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On the use of Off-Nadir Pointing for Increased Temporal Resolution of Earth Observing Satellite Systems

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ON THE USE OF OFF-NADIR POINTING FOR INCREASED TEMPORAL RESOLUTION OF EARTH OBSERVING SATELLITE SYSTEMS

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ABSTRACT

The change in radiance expected at a satellite in a Landsat-type orbit by pointing the sensor across track was examined with simulated data. The simulation incorporated the bidirectional reflectance distribution function of a spherical geometry grass canopy and scattering under clear, light haze and heavy haze atmospheric conditions. The results indicate that if the sensor pointed up to $\pm 37^{\circ}$ off-nadir (up to three tracks east and west) through a clear atmosphere, at least one of the six possible off-nadir views would have red and infrared radiances within $\pm 5\%$ of the nadir radiance between 60° north and 60° south latitudes; between 50% and 75% of the orbital path between 60°N and 60°S would have two or more off-nadir views within $\pm 5\%$ of nadir. Change in the time of overpass from 9:30 to 11:00 a.m. would result in no off-nadir radiance within $\pm 5\%$ of nadir radiance over a considerable length of the pass. Although increased atmospheric scattering causes large variations in across-track radiance, it appears possible, using various combinations of views depending on atmospheric conditions, that at least two views could be obtained with radiances within $\pm 5\%$ of each other over atmospheric visibilities from 23 km to 4 km. A directed modeling, field and satellite data analysis program is recommended to address the incorporation of a pointing sensor on the next generation Landsat system.

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INTRODUCTION

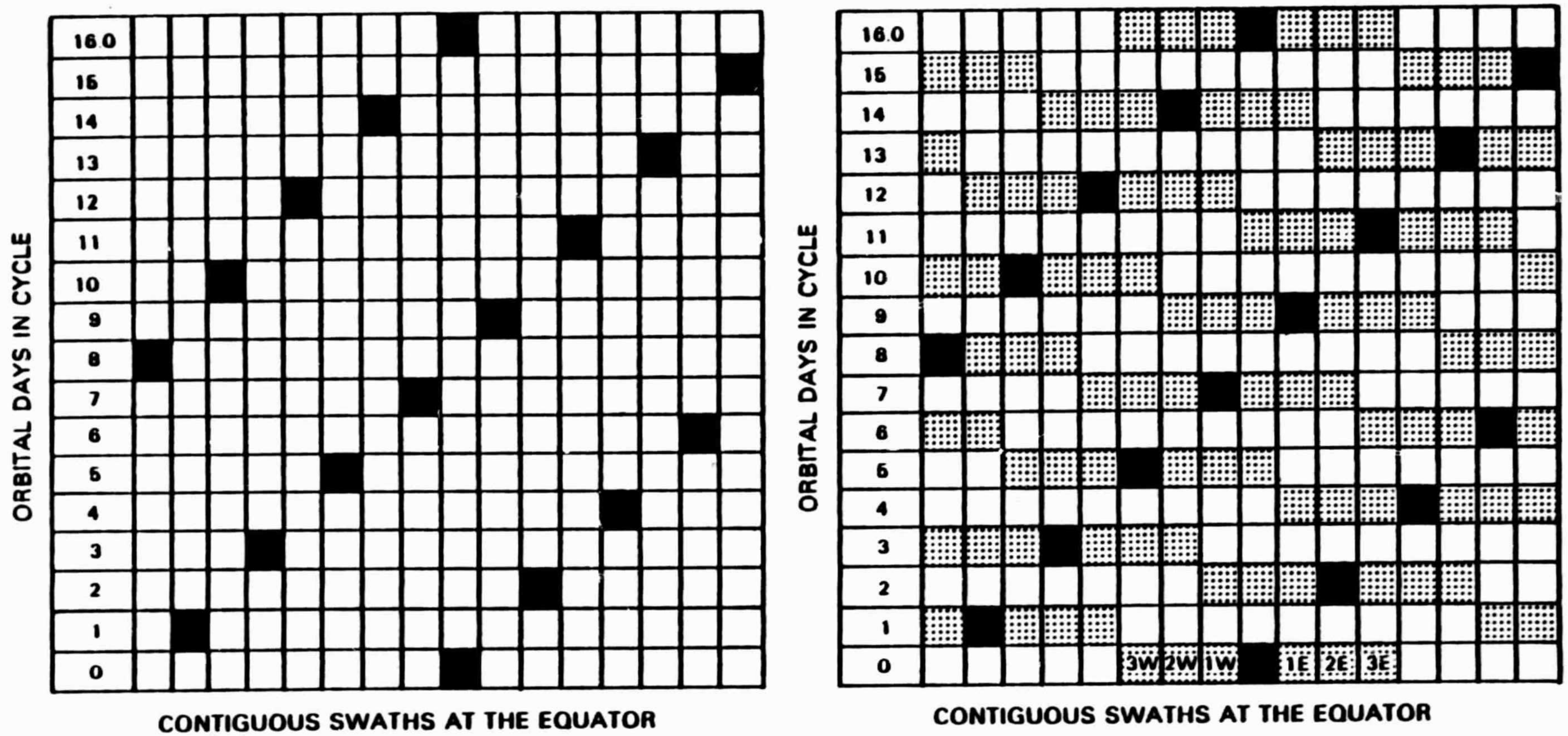
The repeated, synoptic, global coverage of earth orbiting satellites is perhaps their greatest attribute to many users of these systems. Conversely, this regularity of orbit imposes a temporal restriction which in many cases restricts their use as the rate of change of the target may be much greater than the observational frequency of the satellite, which is determined by the orbit, swath width and cloud cover. The present Landsat series has a sun synchronous, polar orbit which passes over the same area every 18 days. This will be changed to every 16 days with the launch of Landsat-D in 1982. Given an approximate world wide average probability of cloud cover of 50%, observational frequency will be approximately every month. Both the present Landsat series and the Landsat-D series have had, and will have, fixed nadir-looking sensors. NASA has increased the temporal frequency by increasing the number of nadir looking satellites in simultaneous flight. During much of the past 8 years, there have been two identical Landsat satellites in orbit at the same time, but "out of phase," thus providing a (nominal) 9 day overpass cycle. In contrast the French will launch the Systeme Probatoire d'Observation de la Terre (SPOT) in 1984, with a sensor which can look up to +26° across track (i.e., at right angle to the direction of movement of the satellite). This pointing capability converts a 26 day overpass repeat cycle to a one to five day viewing cycle.

The advantage of NASA's fixed nadir, multiple satellite approach is that one of the variables, the view angle, in the source-target-view geometry is held constant so that successive looks taken only 16 or 18 days apart in time will have almost the same sun-target-sensor geometry. The primary disadvantage of the multiple spacecraft approach is the expense of multiple spacecraft, sensors, etc. In light of present (and foreseeable) budget constraints of NASA, and the upcoming SPOT flight, it seems appropriate to examine off-nadir viewing as an alternative to the fixed nadir, multiple spacecraft concept.

It is the purpose of this paper to semi-quantitatively examine the changes in target radiance at satellite altitude, which might be expected at a sensor which looks across track in order to increase temporal resolution. In particular, this paper addresses the following three questions:

1. If a common target is viewed by a pointing satellite sensor, what will be the difference in radiances between views at nadir and one, two and three tracks to the east and west?
2. How do these differences change with time of overpass?
3. What is the effect of changes in atmospheric conditions on these differences in radiance?

The manner in which off-nadir pointing can increase the frequency of coverage is graphically shown in Figure 1. Figure 1a shows the swathing pattern of a fixed nadir looking sensor in a 705 km altitude, near polar orbit such as is presently planned for Landsat D. The rows represent orbital days of the 16 day cycle, while the columns represent contiguous swaths (at the equator) on the ground. This shows that the complete area is covered in 16 days, but that each swath is covered only once. Figure 1b indicates the possible coverage by a sensor which can be pointed up to 3 swath widths, or tracks, to the east and west of nadir.



1a
FIXED NADIR SENSOR

1b
±3 TRACK POINTING SENSOR

FIGURE 1. SWATHING PATTERNS (705 km ORBIT)

This shows that if the nadir view is missed, for example, at day zero, that area can be viewed on day 2 by pointing the sensor two tracks to the west, on day 5 by pointing the sensor three tracks to the east, on day 7 by pointing the sensor one track to the east, etc., for a total of 7 views per 16 day cycle. Of course, seven times the amount of data is not taken; when a sensor is taking data off-nadir, it is losing the nadir data. Pointing presents the opportunity to pick up important scenes at the expense of less important (or perhaps cloud-covered) scenes.

If a sensor has the angular freedom to observe up to three tracks to the east and west of nadir at the equator, it can view more than three tracks at higher latitudes, due to the convergence of orbits toward the poles. Figure 2 is based on the same orbital cycle as Figure 1, but also shows the relationship between latitude and the off-nadir angle (or ground distance) the sensor must point to observe various tracks. Thus, if the sensor can point three tracks off-nadir at the equator it must be able to point about $\pm 37^{\circ}$ (in this paper, angles or distances refer to the <u>center point</u> of the image, not the extreme edge). At 60° latitude, this 37° pointing capability would incorporate six tracks on each side of nadir rather than the three at the equator, potentially doubling the temporal frequency at high latitudes.

APPROACH

A previous study (Kirchner et al., 1981) addressed the general subject of directional radiances, over the complete view angle and azimuth hemisphere (i.e., from nadir to the horizon, over azimuths of 360°) for several vegetation canopy geometries and leaf densities. The effects of

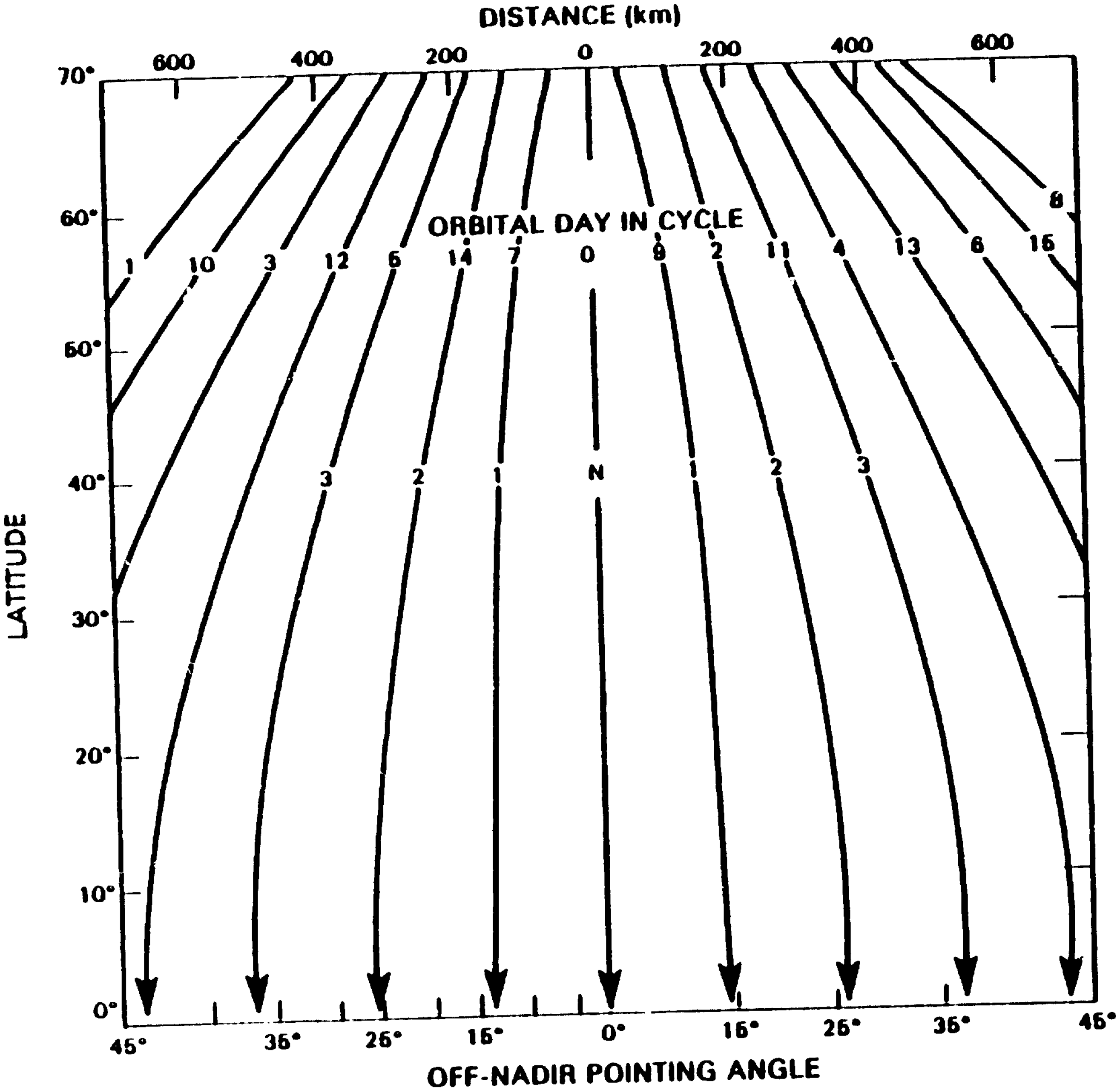


FIGURE 2. OFF-NADIR POINTING ANGLE AS A FUNCTION OF LATITUDE

changing solar zenith angle and changing atmospheric condition were also discussed. The data for that paper, as well as the present paper, come from an extensive simulation modeling data base developed by Smith et al. (1980). The simulation model used considered both the bidirectional reflectance distribution function (Nicodemus, 1970) as measured from targets and the effect of the atmosphere on the distribution of radiation impinging on, and leaving the target. Turner's (1974) atmospheric radiative transfer model was used to model the incoming and outgoing radiation, while the stochastic Solar Radiation Vegetation Canopy (SRVC) model of Smith and Oliver (1972, 1974) was used to simulate the directional spectral reflectance of vegetation canopies. A summary of the modeling used to develop the data base can be found in Kirchner et al. (1981) while a more complete explanation, and the data base itself, can be found in Smith et al. (1980).

The data base consists of a series of tables which give radiances for nine vegetation canopy targets of different geometries and densities, at two wavelengths (0.68 and 0.80 μm), three atmospheric visibilities, and as a function of solar zenith angle, view zenith angle and relative sun azimuth. Solar and view zenith angles are at 5, 15, 25, 35, 45, 55, 65, 75 and 85 degrees; relative sun azimuth angles are at 0, 60, 90, 120 and 180 degrees. Thus, for each target, wavelength, and atmospheric condition, at each of the nine solar zenith angles a hemisphere of radiances (Figure 3a) is given at 45 points (nine view angles times five azimuths). Actually, data for only half the hemisphere is given, as radiances are symmetrical about the principal plane (the plane which

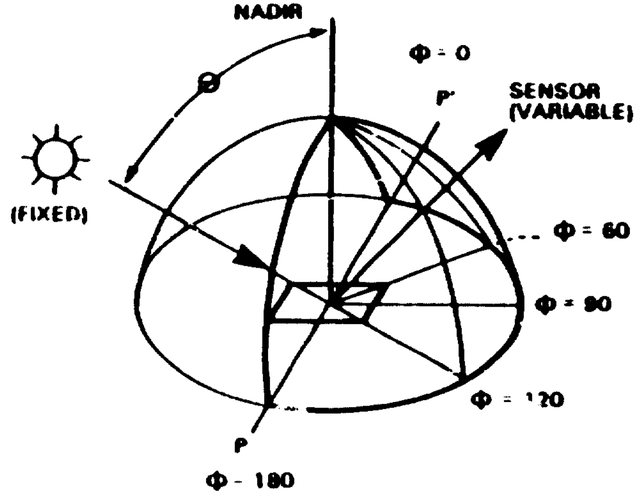


FIGURE 3A

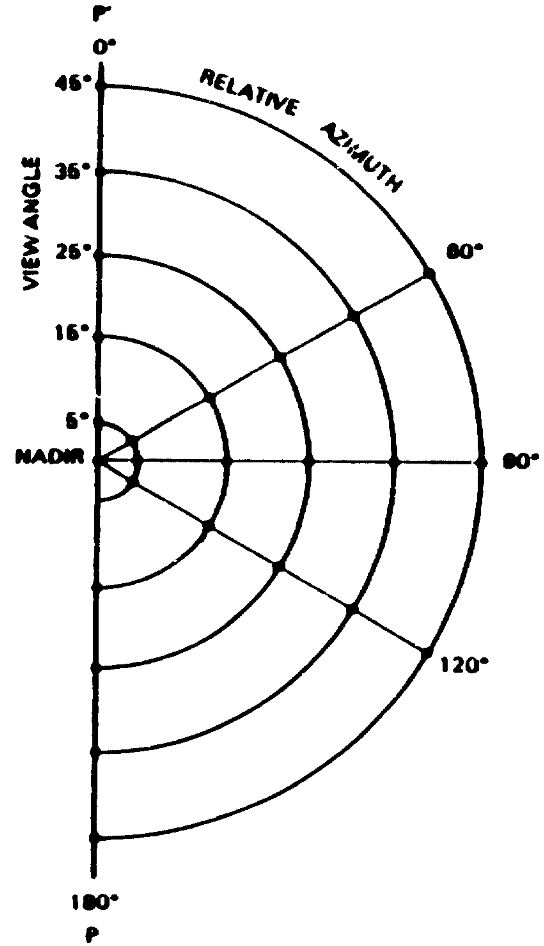


FIGURE 3B

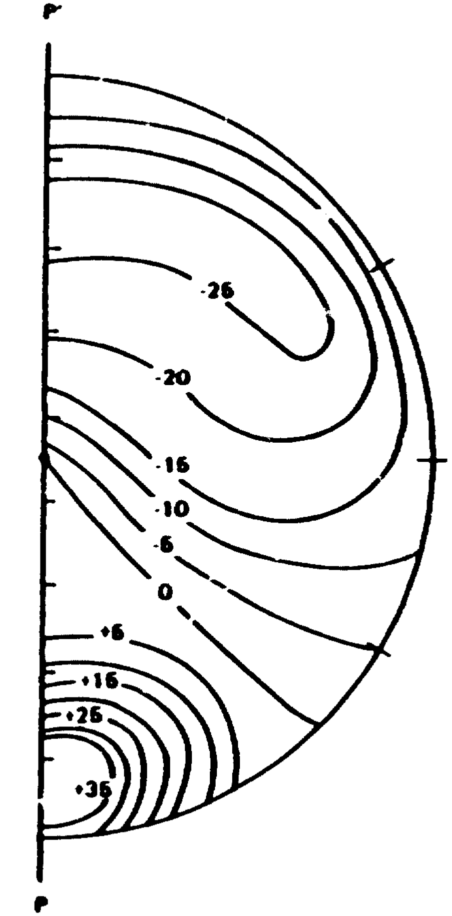


FIGURE 3C

FIGURE 3. DIRECTIONAL RADIANCE GEOMETRY AND PLOTTING PROCEDURE

contains θ, the solar zenith angle; PP' in Figure 3). Figure 3b shows a planar representation of the "upper" 45° of that quarter-sphere, that is, using only view zenith angles between 0° and 45°. View zenith angles beyond 45° have not been used, as this paper is concerned only with excursions from nadir up to approximately 37° (see Figure 2). The distribution of the radiances in the data base are shown in Figure 3b by the black circles at the intersections of the view angle semi-circles with the sun azimuth lines.

Comparison of radiance at different view angles to radiance at nadir rather than absolute radiance is the primary concern of this study. Radiance at nadir is not given in the data base; it was approximated by averaging the five view angle radiances at 5° off-nadir. Then the percent difference in radiance of each of the 25 view angles from the nadir radiance was calculated, plotted on a form such as Figure 3b, and contoured at 5% intervals. Figure 3c is an example of such a plot. A series of these plots, each for a different sun zenith angle, wavelength, and atmospheric conditions was then used to estimate the radiance at particular view angles (depending on latitude and whether pointing across 1, 2 or 3 tracks east or west) at particular relative azimuths (depending on the absolute azimuth of the sun at the day, time and latitude of interest).

Without the ability to derive the radiances from the data base in a speedier manner, it was recognized from the onset that the three questions asked in the Introduction were too broad for the limited time and resources available. Thus, certain bounds were put on the variables. These were:

(a) Target - an almost infinite variety of surface types occur in nature; the data base contains data on nine separate surface types, differing either in geometry and/or density. The previous analyses (Smith et al., 1980; Kirchner et al., 1981) showed that the most consistent results were obtained from grasses of either spherical or planophile geometry. (Spherical geometry is characterized by leaf surfaces which are uniformly distributed at all angles, as if tangent to a sphere, while planophile geometry is characterized by a leaf angle distribution in which the majority of leaves are oriented horizontally. Many natural grasses, wheat and rye have spherical geometry while clover, alfalfa and potatoes tend toward planophile geometry.) As spherical grasses have a wider variation in radiance with sun and view angle than planophile grasses (Kirchner et al., 1981) they have been chosen for this study. The data base has data for three densities of canopy cover, with leaf area indices (LAI) of 0.5, 1.2 and 4.0 representing low, medium and high biomass respectively. Off-nadir variability of scene radiance decreases with increasing biomass, at a given sun and view angle (Kirchner et al., 1980); data for medium LAI (1.2) was chosen for this study.

(b) Location - a range of 60° north to 60° south latitude was used in this study.

(c) Dates - solstice and equinox dates were used.

(d) Orbit - a near polar, sun synchronous orbit similar to that planned for Landsat D was assumed.

(e) time - the 9:30 a.m. equator crossing time similar to Landsat was chosen for the first part of the study; an 11:00 a.m. crossing time (closer to the SPOT time) was used for contrast in the part which addresses the effect of changing the time of day.

(f) Atmospheric conditions - the data base contains radiance under three different atmospheric conditions--clear, light haze and heavy haze conditions; these correspond to visibilities of 23, 10 and 4 km respectively. The latter two conditions were only used in the third part of the study which addressed the effect on varying atmospheric conditions.

(g) Pointing angles - variable, depending on latitude (see Figure 2). Center point of image is at 1, 2 and 3 tracks to east and west of nadir.

RESULTS AND DISCUSSION

This section attempts to arrive at partial, semi-quantitative answers to the three questions listed in the Introduction. Each is addressed in turn:

1. If a common target is viewed by a pointing, satellite-borne sensor, what will be the radiance differences between views at nadir and 1, 2 and 3 tracks to the east and west of nadir?

As stated in the previous section, this question has been addressed only within the context of the following conditions: spherical grass target of LAI of 1.2; clear atmosphere (23 km visibility); 9:30 a.m. equator crossing time; 60°N to 60°S latitude; on the June solstice and March/September equinox.

Figure 4 is a graphical representation of how the radiance distribution changes during a Landsat pass. The Figure has five "radiance semi-circles," similar to Figure 3c, which show the percent red (0.68 μm) radiance difference from nadir out to 45°, at five different latitudes. Each semi-circle represents a different sun zenith position (except the first and third

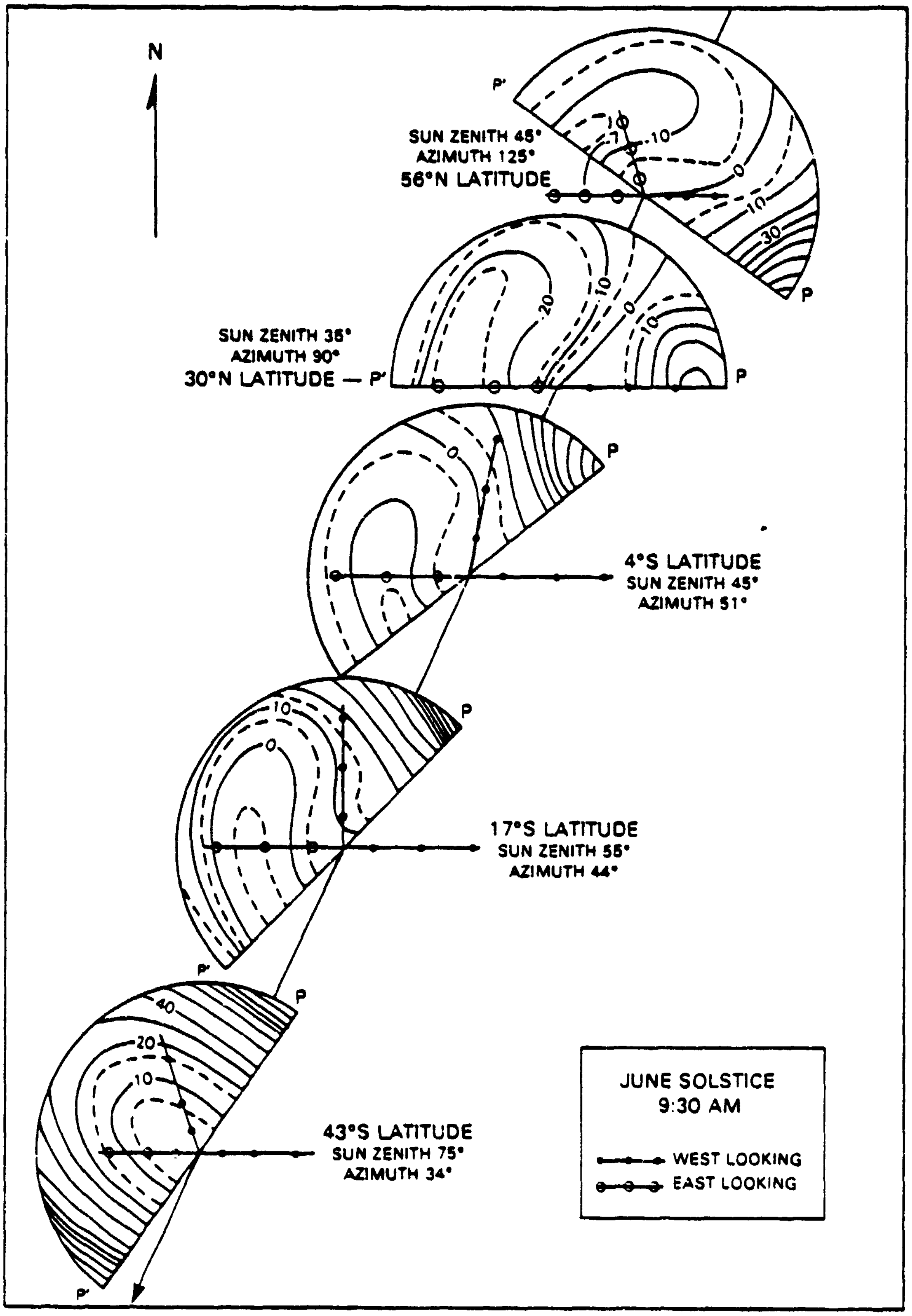


FIGURE 4. CHANGING DIRECTIONAL RADIANCE DURING LANDSAT PASS

which represent 45° sun zenith), and are oriented with respect to north at the proper sun azimuth for that latitude on the particular date and time. They are diagonally placed on the Figure at the angle the Landsat orbit makes with north. On an east-west line thru the nadir point are open or filled circles representing the proper angle for looking 1, 2 and 3 tracks off-nadir eastward and westward, respectively, at that particular latitude. As the radiance semi-circle is symmetrical about the principal plane (PP'), those views which lie outside the semi-circle can be represented on a line in the Figure at an equal angle to line PP'.

From such a series of properly oriented radiance semi-circles, the percent difference from the nadir radiance for red (0.60 μm) and IR (0.80 μm) wavelengths as a function of latitude at 1, 2 and 3 tracks off-nadir was determined for the June solstice and the March/September equinox. These are shown in Figures 5 and 6 respectively. (The December solstice is essentially a mirror image of the June solstice--rotated about the equator--except the December sun azimuths are supplemental angles of the June azimuths.) The data points are shown by the numbers 1, 2 and 3, east or west, and the curves are smoothly interpolated between the data points.

It can be seen from these Figures that the red variation is generally very much larger than the IR variation. The positive differences are believed to be, to a large extent, due to atmospheric backscatter. For example, in Figure 5a note the approximate 30% increase in radiance at about 25° north latitude when looking west three tracks. At this latitude, date and time the sun zenith is approximately 34° and sun azimuth about 90°. A view angle of about 35° is needed to look off-nadir 3 tracks at this latitude (Figure 2). Thus a westward look of 3 tracks is with the sun directly

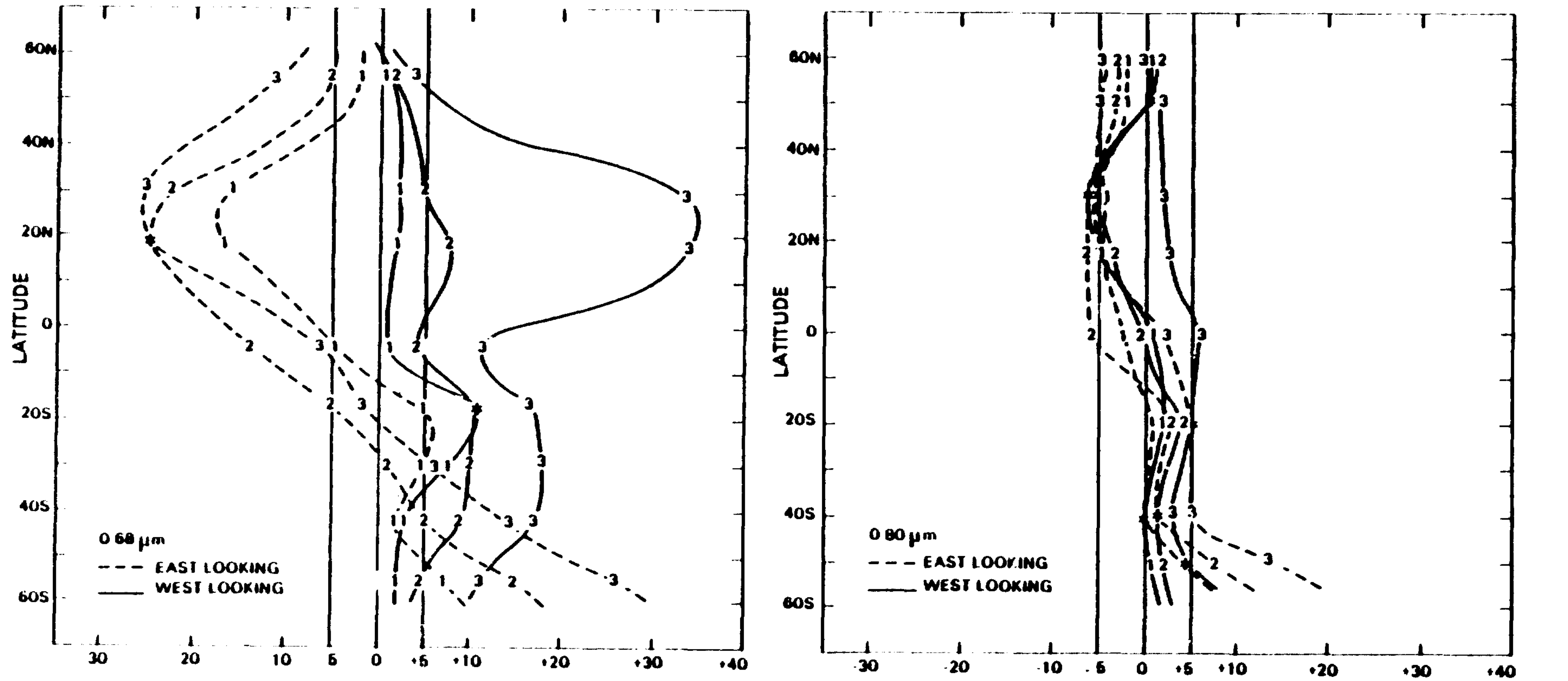


FIGURE 5. PERCENT VARIATION OF RADIANCE FROM NADIR, JUNE SOLSTICE, 9:30 CROSSING TIME

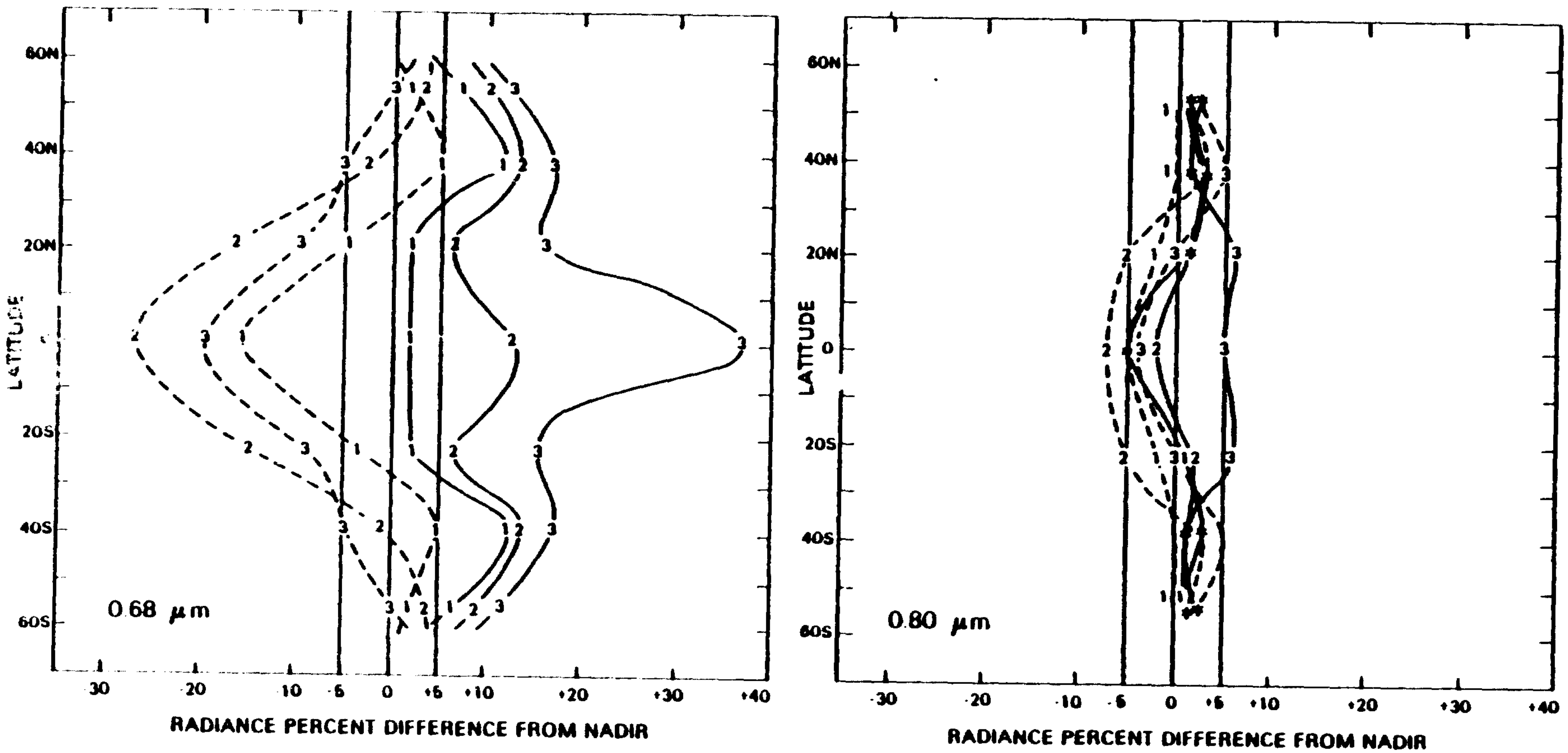


FIGURE 6. PERCENT VARIATION OF RADIANCE FROM NADIR, EQUINOX, 9:30 CROSSING TIME

behind the sensor--the position of maximum backscatter. This atmospheric effect is much reduced in the IR radiance, due to the strong inverse relationship between Rayleigh and Mie scattering and wavelength. The negative differences are largely due to shadows in the canopy and are limited to the east looking views.

An important practical observation from Figure 5 is that there is at all latitudes at least one off-nadir view which has both red and IR radiances within $\pm 5\%$ of the nadir radiances. (Five percent has been arbitrarily chosen in this paper as an "acceptable" amount, considering the natural variation of targets, modeling assumptions and interpolation accuracy.) Moreover, more than 75% of the path between 60°N and 60°S latitudes has two or more off-nadir views where the red and IR are within the $\pm 5\%$ constraint.

The situation does not change substantially at the equinox dates (Figure 6), except the latitude points of the maximum and minimum variations from nadir shift and the length of path (degrees of latitude) where only one off-nadir view is within the $\pm 5\%$ of nadir restriction has approximately doubled to about 50% of the total path between 60°N and 60°S latitude.

Thus it appears that a pointing sensor, with the stated constraints of target and atmospheric conditions, will provide at least two views of the same scene over the whole path from 60°N to 60°S with radiances within $\pm 5\%$ of each other and three or more views for 50 to 75% of the path every 16 day cycle.

2. How do these differences in off-nadir view change with a change in time of overpass?

As new systems/missions beyond the Landsat D series are developed, the issue of change in the equatorial crossing time from 9:30 will arise. For example, a few years ago an alternate 11:00 a.m. orbit for the Landsat D series was studied from a number of aspects (GSFC, 1976). (There were several lines of evidence which suggested the advantages of the earlier crossing time, but the decision was largely made on data compatability considerations.) Also, the French SPOT pointing sensor, due to be launched in 1984, will have a 10:30 a.m. equatorial crossing orbit; thus it is of more than academic interest to compare a time nearer to solar noon with the 9:30 crossing time data. Figure 7 is a plot of radiance differences for an 11:00 a.m. orbit on the June solstice, analogous to the 9:30 a.m. orbit results for that date shown in Figure 5. There are substantial differences, principally the lack of strong backscatter effects, and the bimodal shape of the curve. The important conclusion which can be reached by a comparison of Figure 5 and 7 is that while the 9:30 a.m. orbit had at least one off-nadir view with red and IR radiance within ±5% of nadir, the 11:00 a.m. has over one-third of its path where no view is within ±5% of the nadir radiances. This would support the earlier crossing time for a pointing sensor.

3. What is the effect of changes in atmospheric condition on these off-nadir differences in radiance?

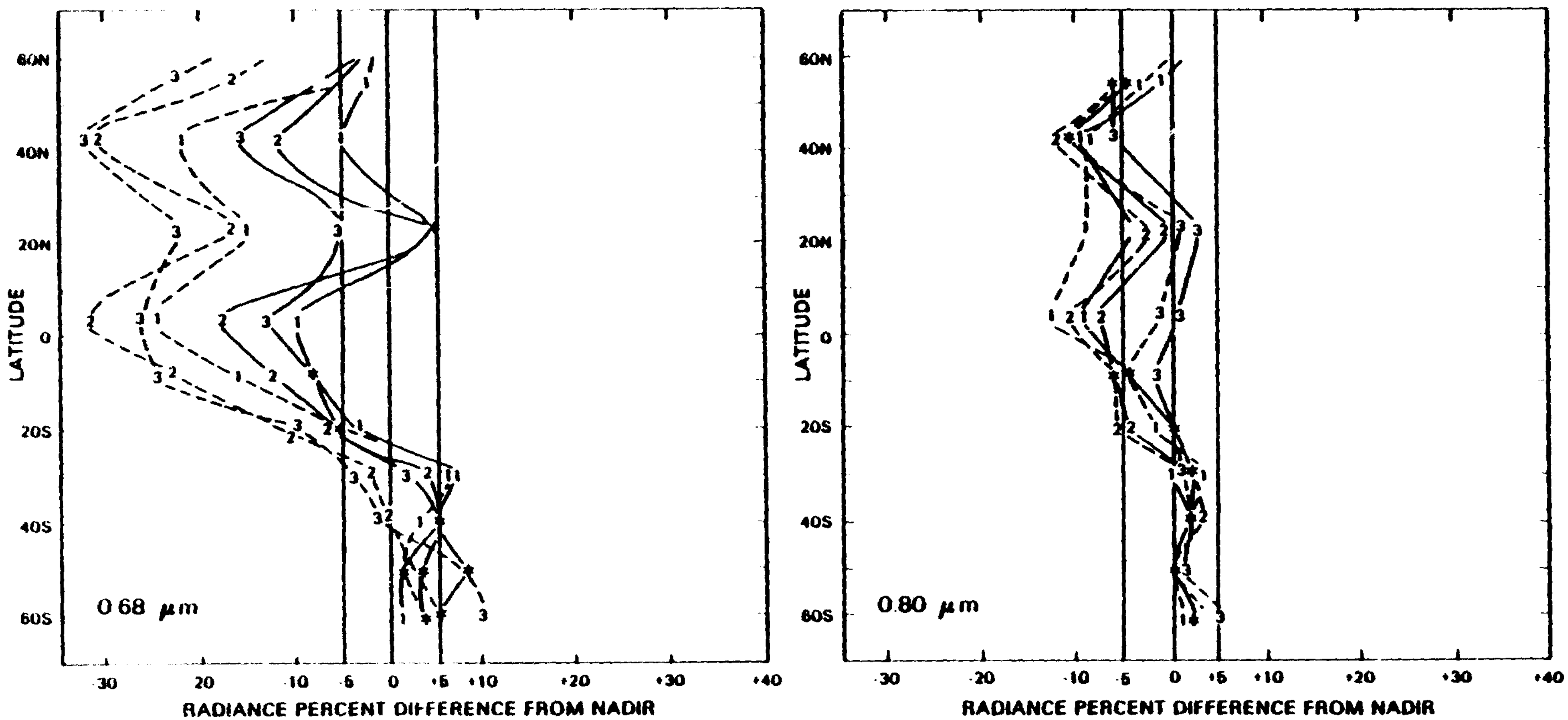


FIGURE 7. PERCENT VARIATION OF RADIANCE FROM NADIR, JUNE SOLSTICE, 11:00 AM CROSSING TIME

The previous discussions have been based on a "rural clear atmosphere" model, i.e., where the horizontal visibility is 23 km, corresponding to an optical depth in the 0.68 μm region of 0.259 and in the 0.80 μm region of 0.222. Kirchner et al. (1981) noted that an increase in atmospheric haze causes large changes in the amount of variation in the radiance hemisphere, primarily due to the increase in backscatter. As stated earlier, the data base contains three sets of data: a clear atmosphere (23 km visibility), a light haze (10 km visibility) and a heavy haze (4 km visibility). To indicate the magnitude of the effect of atmospheric change, only a very small portion of these latter two data bases have been examined. Data for a sun zenith of 35°, sun azimuth of 90°, and view angles of 12°, 20° and 29°, under the three atmospheric conditions were compared. This corresponds to the conditions of looking 1, 2 and 3 tracks east and west on the June solstice with a 9:30 a.m. crossing time at approximately 30°N latitude. As can be seen in Figure 5 this represents the latitude of maximum variation from nadir, and this represents what should be an extreme condition. Figure 8 is a plot of percent difference from nadir as a function of optical length or visibility (note that the percent difference scale is logarithmic). A very large increase in radiance difference with increasing optical depth is apparent for the westlooking views, both in the red and IR portions of the spectrum. Despite this large increase red and IR radiances looking westward 1 track still fall within ±5% of the nadir views under the same conditions, under atmospheric conditions between clear and light haze (23 and 10 km). The eastward views show a much smaller variation with

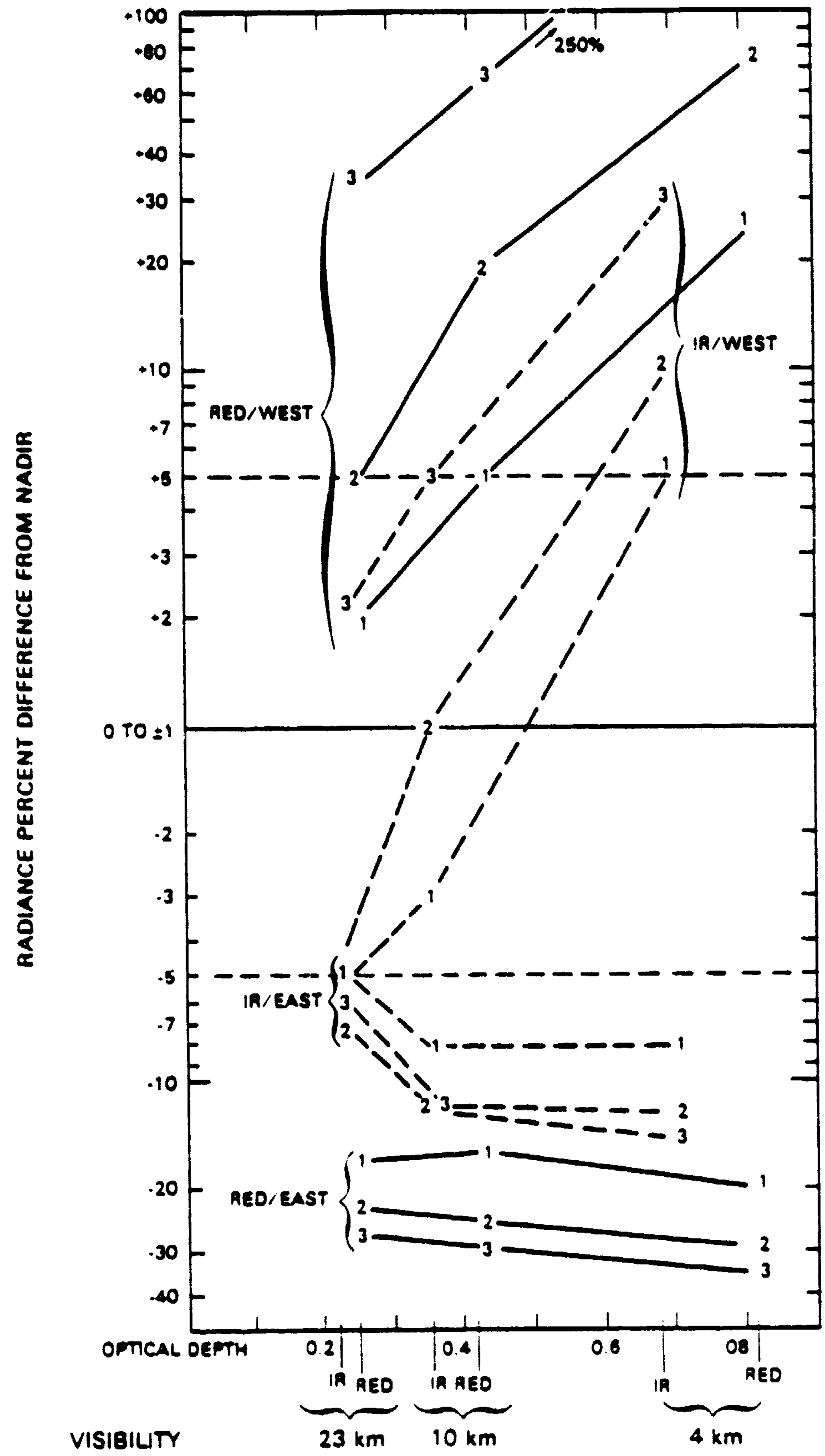


FIGURE 8. VARIATION OF RADIANCE AS FUNCTION OF ATMOSPHERIC CONDITION

optical depth, but under all three atmospheres the radiance differences fall outside the ±5% range. This figure suggests that under clear to light haze conditions (10 km visibility) a 1 track westlooking view will be quite similar to the nadir view and can be used to increase temporal resolution. Under light to heavy haze conditions, none of the views have IR and red radiances within the ±5% limit. In analyses where transformation which involve the ratio of red to IR such as the normalized difference (ND) are used (e.g., Tucker et al., 1979), the eastward looking tracks are comparable to each other within the ±5% limit, but not to the nadir view; thus the eastward off-nadir only tracks can be used to increase the frequency of observation, and will have comparable radiances, but there will be a change from nadir information. If the test of comparability is not with nadir views under the same conditions, but with nadir view under clear conditions (23 km visibility), then no off-nadir view under moderate or hazy condition is within 10% of clear condition nadir view for both red and IR radiance. If the ND transformation is considered, then the 1 track east looking view under 10 km visibility atmospheric condition, and 1, 2 and 3 tracks east looking views under 4 km visibility are within 10% of the nadir ND under clear condition.

It has been suggested that a possible application of a pointing sensor is to measure atmospheric condition, thus (hopefully) allowing some corrections to be made (Kirchner et al., 1981). As a general rule, due to backscatter, westward looking off track views are much more sensitive to changes in atmospheric conditions than east looking views (compare slopes of east and west looking lines in Figure 8); the degree of sensitivity will be a strong function of latitude and date (compare westward views on Figure 5, and between Figures 5 and 6).

RECOMMENDATIONS FOR FUTURE WORK

This paper represents only the "tip of the iceberg" on the issue of the utility of off-nadir viewing, and is meant to stimulate interest in much more quantitative work. Obviously, a great deal needs to be done before intelligent decisions can be made with regard to flying a pointing sensor on a satellite. In light of the flight of the SPOT system in three to four years, and the decisions which must be made soon regarding the configuration of the post-Landsat operational system of the 1990's, a directed effort involving scientists of differing backgrounds and skills should be initiated immediately. The effort should involve model development and analysis, field work to provide the basic data for the models, and analysis of real data, either from high altitude aircraft or satellites, to check the model predictions.

Modeling: The data base produced by Smith et al. (1980) and used in this study contains radiances of nine surfaces at nine view angles, nine solar zenith angles, five azimuth angles, under three atmospheric conditions and at two wavelengths. Thus, the data base has almost 22,000 modeled radiance values. The data itself is on computer tape but not in a format compatible with Goddard computers. Software should be developed to access this data and to interpolate between the sun and view zeniths and azimuths in the data base. Perhaps a contouring scheme similar to that done by hand in this study would be appropriate. The end result should be a capability to input sun zenith and azimuth, view zenith and azimuth, target, and atmospheric condition and have reported the predicted radiance and percent difference from nadir. The sheer size of the data base and number of variables is inhibiting to any investigator who must approach the tabular data base armed only with a hand-held calculator.

A comprehensive attack on canopy target modeling should be initiated. The two most comprehensive canopy models presently in use, the Suits (1972) and Smith and Oliver SRVC (1972, 1974) models have certain deficiencies and assumptions which limit their utility; either a new model should be developed or one or both of these models should be modified as appropriate (see Smith and Ranson, 1979, page 2.128, for specific recommendations regarding model development).

Field Work: Bidirectional reflectance distribution functions (BRDF) for a number of various target materials should be determined as critical inputs to the model. Obtaining this information in the field with reliable, reproducible, and realistic procedures is difficult, and a directed program must be initiated as soon as possible. The data should be obtained in conjunction with measurement of the total irradiance field and the results described by some easily measured atmospheric parameter. Also the BRDF data should be obtained at an azimuthal density greater than in the data base (0, 60, 90, 120, 180°).

High Altitude Aircraft/Satellite Data Analysis: Modeled target responses can be checked under specific sun and view angular relationships and atmospheric conditions through the use of high altitude or satellite multispectral data. An example of such data might be the AVHRR data from Nimbus 6; although the resolution is quite large (~1 km), it should be possible to pick appropriate targets, such as large wheat fields, grasslands, forests, etc.

It will be tempting for such a study to become a basic research program, studying directional reflectance in a general sense. However, it is strongly recommended that the program be initiated to address the specific questions addressed by this paper--the utility of off-nadir pointing to increase temporal resolution in a future Landsat type mission. This will limit the complexity of some of the variables, such as sun and view zenith and azimuth and should permit completion in time to give guidance to the next generation mission.

SUMMARY

Data from a general atmospheric and bidirectional reflectance simulation model for a spherical geometry vegetation of medium density, and sun zeniths and azimuths and view angles appropriate to a 9:30 a.m. equatorial crossing Landsat orbit, indicate that if a satellite had a sensor capable of pointing up to three tracks off-nadir ($\pm 37^o$), at least one off-nadir view could be obtained anywhere between 60^oN and 60^oS which would have red and infrared radiances within $\pm 5\%$ of the radiances obtained at nadir, given a clear rural atmosphere. Between 50% and 75% of the path between 60^oN and 60^oS would have two or more off-nadir views within $\pm 5\%$ of the nadir view, depending on date. Maximum change from the nadir radiance is almost 25% less than nadir for the eastward viewing tracks (due primarily to shadowing in the vegetation) and about 35% more than nadir for the westward viewing tracks (due primarily to atmospheric backscatter). Changing the orbit equatorial crossing time to 11:00 a.m. seems to reduce the general spread of the off-nadir radiances so that they fall between approximately -30% and +5% of nadir. However, there is about one-third of the path between 60°N and 60°S where there are no off-nadir views with both red and IR radiances within ±5% of nadir in contrast with the 9:30 a.m. crossing time where the complete distance had at least one off-nadir view within this range. Analysis of data simulating different atmospheric conditions indicate backscatter will cause significant change in the westward across track view value; the +35% greater than nadir radiance under clear conditions changes to +250% under a heavy haze atmosphere for red radiance. Eastward (toward sun) off-nadir views changed little with atmospheric conditions.

It is recommended that a concentrated, systematic modeling, field aircraft and satellite data analysis program be initiated to both check the general conclusions made in this paper on very limited data and expand the study into areas not addressed by this study. Timely, repeated views of the same scene are a requirement for many users of earth observations data. To pursue the tactic of assuming this requirement will be met by flying multiple, fixed nadir-sensor satellites is to ignore an approach which might give the same or more satisfactory results at far less expense.

ACKNOWLEDGEMENTS

Professor J.A. Smith, Mr. K.J. Ranson and Ms J.A. Kirchner of Colorado State University developed the simulation model and compiled the data base used in this study. This paper was a direct outgrowth of a cooperative effort with Ms. Kirchner and Dr. Smith (Kirchner et al., 1981); I wish to thank both Ms. Kirchner and Dr. Smith, as well as Dr. Donald Deering and Dr. Philip Cressy for helpful comments and suggestions. Mr. Charles Kouns aided in data reduction and Mrs. Barbara Lueders typed the manuscript.

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