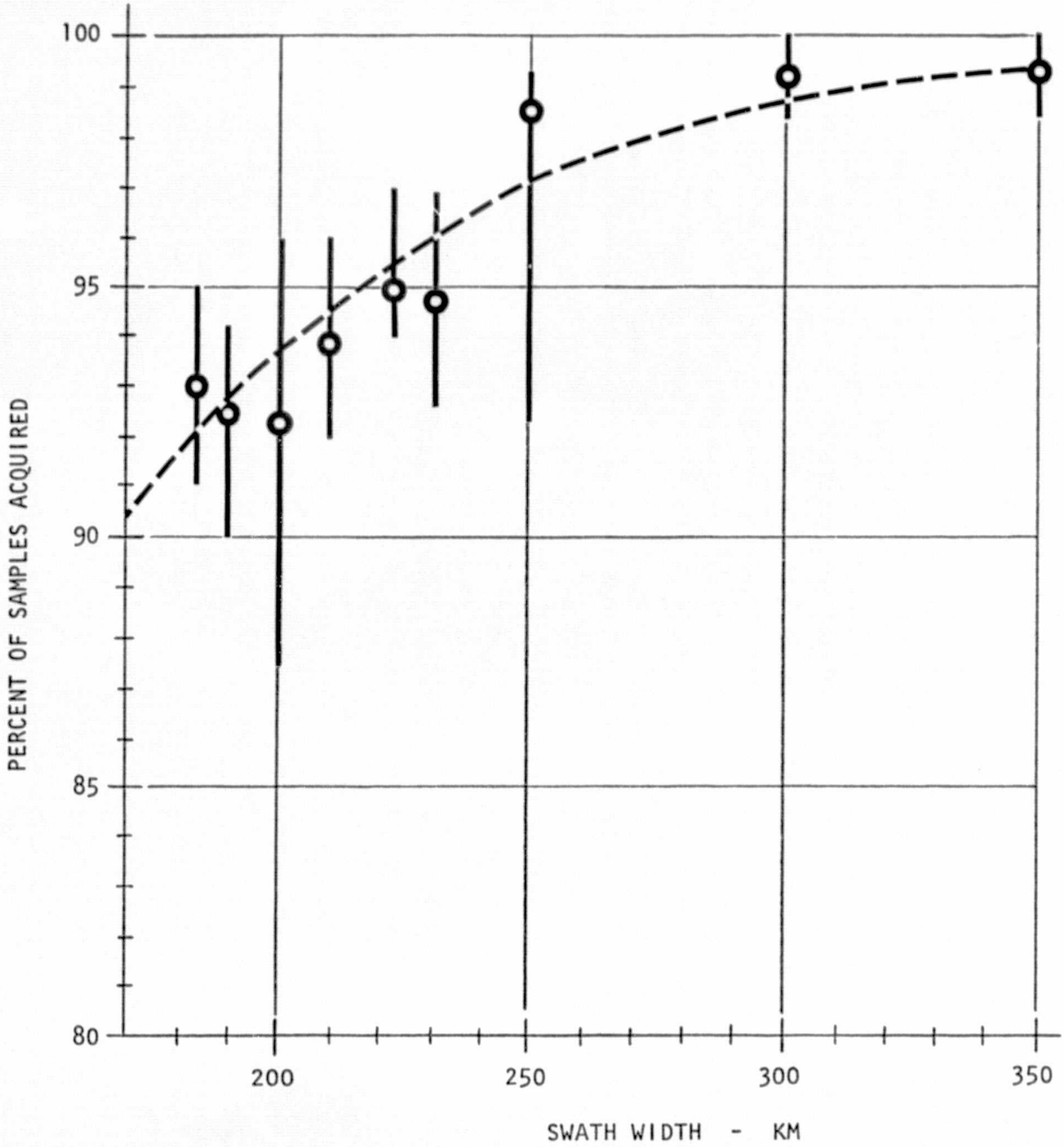



Figure 6. Percent of Samples Acquired for Central China with 2 Landsat-D Satellites

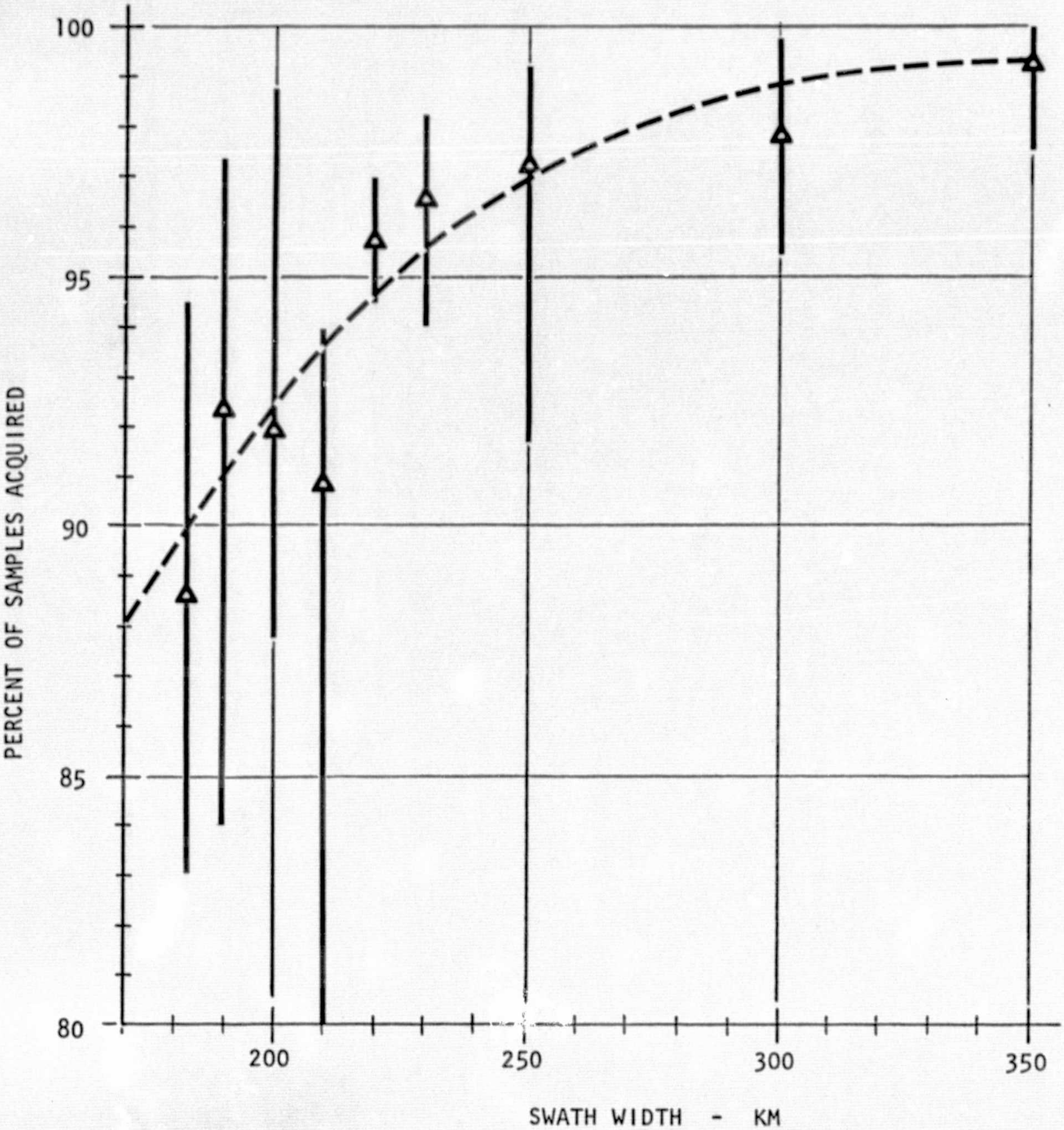



Figure 7. Percent of Samples Acquired for India-Ganges with 2 Landsat-D Satellites

viewing opportunities for all regions regardless of latitude. This can be accomplished by reducing the orbit repeat cycle.

The effect of increased swath width as a function of latitude for the Landsat-D orbit is shown on Figure 8.

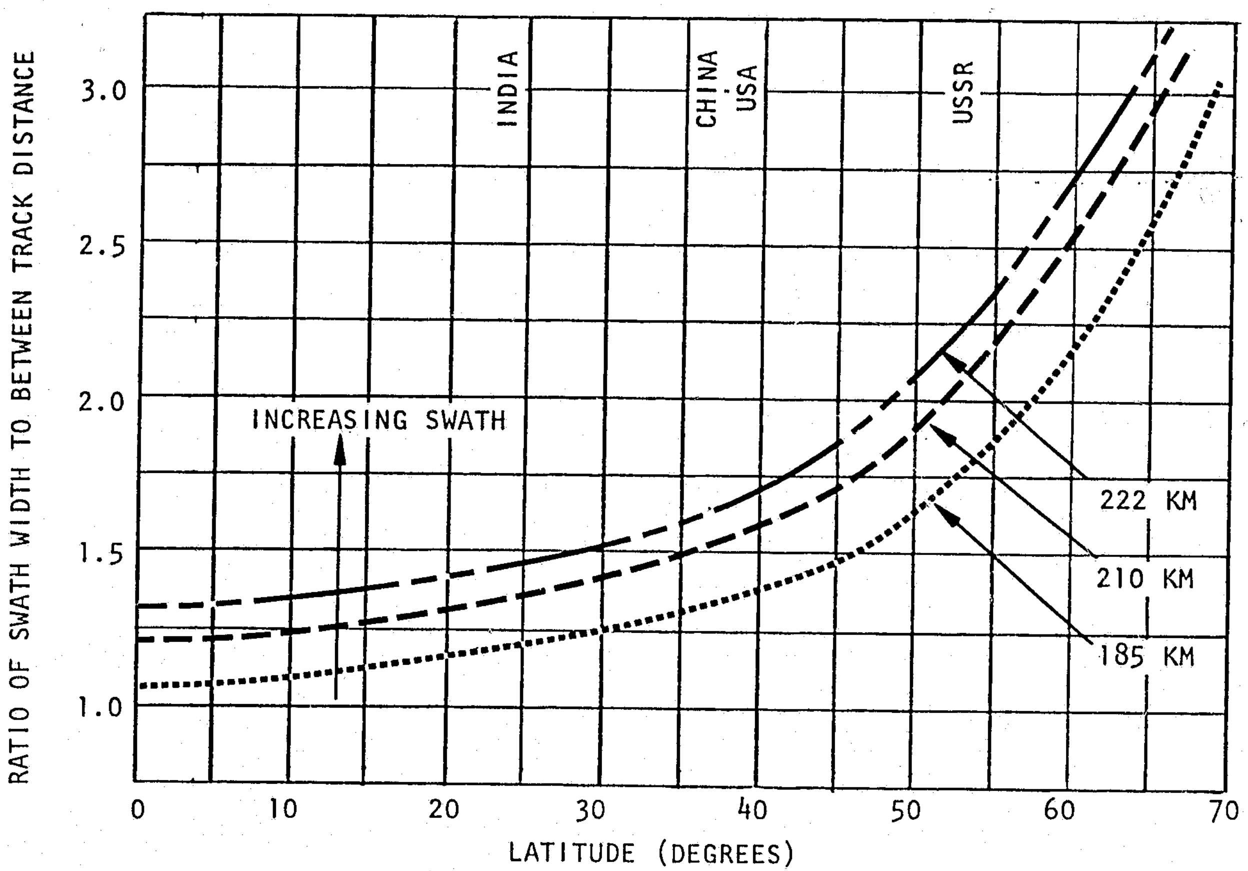



Figure 8. Ratio of Swath Width to Between Track Distance as a Function of Latitude for Landsat-D

The ratio of swath width to the distance between adjacent ground tracks was calculated as follows:

$$R_S = \text{Ratio of Swath Width to between track distance} = \frac{N*SW}{C_E \cos\theta}$$

where: $N$ = Number of orbits per repeat cycle = 233 (for Landsat D)

$SW$ = Swath Width

$C_E$ = Equatorial Circumference of Earth = 40075.2 km

$\theta$ = Latitude

The percent of overlap versus latitude is then simply:

$$\% \text{ Overlap} = 100*(R_S-1)$$

Also shown on Figure 8, are the mean latitude for the crop growing regions of USSR, USA, China, and India. The percent of overlap at the equator and for the median crop growing regions of India and the USSR are listed in Table 6.

Table 6. Parameter Affecting Coverage at Selected Crop Regions

| SWATH WIDTH | % INCREASE IN SWATH WIDTH | PERCENT OVERLAP | | |
|---|---|---|---|---|
| | | EQUATOR | INDIA | USSR |
| 185 | 0 | 7.5 | 18.0 | 76.7 |
| 210 | 13.5 | 22.1 | 34.0 | 99.2 |
| 222 | 20.0 | 29.1 | 41.7 | 112.0 |

With 185 km swath width, the Landsat-D provides 7.5% overlap at the equator, 18% for India and 76.7% for USSR. A 13.5% increase in swath width provides total overlap for USSR whereas only 1/3 of the area of India receives overlap coverage.

Increasing the swath width doubles the number of observations for targets in the overlap area but does not benefit the targets in the non-overlap area. If increased swath width is used with a modified orbit to reduce the repeat cycle, all target areas benefit equally. That is, with a 42-day observation window, a 14-day repeat cycle provides a minimum of 3 observations for all targets whereas with a 16-day repeat cycle 3/8's of the targets are only covered twice. To evaluate the benefits obtained from a reduced repeat cycle, two 14-day repeat orbits were evaluated. The parameters for the two orbits are listed in Table 7 with the corresponding parameters for the 16-day repeat Landsat-D orbit. The orbital parameters were determined using the methods proposed by King (Ref. 10). For all cases, the inclination angle was set to obtain a sun-synchronous orbit.

The ratio of swath width to the distance between adjacent satellite ground tracks as a function of latitude is shown in Figure 9 for the 14-day repeat orbit at 771 km. With a 185 km swath width, this orbit will not provide total coverage at the equator. If the swath width is increased to 222 km, there is 11.4% overlap at the equator and 22% and 83% overlap, respectively, for India and the USSR.

Table 7. Parameter for Orbits Studied

| PARAMETER | ORBIT | | |
|---|---|---|---|
| Nominal Altitude (km) | 704 | 771 | 867 |
| Repeat Cycle (days) | 16 | 14 | 14 |
| Repeat Cycle (orbits) | 233 | 201 | 197 |
| Swath Width Required for 5% Overlap at Equator (km) | 180 | 209 | 214 |
| Period (seconds) | 5933 | 6018 | 6140 |
| Ground Trace Velocity (km/sec) | 6.87 | 6.77 | 6.64 |
| Inclination (degrees) | 98.2 | 98.5 | 98.9 |
| Resolution with Standard T.M. Optics (meters) | 30 | 32.9 | 37 |
| Other | Landsat-D | | Min-Drift |

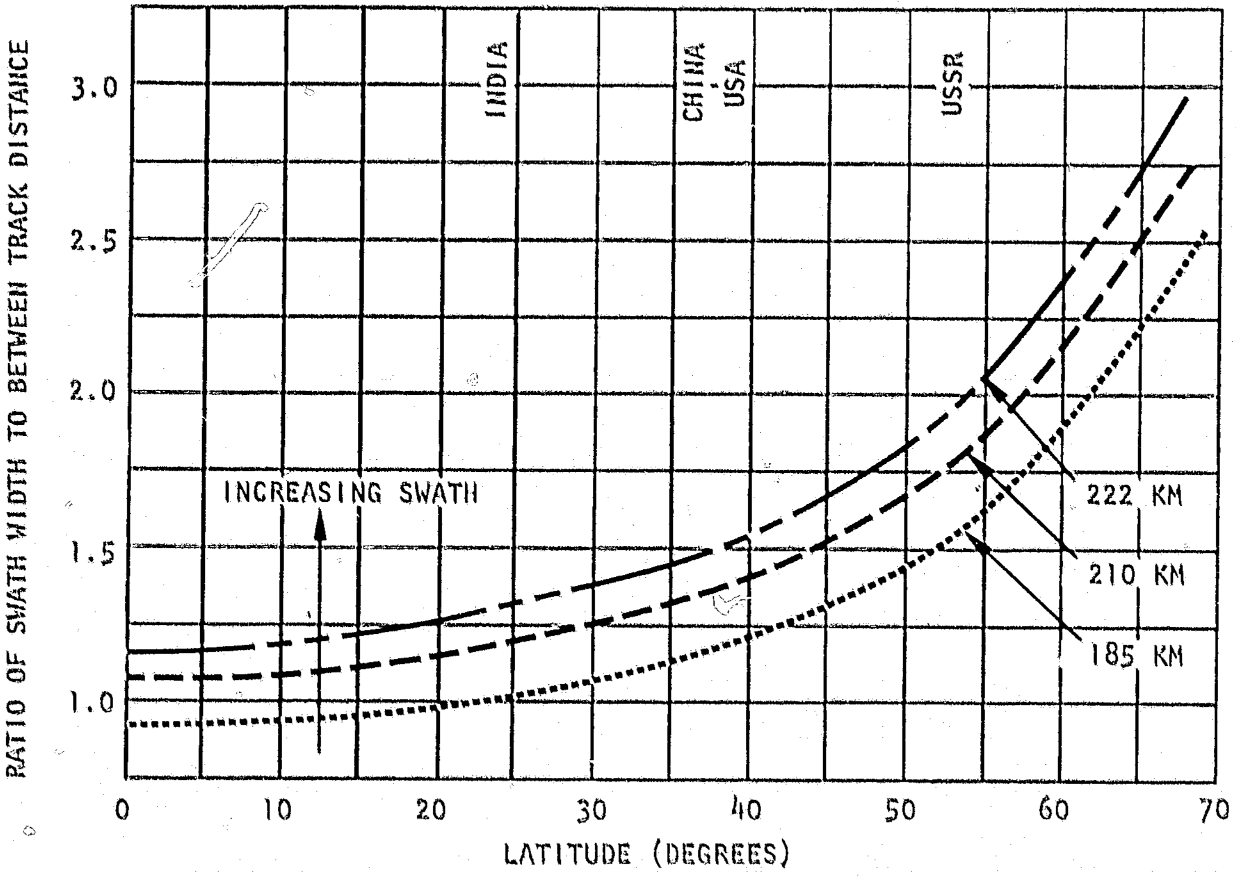



Figure 9. Ratio of Swath Width to Between Track Distance as a Function of Latitude for 771 KM Orbit

The theoretical viewing opportunities for India and USSR are presented in Table 8 for the following conditions:

- 14 and 16-day repeat cycles
- 42-day observation period
- Swath width of 185, 210, and 222 km
- 200 target areas in each country

For each case, the targets are divided into groups based on the number of observations they would have during a 42-day window considering both the probability of observation based on overlap as a function of latitude and the ratio of the observation period to the repeat cycle. With a 14-day repeat cycle, all targets in both regions have at least 3 viewing opportunities regardless of sensor swath width. With a 16-day repeat cycle, even with the swath width increased to 222 km, there are 44 targets (22%) in India that only have two viewing opportunities during the window. Under the same conditions, because the overlap exceeds 100%, there are 15 targets in the USSR with 9 viewing opportunities.

Table 8. Coverage Comparison for India and USSR

| | | | 14-DAY REPEAT CYCLE | | | | 16-DAY REPEAT CYCLE | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | WITHOUT OVERLAP | 185 SWATH | 210 SWATH | 222 SWATH | WITHOUT OVERLAP | 185 SWATH | 210 SWATH | 222 SWATH |
| PERCENT OVERLAP | | | 0 | 2 | 15 | 22 | 0 | 18 | 34 | 42 |
| INDIA | NUMBER OF OBSERVATIONS | 2 | | | | | 75 | 61 | 50 | 44 |
| | | 3 | 200 | 196 | 170 | 156 | 125 | 103 | 83 | 73 |
| | | 4 | | | | | | 14 | 25 | 31 |
| | | 5 | | | | | | | | |
| | | 6 | 0 | 4 | 30 | 44 | | 23 | 42 | 52 |
| TOTAL OBSERVATIONS | | | 600 | 612 | 690 | 732 | 525 | 622 | 701 | 742 |
| PERCENT OVERLAP | | | 0 | 52 | 73 | 83 | | 77 | 99 | 112 |
| USSR | NUMBER OF OBSERVATIONS | 2 | | | | | 75 | 17 | 1 | 0 |
| | | 3 | 200 | 96 | 54 | 34 | 125 | 29 | 1 | 0 |
| | | 4 | | | | | | 58 | 74 | 66 |
| | | 5 | | | | | | | | |
| | | 6 | 0 | 104 | 146 | 166 | | 96 | 124 | 119 |
| | | 7 | | | | | | | | |
| | | 8 | | | | | | | | |
| | | 9 | | | | | | | | 15 |
| TOTAL OBSERVATIONS | | | 600 | 912 | 1038 | 1098 | 525 | 929 | 1045 | 1113 |

If the system requirement is for one cloud free observation during the window, as for GCPF, the additional opportunities in the USSR have a much lower probability of providing needed information than do the additional opportunities gained in India by going to a 14-day repeat cycle.

In both countries, when considering the same swath width, there are more total observations for the 16-day repeat orbit. The 16-day repeat orbit has a shorter orbital period and completes approximately 9 additional orbits during the 42-day window.

## 4.5 TARGETS OBTAINED USING A REDUCED REPEAT CYCLE

Simulation runs were made to compare the 14-day and 16-day repeat orbits on the basis of the percent of desired samples obtained. The conditions simulated were:

- o Orbital altitude - 771 km and 867 km
- o Number of satellites - 2
- o Five 1-year runs
- o Scene acceptance - less than 50% cloud cover
- o Sample acceptance - less than 10% cloud cover
- o Swath width - 210 and 222 km

The results obtained for the 771 km and 867 km orbits are plotted on Figure 10. Also shown are the corresponding curves for the 2 and 3 satellite 704 km Landsat-D orbits. The 771 km and 867 km orbits were only run for two swath widths. It was assumed that the shape of the curves would be the same as the 704 km orbit. The 771 km and 867 km orbits require a minimum swath width of 209 km and 214 km, respectively, to achieve 5% overlap at the equator. Thus, the curves for these orbits are only plotted for swath widths greater than these values.

If the swath width for the 704 km Landsat-D orbit is increased by 20% (to 222 km), the percent of targets for which cloud free samples are obtained increases from 96.67% to 98%. This reduces the percent of samples missed from 3.33% to 2% which represents a 40% reduction. The results also indicate that an incremental benefit can be achieved by using the 771 km 14-day repeat orbit regardless of swath width. With a 222 km swath width, the 771 km orbits provide a 46% reduction in the percent of samples missed when compared with the nominal Landsat orbit. In addition to providing additional reduction in the percent of samples missed for a given swath width, the 771 km orbit also provides total coverage every 7 days when two satellites are deployed. This provides a significant benefit from an operational standpoint. Since reports are generally issued on a weekly or biweekly basis, each update would contain data from all areas of the world. This would reduce any bias caused by a lack of data from areas not covered by a longer repeat orbit.

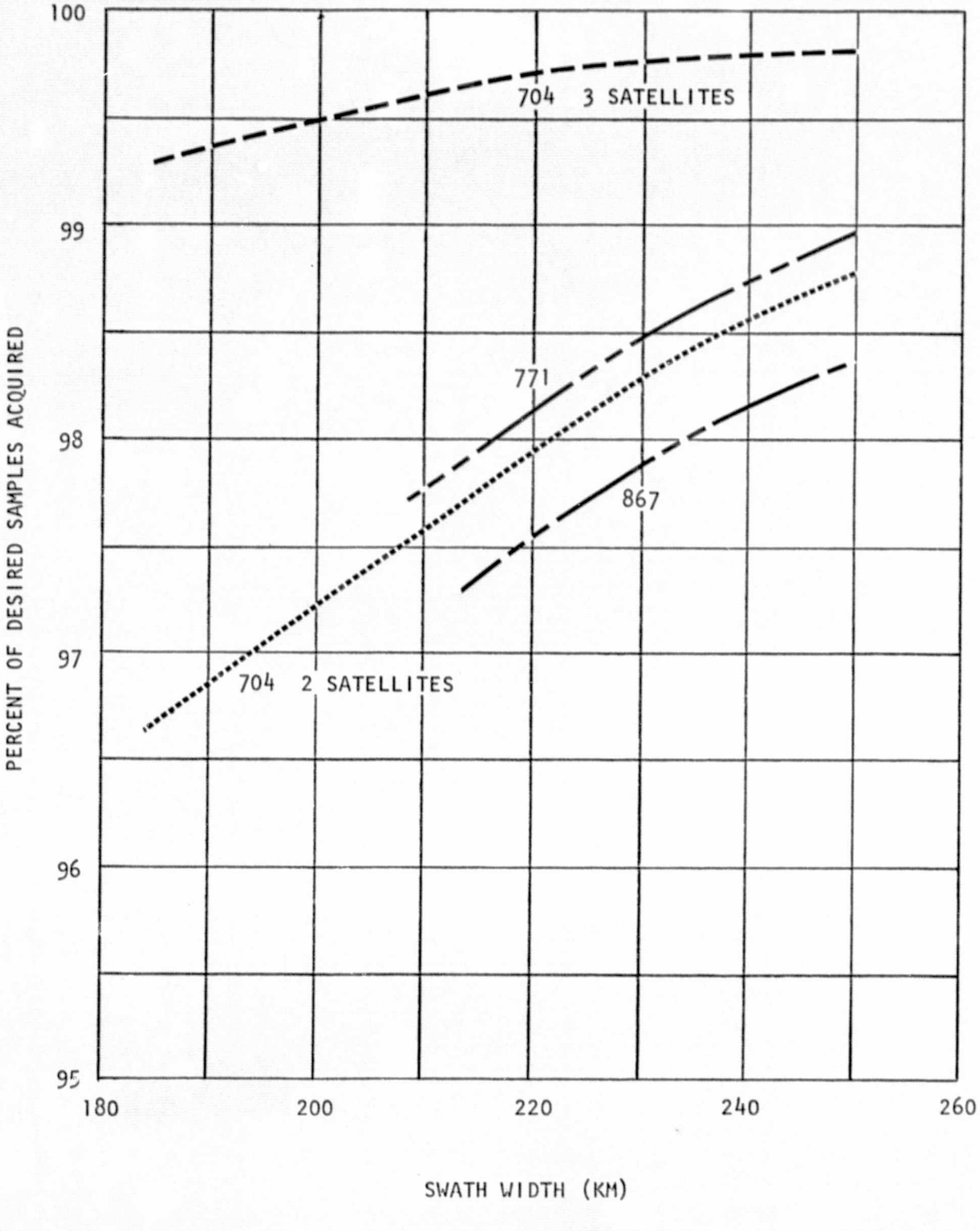



Figure 10. Comparison of 14 and 16-Day Repeat Orbits

The 867 km minimum drift orbit did not perform as well as the other orbits. To match the performance of the 704 km orbit, the 867 km orbit would require a 13% wider swath.

The results of the 771 km orbit on regional acquisition was analyzed using two satellite data for Central China and Ganges India. The partially smoothed data is presented in Table 9. Considerable smoothing is required to draw any inference from so few data points involving such wide variances as result from cloud conditions. The regional data from the previous study (Ref. 3) is in Column A. Since it was the result of 20 runs, it more nearly reflects the true mean than the results from only 5 runs. A comparison of Columns B and A provides an appreciation for the statistical variations that can be expected. One method of decreasing the variations is to increase the base by combining both sets. This combined set is the average in row 3. The average percent acquisition for the 704 km orbits are in entry B3, C3, and D3. They exhibit increasing benefits at the regional level consistent with the global level. Caution must still be exercised because of the wide variance due to the still small populations. A qualitative comparison of the data in E3 and E3 to C3 and D3 indicates improvement at the regional level for the 771 km orbit. An average of the 210 km and 222 km swath data yields an acquisition of 92.4% for 704 km and 94.0% for 771 km. This is only a 1.7% increase. However, keeping in mind the requirement for high acquisition is to reduce sampling errors from missed samples. The 771 km orbit provides a 21% reduction in the samples missed for the difficult regions.

Table 9. Two Satellite Data Comparing 704 km and 771 km Orbit Effects on Central China and Ganges India

| COLUMN → | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| | PREVIOUS STUDY (20 RUN AVERAGE) | PRESENT STUDY (5 RUN AVERAGE) | | | | |
| ROW | 704/185 | 704/185 | 704/210 | 704/222 | 771/210 | 771/222 |
| 1 CENTRAL CHINA | 90.4 | 93.0 | 93.7 | 94.8 | 95.0 | 93.7 |
| 2 GANGES-INDIA | 91.8 | 88.5 | 90.6 | 95.4 | 93.2 | 94.2 |
| 3 AVERAGE | 91.1 | 90.8 | 94.1 | 95.1 | 94.1 | 94.0 |

ORBIT/SWATH IN KILOMETERS - ACQUISITION IN PERCENT

If a new sensor is designed for this application, further reduction in repeat cycle should be considered. Each reduction in repeat cycle requires an increase in swath width which is inversely proportional to the reduced repeat cycle. Also, a reduction below the 14-day repeat cycle negates the advantage of having total coverage on a weekly basis with two satellites.

The alternatives for achieving increased swath width for each orbit and the associated penalties are discussed in the next section.

## 4.6 CHALLENGES OF WIDER SWATH SENSORS

Challenges are encountered because of the costs of developing and testing, performance degradation, and operational difficulty. An approach to selecting alternatives is to consider incremental penalties for deviations from a given baseline. In this study, trade-offs involved in increasing the Thematic Mapper swath width from the currently planned 185 km are considered.

The development of a totally new sensor system, a linear array, is also considered in a cursory manner. It will require a greater amount of testing and space qualification than will a modification. However, it will overcome several of the difficulties that are analyzed in the following paragraphs.

### 4.6.1 THEMATIC MAPPER BASELINE

As an aid to understanding the challenges encountered and an assessment of the trade-offs involved in increasing the Thematic Mapper swath width, the current design (Ref. 11) is summarized.

The Thematic Mapper is a whisk broom type scanning sensor system that produces a strip image of the earth in seven spectral bands as shown in Table 10. The princiapl uses (Ref. 12) of each band are also identified. The IFOV is 30 meters with eight (8) bits of digitized quantization levels. The characteristic parameters of the Thematic Mapper (Ref. 11) are reproduced in Table 11. An oscillating mirror provides a sweep of 7 bands

Table 10. Thematic Mapper Spectral Bands

| BAND | TYPE | BAND LIMITS, MICROMETERS | TYPE | PRINCIPAL SENSITIVITY |
|---|---|---|---|---|
| 1 | Si | 0.45 - 0.52 | BLUE | CAROTENOID CONCENTRATIONS |
| 2 | Si | 0.52 - 0.60 | GREEN | CHLOROPHYLL |
| 3 | Si | 0.63 - 0.69 | RED | CHLOROPHYLL |
| 4 | Si | 0.76 - 0.90 | NEAR IR | BIOMASS |
| 5 | InSb | 1.55 - 1.75 | IR | MOISTURE STRESS |
| 6 | HgCdTe | 10.4 - 12.5 | FAR IR | MOISTURE STRESS |
| 7 | N/A | 2.08 - 2.35 | IR | THERMAL, GEOLOGY, POSSIBLY YIELD |

Table 11. Thematic Mapper Characteristic Parameters

| | | | |
|---|---|---|---|
| ORBIT | | TELESCOPE | |
| o Type | Sun Synchronous | o Type | Ritchey-Chretien |
| o Altitude | 705 KM | o Effective Focal Length | 96 In. |
| o Orbit | Near Polar | o Optical Diameter | 16 In. |
| o Earth Coverage | 16-Day Period | o Aperture Stop | f/6.0 |
| o Swath Width | 185 KM | o Optics | All Mirror Surfaces |
| o Resolution | 30 M (Visual)<br>120 M (IR) | SCAN MIRROR | |
| SCAN SYSTEM | | o Size | 21 In. x 16 In. Elliptical |
| o Type | Object Plane Mirror | o Material | Beryllium |
| o Scan Rate | 7.1 Hz | o Mirror Motion | $\pm 3.75^{\circ}$ |
| o Scan Angle | $\pm 7.5$ Deg | DETECTORS | |
| o Scan Efficiency | 85% | o Bands 1-5,7 | 16 per Band |
| o Mirror Motion | Bidirectional Scan | o Band 6 | 4 per Band |
| PHYSICAL | | DATA | |
| o Weight | 362 Lb. | o Type | High Speed Multiplex |
| o Length | 77 In. | o Data Rate | 84.5 MP BS |
| o Width | 24 In. | o Resolution | 8 Bit PCM |
| o Height | 39 In. | o Data Relay | TDRSS |
| o Electrical Power | 171 W. | | |

simultaneously as illustrated in Figure 11. Six of the bands are of primary interest for agricultural applications. A seventh infrared band was added at about 2.2 micrometers. Its use is not considered in the analysis of wider sensors for GCPF except data from this band is considered in communication bandwidth considerations.

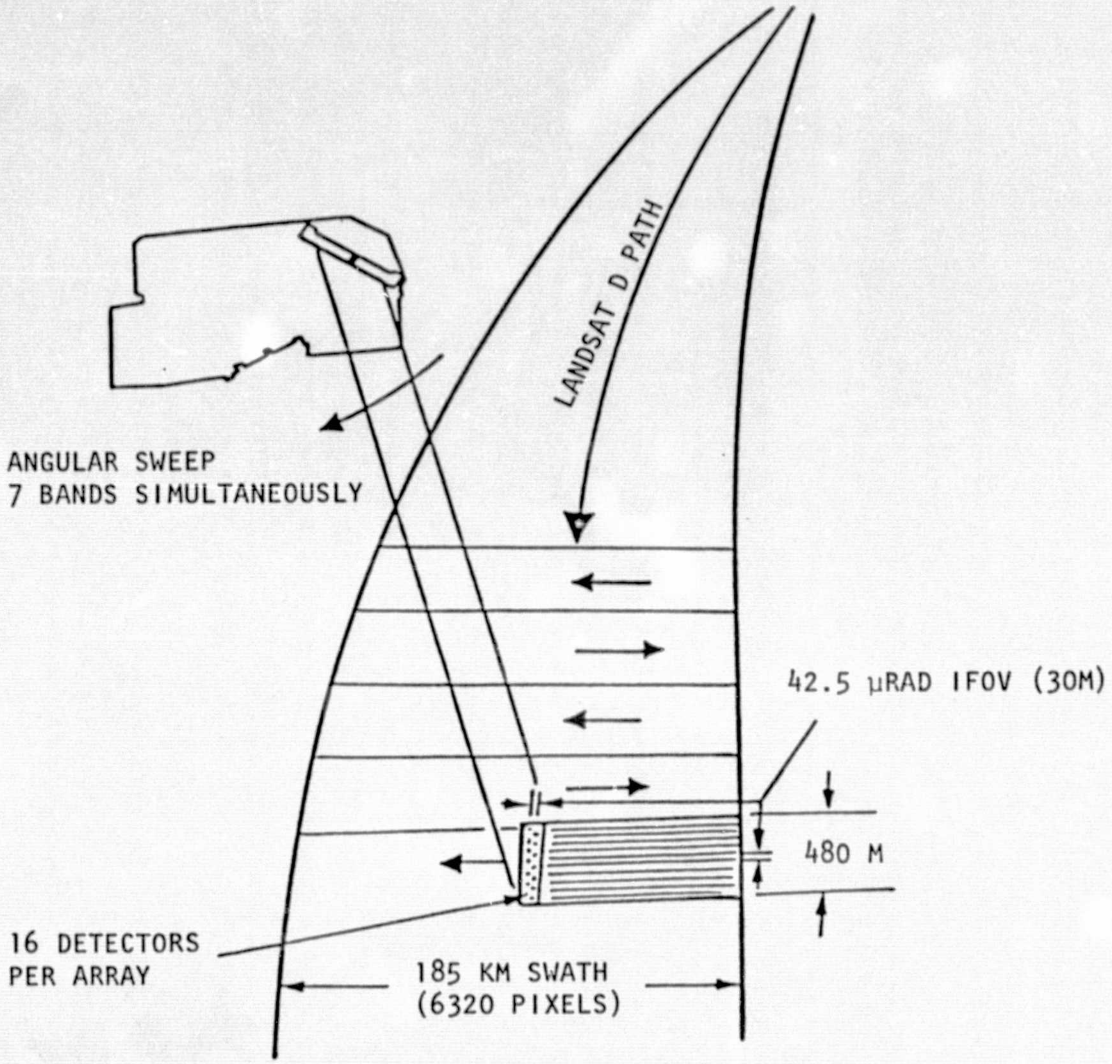



Figure 11. Thematic Mapper Mission Requirements

### 4.6.2 SWEEP TIME REQUIREMENTS WITH INCREASED SWATH

In this section, alternatives for achieving increased swath width for the 704 km Landsat-D orbit and the 771 km 14-day repeat orbit are discussed. For a given orbit, with a constant ground trace velocity, controlling the time per sweep is analogous to controlling the distance along track from the start of 1 sweep to the start of the next. The along track distance covered per sweep for a given orbit can only be changed by changing the number of sensor elements for each band. To maintain the 4:1 ratio in resolution between the visible bands and the IR band, only incremental increases of four sensor elements were considered in this analysis.

The sweep period must include time for mirror turnaround plus a scan time that increases linearly with swath width. For this analysis, the following conditions were assumed. The sensor materials used in the TM represent the state of the art in sensor development. Thus, the cross track scan time per pixel was held at 9.8 microseconds to maintain the radiometric resolution, quantization levels and signal to noise ratio specified for the TM. A minimum of 9.5 milliseconds is required for mirror turnaround. The mirror turnaround time is not a function of the scan angle because the mirror size increase is not significant.

The added scan time will be achieved either by increasing the number of sensor elements per band or by taking advantage of the decreased resolution of the 771 km orbit to provide both additional time between sweeps and additional width per pixel.

The achievable swath width is calculated in Table 12 for the following conditions.

- o Landsat-D orbit with the number of sensor elements per band increased from 16 to 20.
- o The 771 km orbit with the number of sensor elements per band increased from 16 to 20 with 30 meter resolution.
- o The 771 km orbit with the spatial resolution reduction caused by increased altitude (i.e., 32.85 meters/pixel).
- o The 771 km orbit with reduced spatial resolution and the number of sensor elements per band increased from 16 to 20.

Table 12. Increased Swath Width Alternatives

| | NOMINAL LANDSAT-D | LANDSAT-D 20 SENSORS PER BAND | 771 KM ORBIT 20 SENSORS PER BAND | 771 KM ORBIT 20 SENSORS PER BAND REDUCED RESOLUTION | 771 KM ORBIT 16 SENSORS PER BAND REDUCED RESOLUTION |
|---|---|---|---|---|---|
| NOMINAL ALTITUDE | 704 | 704 | 771 | 771 | 771 |
| SPATIAL RESOLUTION | 30 | 30 | 30 | 32.85 | 32.85 |
| GROUND TRACE VELOCITY (METERS/SEC) | 6870 | 6870 | 6770 | 6770 | 6770 |
| NUMBER SENSOR ELEMENTS/HI RESOLUTION BAND | 16 | 20 | 20 | 20 | 16 |
| ALONG TRACK TRAVEL/SWEEP (METERS) | 480 | 600 | 600 | 657 | 525.6 |
| SWEEP PERIOD (MILLI SEC) | 69.87 | 87.34 | 88.63 | 97.05 | 77.64 |
| MIRROR TURNAROUND TIME (MILLI SEC) | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |
| SCAN TIME/SWEEP (MILLI SEC) | 60.37 | 77.84 | 79.13 | 87.55 | 68.14 |
| SCAN TIME/PIXEL (MICRO SEC) | 9.8 | 9.8 | 9.8 | 9.8 | 9.8 |
| MAX. CROSS TRACK PIXELS | 6160 | 7943 | 8074 | 8933 | 6953 |
| ATTAINABLE SWATH WIDTH (KM) | 185 | 238 | 242 | 293 | 228 |
| SCAN ANGLE (DEGREES) | 15.0 | 19.2 | 17.9 | 21.6 | 16.9 |
| PERCENT OF TARGETS ACQUIRED WITH 2 SATELLITES | 96.65 | 98.5 | 98.8 | 99.3 | 98.4 |

For comparison, the values for the nominal 185 km swath Landsat-D orbit are shown in Column 1 of Table 12.

In each case:

Along Track Travel/Sweep = (Number Picture Element/Band)*(Spatial Resolution)

$$\text{Total Time/Sweep} = \frac{\text{Along Track Travel/Sweep}}{\text{Ground Trace Velocity}}$$

Scan Time/Sweep = Total Time/Sweep - Mirror Turnaround Time

$$\text{Max. Cross Track Pixels} = \frac{\text{Scan Time/Sweep}}{9.8\ \text{microseconds}}$$

Attainable Swath Width = (Max. Cross Track Pixels)*(Spatial Resolution)

$$\text{Scan Angle} = 2 * \text{Tan}^{-1}\ \frac{\text{Swath}/2}{\text{Altitude}}$$

Table 12 indicates that a swath width of up to 238 km can be achieved with the Landsat-D orbit if the number of sensor elements per band is increased from 16 to 20. The penalties associated with this change are increased weight, complexity, and data rate. These penalties are discussed in later paragraphs.

The swath width for the 771 km 14-day repeat orbit can be increased to 228 km by sacrificing the spatial resolution incurred by going from a 704 km orbit to a 771 km orbit, that is by allowing a picture element to increase approximately 10% on a side. In addition, the timing circuits would have to change because of the increased number of minor frames per major frame.

Also, if the number of sensor elements per band is increased from 16 to 20, the swath width for the 771 km orbit can be increased to 242 km with a 30 meter spatial resolution or to 293 km with a 32.85 meter spatial resolution. These changes would increase the weight, complexity, and data rate for the TM. In addition, changing the resolution from 32.85 meters back to 30 meters would require a change in the optical system. In all cases, there is an increased scan angle which would necessitate a mechanical repositioning of the scan mirror bumper assembly.

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*The asterisk is used to indicate multiplication.

## 4.7 PHYSICAL LIMITATIONS

There are physical limitations on the performance of a whisk broom sensor that limit the swath width obtainable. They are a result of the basic physics of sensing electromagnetic energy and converting it to a measurable quantity of electrical energy. A minimum quantity of light must fall on the element to produce a given amount of electrical current. The quantity of light required depends upon the photosensitive material, the frequency of the light, and the physical properties of the material.

Generally, a satellite-borne sensor will exhibit the following characteristics:

1. The output current is predictably related to the amount of light incident on the sensor element.

2. The physical size, weight, and power requirements of the sensor elements are modest and conform to restrictive budgets.

3. The amount of light needed for the operational range is reasonably attainable.

The above characteristics force a trade-off of sensor spectral resolution, radiometric resolution, spatial resolution, and physical complexity whenever swath width is increased. For a given light gathering geometry, radiometric resolution depends upon the sensitivity of the primary sensor material, the spectral frequencies accepted, and the signal to noise ratio of the system. It was a premise of this study that the Thematic Mapper design represents the state-of-the-art in primary sensor element manufacture. It was also assumed that the requirements for spectral resolution and radiometric resolution for which it was designed would have to be met by any modified sensor system. These assumptions and groundrules restricted the areas of trade-offs to obtaining increased swath width by either a sacrifice in spatial resolution or by increasing the sensor system complexity. An objective was to not sacrifice the planned 30 meter spatial resolution; however, some alternatives admitted minor degration of the parameter.

Within the limitation of size, weight, and power, certain increases in system complexity were subjected to trade-off analyses to optimize overall performance. These fall into three categories. One is to maintain the present resolution (spatial, spectral, and radiometric) by adding elements. Two is to maintain the present resolution for minor swath width increase by using some of the turnaround time for sensing additional pixels. The third category of alternatives is to accept a slight degradation in spatial resolution and achieve a slight increase in swath width by altering the orbital altitude.

Each of these alternatives have associated problems which required additional alternative trade-offs. The problems analyzed fall into six categories. They are 1) electronic complexity, 2) mirror size and inertia, 3) Maintenance of pixel aspect ratio, 4) communication bandwidth requirements, 5) scene dynamic radiometric range, and 6) ground processing complexities. They are summarized in Table 13 and discussed below.

Table 13. Trade-Study Alternatives

| SENSOR SYSTEM ALTERNATIVES |
|---|
| o More Elements |
| o More effective use of turnaround time |
| o Reduced spatial resolution |
| **PROBLEMS** |
| o Electronic complexity |
| o Mirror size and inertia |
| o Pixel aspect ratio |
| o Communication bandwidth |
| o Scene dynamic range |
| o Ground processing complexity |

### 4.7.1 INCREASE SENSOR ELEMENTS

This alternative maintains the spatial and radiometric resolutions of the current design with existing materials. Additional swath width is achievable by allowing additional time for each sweep. The ground-trace will advance further along track as the sweep time is increased so it is necessary to increase the along track coverage for each sweep. With this alternative, additional sensor elements for a total of n are used. Thus, instead of 16 elements, as in the Thematic Mapper, sweeping a ground swath of 480 meters, n elements will sweep a swath 30 times n meters according to the time required.

The implementation of this alternative for a whisk broom type scanner incurs the following disadvantages:

- It is a major design change
- It requires a change in data formats
- It requires increased communications bandwidth
- It requires more weight for the sensor system
- It requires more power to operate the system
- It requires more physical space for the sensor system

Any major design change incurs a substantial penalty in cost and schedule. There will be a small penalty in reliability because of the need for additional parts. Additionally, the data frame formatting would need modification to accommodate additional elements. This change will impact both the on-board formatting electronics and the ground processing software. The impact on the on-board electronics is minor but the effect upon ground processing depends upon the timing of any changes. Format changes after the currently planned system is implemented would have a major impact.

The impact upon communications bandwidth must be evaluated according to degree. Wider swath with no compromise in resolution requires more communication bandwidth. If the additional data is truly needed, then the bandwidth must be provided. The planned rate of 84.5 megabits per second is not at the limits of technology. Any increase in swath width should be modest to stay within the limits of available communications bandwidth. A guideline is to not exceed an instantaneous demand for more than 120 megabits per second. Within this guideline, a swath width of 275 km could be accommodated with 6 high resolution and 1 low resolution band while maintaining the currently planned resolutions. For additional swath width within the current communications bandwidth of 120 megabits per second, instantaneous compromise must be accepted. Some on-board data compression or tightly controlled data taking must be incorporated. Control on data taking may take the form of restricting the data to specific bands or portions of the total sweep. These alternatives are only suggested and are not evaluated here.

Any major increase in swath of a sensor system using a mechanical scan will require penalties in space, weight, and power requirements. These are primarily due to the need to provide the optics of rigid high quality to gather sufficient light. As the swath increases, so does the mirror angle and the need for a bigger mirror. The bigger mirror must have greater mass to maintain the needed rigidity and to provide reliable operations under repeated acceleration. Since this mechanical limitation is currently near the state-of-the-art for the Thematic Mapper, little additional sweep can be expected for this type sensor system.

The analysis of the alternative of providing increased swath while maintaining current resolution is summarized in Table 14. The conclusion of this analysis is any major increase such that a new development and qualification program would be required, is not practical. A minor increase of 20% or less will be investigated further.

### 4.7.2 USE SWEEP TIME MORE EFFECTIVELY

This alternative calls for data taking over a larger percentage of each sweep. If no sacrifices in radiometric resolution or signal to noise ratios are permitted and no improvement in the sensor element is postulated, any increase must come from the time used for calibration and mirror turnaround. However, the currently allotted time of 9.5 milliseconds for mirror turnaround appears to be the minimum that can be accepted using currently available mirror and mechanical materials. Thus, this alternative is not viable.

Table 14. Comparative Analysis of Adding Elements

| FEATURE/IMPACT | COMMENT | EFFECT |
|---|---|---|
| o MAINTAINS RESOLUTION | - MAJOR REASON FOR IMPLEMENTING | - VERY DESIRABLE |
| o INCREASE SWATH BEYOND 220 KM | - MAJOR DESIGN CHANGE | - FIRST COST ~50 MILLION DOLLARS |
| o INCREASED COMPLEXITY | - SLIGHT COST INCREASE<br>- SLIGHT RELIABILITY DECREASE | - NEGLIGIBLE |
| o INCREASED SIZE AND WEIGHT | - INCREASED PAYLOAD CAPACITY WILL ACCOMMODATE THIS PENALTY | - TOLERABLE |
| o INCREASED POWER | - PRIMARILY FROM INCREASE IN MIRROR SIZE FOR WHISK BROOM SCANNER | - PROBABLE LIMITING PARAMETER |
| o CHANGE IN FORMATS | - IMPACT PROPORTIONAL TO TIME DELAY IN IMPLEMENTING | - SERIOUS IMPACT ON USERS |
| o INCREASED COMMUNICATIONS BANDWIDTH REQUIREMENT | - MAY REQUIRE TEMPORARY SACRIFICE OF CHANNELS | - REDUCES COST ADVANTAGE OF USING WIDER SWATH SENSOR |

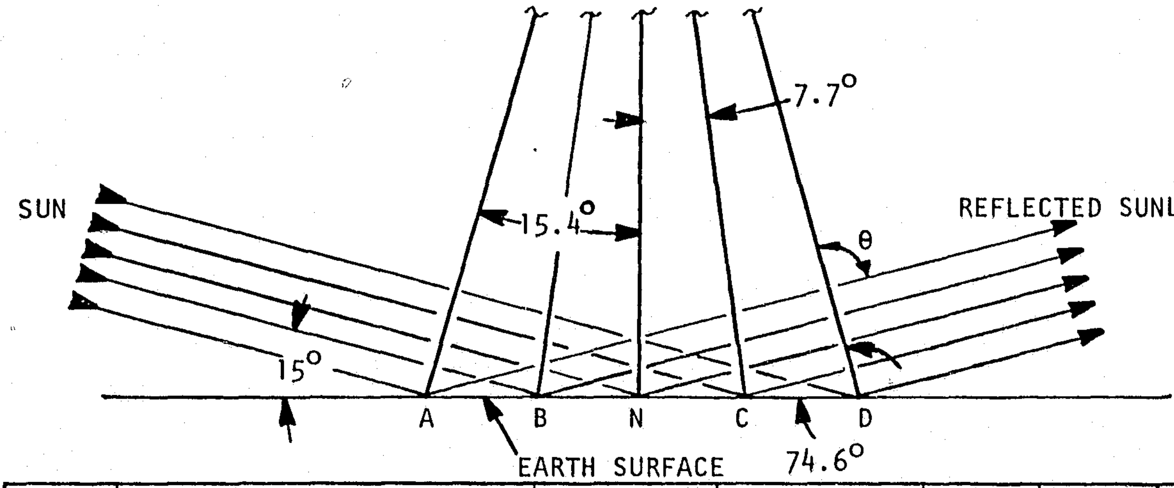
### 4.7.3 ACCEPT SOME REDUCTION IN SPATIAL RESOLUTION

This alternative is viable because it has a minimum impact on the current sensor design. It is only viable for a slight increase in effective swath width and is suggested only for a near term application pending future development of pushbroom type sensors. The parameters achievable with the Thematic Mapper flown at 771 km in a 16-day repeat cycle are listed in Table 12.

### 4.7.4 OTHER ALTERNATIVES

Another alternative for more effective use of the planned Thematic Mapper applies advances in ground processing capability to improve the signal to noise ratio and to minimize the scene dynamic range. Scene dynamic range is of particular concern as the swath width is increased. For the application of this analysis, a constant sun angle is postulated. This simplifies the considerations of scene dynamic range. The light reaching the sensor is all reflected from the sun's illumination. When the sensor is pointed toward the sun, the majority of the light is directly reflected off the earth's surface. When the sensor is pointed away from the sun, all of the reflected light is a result of scattered illumination, either from the atmosphere or surface roughness. The variation in the amount of light directly reflected as the sensor changes pointing direction from toward the sun to away from the sun is the biggest contributor to the scene dynamic range. Other contributing factors are the variation in the object reflections, and variation in atmospheric absorption. Clouds over a portion of a scene may cause shadowing.

The variations in directly reflected light resulting from the pointing direction of the sensor are illustrated in Figure 12 for a sensor scan angle of 15.4 degrees which corresponds to the planned Thematic Mapper design. Three cases are illustrated. Case 1 directs the scan towards the sun. Case 3 scans around nadir as do the sensors on Landsats 1, 2, and 3. Two important effects are influenced by the sensor pointing direction. One is the absolute signal strength and the other is the variation in signal strength across the scene. A large value of absolute signal strength is desirable as it allows better signal to noise ratios. A small value of scene dynamic range is desirable as it reduces the bandwidth required to quantize a given radiometric resolution.




| CASE | | LEFT ANGLE | RIGHT ANGLE | COSθL | COSθR | DELTA |
|---|---|---|---|---|---|---|
| 1 | NADIR TOWARDS SUN (A-N) | 59.6 | 75 | .506 | .259 | .247 |
| 2 | NADIR AWAY FROM SUN (N-D) | 75 | 89.6 | .259 | -.007 | .266 |
| 3 | AROUND NADIR (B-C) | 67.3 | 82.7 | .386 | .127 | .259 |

Figure 12. Relative Strength of Directly Reflected Signal (Signal exclusive of scattering is proportional to COSθ)

A comparison of these effects for the three cases favors case one. The absolute illumination available for case 1 is nearly twice that available for the around nadir scan pattern. The scene dynamic range is also reduced. A scan pattern away from the sun, as in case 2, is particularly undesirable because at the far edge of the scene all the illumination must originate from scattered light as evidenced by the negative cosine.

The penalty for scanning off nadir towards the sun is an increase in the geometric distortion at the scene edges. The amount of distortion increases with the distance away from nadir. The error at 92.5 km off nadir is approximately 15 meters for every 100 meters in elevation. This effect is illustrated in Figure 13. However, this effect can be compensated for by the use of terrain maps when performing geometric corrections. The Defense Mapping Agency currently has digitized data on the 1: 250000 scale maps for the entire United States which has been placed with the U.S. Geological Survey for archiving, maintenance, and dissemination. Several programs are underway to obtain digital terrain data for other countries as well as for the U.S. at a finer resolution (Ref. 13). With the advent of high speed pipe line processors, as are

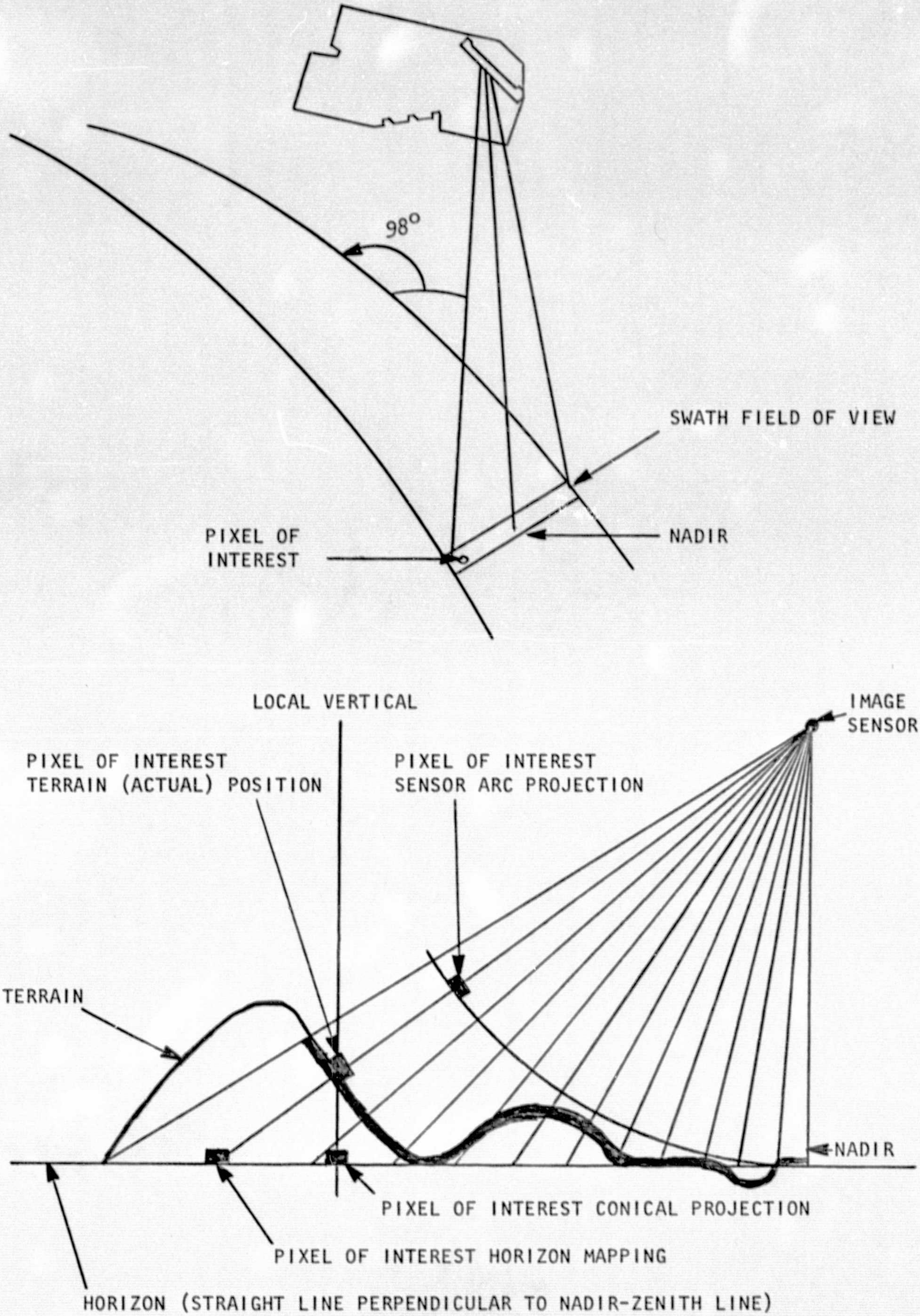



Figure 13. Terrain Distortion

frequently used for the geometric correction operation, this added complexity can be incorporated with a minimum impact on processing time (Ref. 14).

There is an additional consideration involved with toward the sun scanning and that is the so called "hot spot" occurring at the point of maximum reflection. While this region, when used exclusively, can provide additional information, it is troublesome, increasing the scene dynamic range when it appears as a spot in the larger image. However, for the swath widths attainable through the modifications previously discussed, this bright spot will fall outside the sensor field of view.

## 4.8 LINEAR ARRAY SENSOR

The previously discussed physical limitations are applicable to modifications of the planned Thematic Mapper. A more radical approach to obtaining wider swaths is to develop a totally new sensor system of the pushbroom type. Such a sensor would utilize an array of sensors across the entire width of the swath. Readout is accomplished by electronically scanning the array of sensors during the time the spacecraft advances one resolution element along track. The advantages of such a sensor system, which include better signal to noise ratio, geometric registration, light weight, low power, high sensitivity, and especially nonmoving optics are discussed by Thompson (Ref. 15).

While the technology of producing multispectral linear arrays is not as mature as for mechanical scanners, it is appropriate to consider it as an alternate to any major redevelopment to the Thematic Mapper. There are some peculiar processing problems, such as the need to radiometrically calibrate thousands of individual detector elements. However, this does not appear to be a significant problem. Tracy and Noll (Ref. 16) discuss the processing implications. They indicate the feasibility of accomplishing all the necessary processing in real time with the added benefits of better geometric stability and an increased dynamic range.

A brief survey of the literature (Ref. 12, 15, 16, 17, 18, and 19) indicates there is significant progress and acceptance of linear array sensor systems in the visible and near infrared spectrum. Further investigation directly with the major manufacturers of the detector arrays indicate that the technology of accomplishing the electronic readout is reasonably mature using Charge Coupled Devices (CCD) for sensors in the visible and near IR range. For most applications, the thermal IR (10.4 to 12.5 micrometers) band is very desirable (Ref. 12). The technology of interfacing CCD electronics to detectors sensitive to this band is not as mature; however, no technological breakthrough is required.

A preamp stage is required between the sensor and the CCD readout. Also, the current detectors operate in the photo resistive mode, requiring approximately one-milliwatt of bias power. It is also necessary to cool the detector to liquid nitrogen temperatures. For a single detector element, or small array, this poses no problem. However, when an array of 1500 elements is conducted, the bias power of one and one-half watts poses a difficult cryogenic cooling problem. With the advent of the shuttle space transportation system, this problem is directly solvable. An even more elegant solution that appears likely is the development of basic detectors for the thermal IR regions that operate in a photovoltaic mode, thus eliminating the requirement for bias current and the concomitant cryogenic cooling problems. The development of a thermal IR linear array is considered feasible by the major sensor system suppliers and an availability by 1985 is not unrealistic.

## 4.9 SELECTIVE DATA TAKING

An increase in swath width will result in an increased need for communications bandwidth. Various data compression schemes have been considered in an effort to minimize the communications bandwidth requirement. For Global Crop Production Forecasting, one of the most effective methods of data compression is to perform selective on-board sample extraction. This option is particularly viable for a new sensor development using electronic array scanning such as CCD implementation. The incorporation of such a feature would provide the flexibility of frequent revisit opportunity. While not quantitatively investigated during this study, the concept could employ a sensor with a swath width of three times the planned 185 km. This would allow a revisit opportunity every four days. A 185 km image could be selectively extracted from any portion of the swath with no increased communications bandwidth. If agricultural samples only were selected, the communications requirement would be considerably less. Such a system would meet the needs for GCPF with only one satellite.

## 5.0 DATA ACQUISITION COSTS

The total cost of data acquisition includes not only the cost of the data sensor system, but the non-recurring costs of the platform and support equipment and the operational costs. It is beyond the scope of this report to develop detailed cost breakdowns for the different sensor systems considered. What will be attempted is to compare the relative costs of five sensor systems using engineering judgments to obtain a rough order of magnitude cost for each major cost element. The hope is this approach will provide a vehicle of identifying the major differences in the costs of each approach. This will permit a reduction in choices and provide some guidelines for more detailed costing analyses of the recommended alternative.

The performance of the alternative sensor system was compared using the data plotted on Figure 3. The baseline for comparison is a three satellite system using Landsat-D type vehicles with Thematic Mappers as the basic sensor system. This was chosen because it was the only planned approach that acquired 98 percent of the desired targets with no modifications. This baseline is sensor system 1 in Table 14.

Each of the other alternatives is distinguished from the baseline system in using two instead of three satellites. The alternatives offer methods of meeting the agricultural objective of obtaining 98 percent of the desired targets. The tradeoffs are between costs and technical problems of modifying the sensor and the cost of obtaining and operating an additional satellite.

Table 15. Alternative Sensor Systems

| SENSOR SYSTEM | DESIGNATION | NO OF SATELLITES | SWATH WIDTH (km) | SIGNIFICANT FEATURES |
|---|---|---|---|---|
| 1 | Baseline | 3 | 185 | o Uses planned hardware with no modifications.<br>o Acquires over 98 percent of desired agricultural targets. |
| 2 | 14-Day Maintained Resolution | 2 | 242 | o Uses planned hardware with modifications.<br>o Acquires over 98 percent of desired agricultural targets, but not as many as system 1.<br>o Permits sizing of data processing facilities to weekly cycle.<br>o No sacrifice in spatial resolution. |
| 3 | 14-day Reduced Resolution | 2 | 228 | o Uses planned hardware with minor modifications.<br>o Acquires over 98 percent of desired agricultural targets, but not as many as system 2.<br>o Permits sizing of data processing facilities to weekly cycle.<br>o Spatial resolution sacrificed to 32.85 meters to minimize hardware modifications. |
| 4 | Wide Swath Thematic Mapper | 2 | 315 | o Performs as well as system 1 using two satellites.<br>o Requires major sensor system redesign. |
| 5 | Wide Swath Pushbroom Sensor | 2 | 315 | o Performs as well as system 1 using two satellites.<br>o Is a new sensor system.<br>o Avoids mechanical problems of system 4.<br>o Eliminates many problems of older technology of system 4. |

Alternate system 2 uses a Thematic Mapper modified to obtain a swath sufficiently wide to permit acquisition of 98 percent of the targets and to achieve total earth coverage for each satellite every 14 days. The significance of 14 days with 2 satellites is the data loading will repeat on a weekly cycle. The data processing system can be sized and operations involving personnel can be planned more efficiently when the loading can be determined on a weekly basis. This system maintains a 30 meter spatial resolution by the addition of sensor elements. Four elements are added to maintain coincidence with the low resolution sensor which requires one-fourth the number of elements as the high resolution bands.

Alternate system 3 uses a Thematic Mapper with a minimum of modifications. No additional elements are added to the sensor. The swath angle is maintained and a wider ground swath is achieved by using a higher altitude orbit. An orbit at 771 km provides 100 percent earth coverage in a sun-synchronous orbit that repeats every 14 days. This swath width of 228 km does not acquire as many targets as system 2, but it does meet the 98 percent goal. This higher altitude orbit has a slower along track ground trace than system 1. To maintain the square aspect ratio of each pixel and to avoid overlap on adjacent sweeps because of the increased along track distance represented by each pixel, a modification to the total sweep time is required. This increased turnaround delay can be accomplished by adjusting the mirror spring stops and cams. This is a minor modification that will not incur the large non-recurring costs of a major sensor redesign. The penalty for employing this alternative is a slight sacrifice in spatial resolution from 30 meters to 32.85 meters.

Alternative 4 employs a Thematic Mapper modified to achieve the same performance from two satellites as is obtained from three satellites with the present design. Using the simulation results plotted on Figure 2, this is determined to be 315 km.

Alternative 5 employs a push broom type sensor to achieve similar results. This alternative was not subjected to the same degree of analyses as the other alternatives. It is presented as a solution to the difficulties anticipated in implementing alternative 4.

The cost of Data Acquisition as a function of the sensor system is portrayed in Table 16. The major cost impact for each alternate system is analyzed. A consistency was maintained in comparing systems within each cost category. Weighting factors were employed to obtain overall cost comparisons based on a five year operating lifetime.

The first cost considered is the non-recurring cost for the sensor system. A representative estimate to produce a new sensor system such as the Thematic Mapper is fifty million dollars. This includes the design costs and all the costs of testing, prototyping, and qualifying the sensor system for space flight. Using the numerical value of 50 as applicable to systems 4 and 5, and the value of 0 for the baseline system, systems 2 and 3 were estimated at 10 and 5 respectively. This is based upon an engineering judgment of the relative amount of modification required.

The second cost consideration is the delta in recurring costs for the system as the sensor system is increased in complexity. The numbers were chosen based upon the relative value of this cost compared to the non-recurring cost of column 1.

The third cost consideration is the cost of the vehicle. It is the major differentiation between the baseline and the alternate systems. These numbers were chosen to be consistent with the number of columns 1 and 2, thus, for comparison, each column can be weighted at 1.

An additional operating cost can be expected for each satellite in orbit. This is primarily due to the need for additional control center personnel, the generation of control data, the analyses of engineering data from the satellite, and additional tracking requirements. As a rule of thumb, the incremental operational cost for each additional satellite in a program costs 30% more than for the first unit only. Thus, if a three satellite system, as in alternate 1, is the baseline, the two satellite system will cost .8125 as much to operate. To permit a comparison with the other cost elements, an operation cost of 20 million per year was assumed for the basic system. Over a five year operating life, a negative incremental value may be expected for each of the 2 satellite systems.

Table 16. Cost of Data Acquisition as a Function of Sensor System

| | SENSOR SYSTEM \ COST | NON-RECURRING INCREMENTAL DESIGN & PROTOTYPE SENSOR | RECURRING INCREMENTAL FOR ADDITIONAL SENSOR COMPONENTS | RELATIVE SATELLITE NON-RECURRING | OPERATIONAL RELATIVE/INCREMENTAL | RELATIVE COMMUNICATION CHANNEL/SCALED | SUMMATION OF RELATIVE DATA ACQUISITION COSTS | PERFORMANCE PENALTY % ACQUISITION/SCALED INCREMENT | INCREMENTAL RISK | RELATIVE COMPOSITE |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | BASELINE | 0 | 0 | 210 | 1.0<br>0 | 84.5<br>84.5 | 294 | 99.2<br>0 | 0 | 294 |
| 2 | 14-DAY MAINTAINING RESOLUTION | 10 | 1 | 140 | .8125<br>-18.75 | 104.0<br>69.3 | 202 | 97.4<br>54 | 5 | 261 |
| 3 | 14 DAY REDUCED RESOLUTION | 5 | 0 | 140 | .8125<br>-18.75 | 81.0<br>54.0 | 180 | 98.4<br>24 | 0 | 204 |
| 4 | WIDE SWATH THEMATIC MAPPER | 50 | 2 | 140 | .8125<br>-18.75 | 136.0<br>90.7 | 264 | 99.2<br>0 | 25 | 289 |
| 5 | WIDE SWATH PUSH BROOM SENSOR | 50 | Insig-nifi-cant | 140 | .8125<br>-18.75 | 136.0<br>90.7 | 262 | 99.2<br>0 | 10 | 272 |

The cost of communications was viewed as linearly related to volume and rate over the ranges involved in this comparison. The basic system uses a bandwidth of 84.5 megabits per second for each satellite. Each alternative has a bandwidth requirement as identified by the first number in the column. The relative cost is indicated by the second number which is n/3 for n equal to the number of satellites in the system.

The next column provides a ranking of the alternate systems when only those factors thus far identified are considered. This indicates the use of the present sensor system in a higher orbit with reduced resolution as the least cost option. This is based on the supposition that 98% of the samples is sufficient, and that the slightly reduced spatial resolution is acceptable.

However, it is reasonable to attach a value to the missed samples on the theory that they directly impact the accuracy of a Global Crop Production Forecast. The next column attempts to include this factor in the system comparison. The first numbers are the percent of samples acquired. If a value of 30 is attached to each percentage point difference between the alternate system and the baseline system, the second numbers in the column are obtained.

An additional concern that is somewhat difficult to quantify is the technical risk involved with each alternative. There is obviously no technical risk if the sensor is not redesigned as in options 1 and 3. The greatest risk is involved with option 4 because of the mechanical limitations. The numbers in this column quantify the risk of not being able to achieve design performance for a particular option.

The next column is the summation of the preceding three columns. The inclusion of the additional factors did not alter the numerical ranking of the alternatives--it just brought them closer together.

## 6.0 CONCLUSION

In Figure 14, the numerical rank for each system from Table 15 is plotted against the percent of targets acquired. This illustrates how system 3 with its best numerical rank may be preferred. If the reduced spatial resolution and the reduced absolute acquisition performance are not acceptable by the application scientists, then system 5 is the logical choice.

The conclusions of this study are summarized below:

- Implement the system for Global Crop Production Forecasting (GCPF) in phases.
- Two Landsat D satellites with slightly modified Thematic Mapper is favored over three satellites.
- Modify swath width to approximately 315 km.
- Choose a 14-day revisit orbit for maximum effectiveness of wider swath.
- Obtain wider swath by raising altitude of satellite.
- Concentrate major effort on new sensor development.
- Incorporate terrain data into geometric correction process for wide swath images.
- Offer selective data taking from less than the full swath.

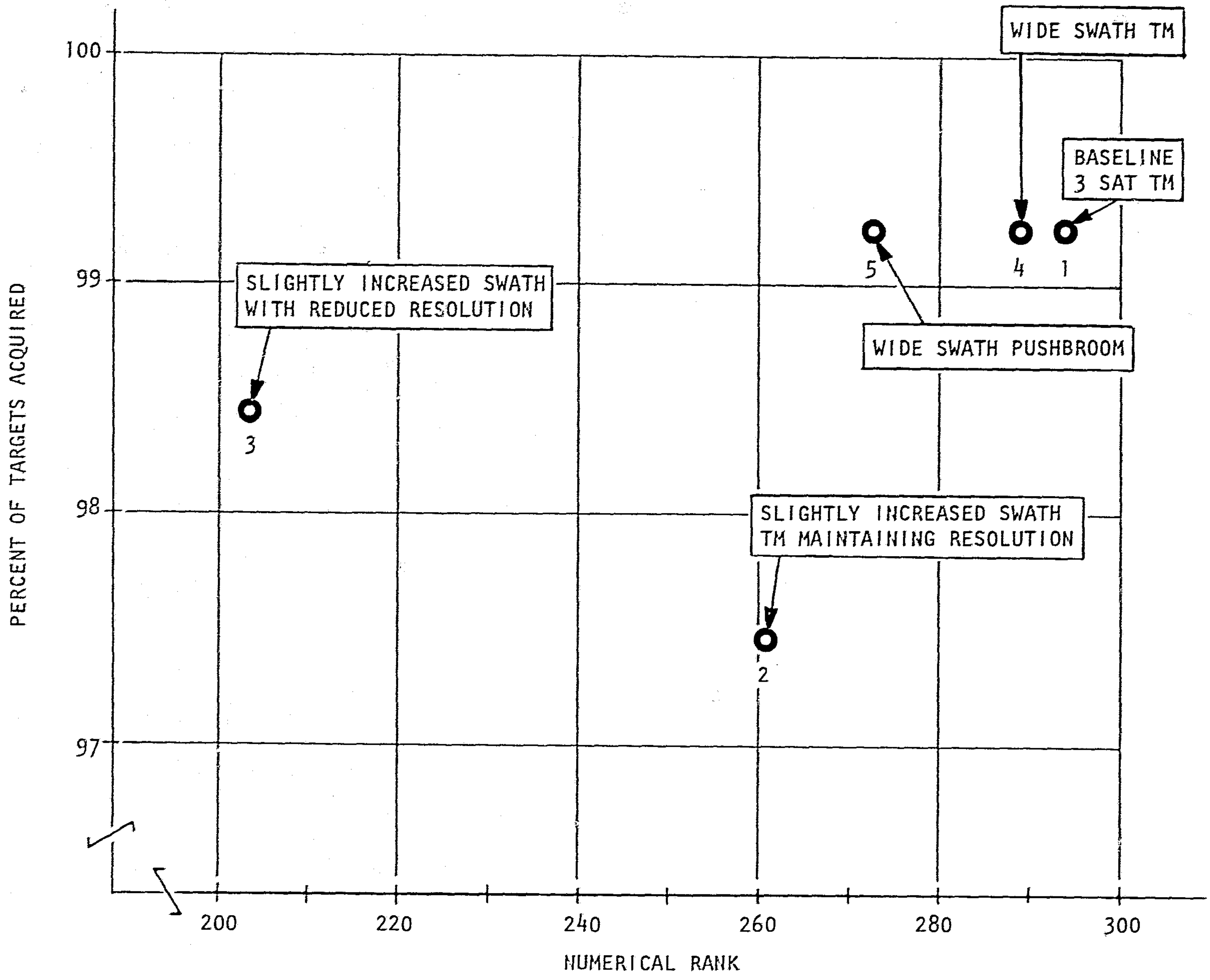



Figure 14. Plot of Alternate Systems Ranking vs Performance

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