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PREDICTION OF SUN TRANSIT OUTAGES IN AN OPERATIONAL COMMUNICATION SATELLITE SYSTEM*

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ABSTRACT

The method and the computer program used to generate sun transit predictions are described. The program is universal in that (i) the satellite can be at any longitude, (ii) the earth station can be located anywhere on earth, and (iii) the prediction is for any given year. The predictions allow earth station users to accurately predict the effect of sun transits on their operations well in advance.

INTRODUCTION

A sun transit outage occurs when the pointing angles from the receiving earth station to the satellite and to the sun are so nearly coincident that additional noise power presented by the sun causes the demodulator to operate below its threshold. Consequently, communication performance will be degraded below acceptable quality.

For a geostationary satellite and a fixed earth station, the sun transit outage occurs once a day for several minutes during a few days near the spring and fall equinoxes. The number of outages and their duration depend on the minimum tolerable C/N ratio and on the actual C/N ratio at the receiver input during sun transit. The latter, or equivalently, the additional solar noise power received, is affected by the coordinates of the satellite and of the earth station, the motion of the sun with respect to the earth, the solar disk temperature, and the antenna gain pattern of the receiving earth station.

Sun transit outages have been cited in the literature. A satellite system to avoid sun transit outage was proposed by Lundgren[1]. Ito et. al.[2] provided solar outage measurements. Recently Loeffler[3] supplied a rule of thumb for solar outage calculation.

In this report, the method and the computer programs used to provide accurate sun transit outage prediction will be described. The prediction includes time of sun transit peak degradation, sun transit outage duration, and C/N-degradation during sun transit. Comparison with measured data will also be made.

THE METHOD

As shown in Figures 1 and 3, E'E is a sunray passing through the earth station E, S is the satellite, and E'ÊS is the off-axis angle OFFAX. As the earth revolves around the sun and spins on its own axis, the direction of the sunray E'E changes. Once a day, the sunray will lie in the plane which is perpendicular to the equatorial plane and contains SE. This coplanar instant is of interest because it is when the off-axis angle can be computed with ease and takes a minimum value for any day.

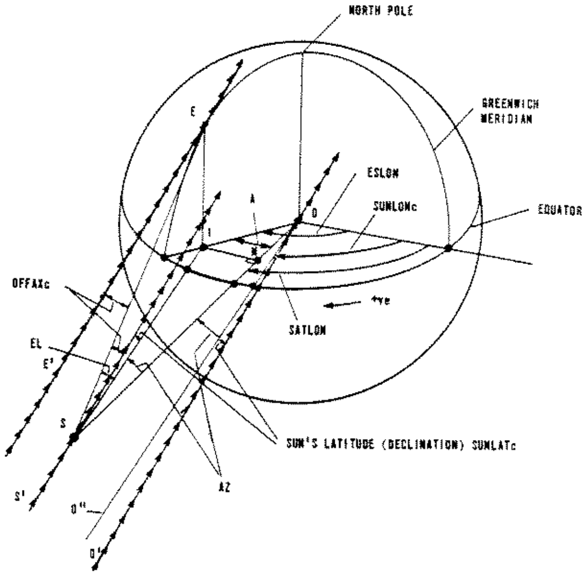

FIGURE 1: GEOMETRIC REPRESENTATION OF SUN TRANSIT. - COPLANAR INSTANT.

Let S'S and O'O be sunrays passing through the satellite S and the earth center O, respectively. Let their projections onto the equatorial plane be SI and O"O. Since the sun is far away from the earth, it is valid to assume that all the sunrays are parallel. Consequently, SI is parallel to O"O and the coplanar instant corresponds to the time when the sun has a longitude of SUNLONc. From the geometry of Figure 1, SUNLONc can be expressed as,

$$\mathrm{SUNLONc} = \mathrm{SATLON} - \mathrm{AZ} \qquad (1)$$

where SATLON is the longitude of the satellite which takes a value from 0 to 360 (e.g. 120°W and 40°E correspond to 120 and 320 respectively) and AZ is the azimuth angle of the earth station with respect to the satellite which takes a negative value if the earth station is east of the satellite. This azimuth angle should not be confused with the more familiar azimuth angle of the satellite with respect to the earth station. Its relationship with the coordinates of the satellite and the earth station is derived in Appendix A.

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Note that by definition, the sun's longitude (latitude) is that of a sunray passing through the earth center. Its accurate prediction for a given time is complicated since it is a function of the motions of the moon and the neighboring planets. Once a year, the Nautical Office of the US Naval Observatory issues an almanac[4] which contains the predicted position of the sun for the coming year. To avoid annual reference to the almanac, mathematical models have been developed to predict the sun's position many years is advance[5,6]. The prediction based on the model described in Reference 5 is quite accurate for our purposes. Using the model, and by performing a one dimensional search, the time of the coplanar instant (and the corresponding latitude of the sun) can be found for any given day.

From the geometry shown in Figure 1, at the coplanar instant, the off-axis angle OFFAXc can be computed from the following:

$$\mathrm{OFFAXc} = \left| \mathrm{EL} + \mathrm{SUNLATc} \right| \qquad (2)$$

where SUNLATc is the sun's latitude at the coplanar instant, which has a negative value for a southern latitude, and EL is the elevation angle of the earth station with respect to the satellite, which takes a negative value if the earth station is located in the southern hemisphere. The relationship of EL with the coordinates of the satellite and the earth station is derived in Appendix A.

Figure 2 is a typical variation of the sun's latitude with respect to time for a given year (the year 1983). In this plot, the spring and fall equinoxes are on March 16 and Sept. 23, respectively, and the sun's latitude is positive from March 16 to September 23. The elevation angle, has a range somewhere from -8.67° to +8.67°, depending on the latitude of the earth station and the longitude of the earth station, relative to that of the satellite. Thus, from the figure, the worst sun transit noise for a northern hemisphere earth station ($EL > 0$) occurs for some days in the intervals (Feb. 26, March 16) and (Sept. 23, Oct. 16), and those for a southern hemisphere earth station in the intervals (March 16, April 12) and (August 31, Sept. 23).

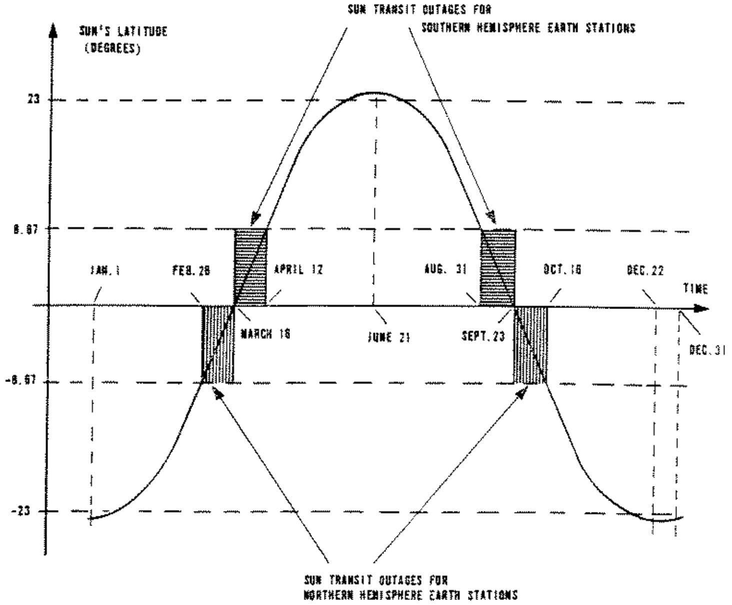


FIGURE 2: THE SUN'S LATITUDE AS A FUNCTION OF TIME FOR 1983 SHOWING POSSIBLE SUN TRANSIT OUTAGE PERIODS.

Next, we consider the geometry at times other than the coplanar instant. When the sunrays are not parallel to the plane SEI, then, as shown in Figure 3, the off-axis angle OFFAX can be computed from the following equation:

$$\mathrm{OFFAX} = \arccos\left\{\frac{\overline{SE}^2 + \overline{SK}^2 - \overline{EK}^2}{2.\overline{SE}.\overline{SK}}\right\} \qquad (3)$$

where the slant range $\overline{SE}$ and the distances $\overline{SK}$ and $\overline{EK}$, can be computed, as shown in Appendix B, from the coordinates of the earth station and of the satellite, and from the directions of the sunrays at both the coplanar instant and the noncoplanar instant under consideration

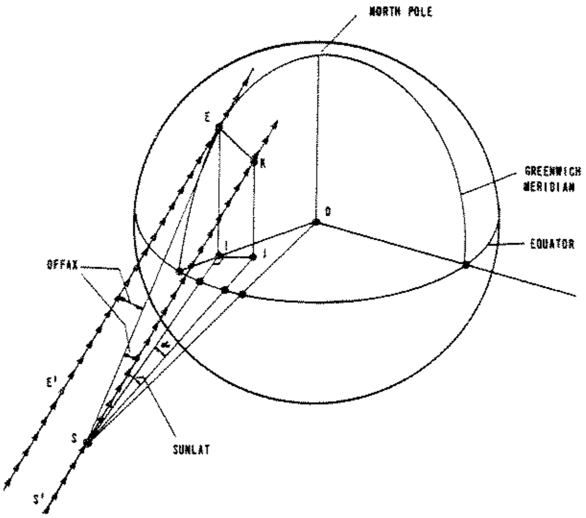


FIGURE 3: GEOMETRIC REPRESENTATION OF SUN TRANSIT. - NONCOPLANAR INSTANT.

Once the off-axis angle OFFAX is known, the solar noise temperature received at the receiver input, Ta, can be computed with the standard assumption that the sun is a disk of constant temperature, Ts, and of 0.5° diameter[1,7].

$$\mathrm{Ta} = \frac{\mathrm{TsG}}{4\pi} \underbrace{\iint}_{\text{Sun's Solid Angle}} f(\theta,\phi)\sin\theta\, d\theta\, d\phi \qquad (4)$$

where θ and ϕ are two of the three spherical coordinates expressed in radians, the sun's solid angle is defined by the shaded area shown in Figure 4, G is the earth station antenna maximum gain expresseed as a power ratio, and $Gf(\theta,\phi)$ is the antenna gain pattern expressed as a power ratio. This can be estimated from the following Gaussian model[8,9].

$$f(\theta,\phi) = f(\theta) = \mathrm{antilog}\left[-6\times10^{-5}(G-1)\theta^2\right] \quad (5)$$

$$G = k4\pi A/\lambda^2 = 109.66kD^2F^2 \qquad (6)$$

where k, D, F, and θ are, respectively, the antenna efficiency, the antenna aperture diameter in meters, the receive carrier frequency in GHz, and the off-axis angle from the antenna boresight axis in degrees.

In general, the antenna pattern is given with respect to the spherical coordinate system whose Z-axis coincides with the antenna boresight axis. In this case, determination of the limits of the double integral over the solid angle is not directly possible. However, through coordinate transformations[10], the antenna pattern can be expressed as $f(\theta^*, \phi^*)$ in the spherical coordinate system whose Z-axis is pointed to the center of the sun (as shown in Figure 5). Then, Eq. (4) can be rewritten as:

$$Ta = \frac{TsG}{4\pi} \int_0^{\frac{.25\pi}{180}} \int_0^{2\pi} f(\theta^*,\phi^*) \sin\theta^* d\theta^* d\phi^* \qquad (7)$$

The double integral can easily be carried out by a numerical integration procedure such as Romberg Integration, or Simpson's Rule[11].

The solar disk tempertature, Ts, varies in a complicated fashion. It follows the sun's eleven year cycle, and depends on the radio emission from the sun. This emission has three distinct components, originating from the quiet sun, the bright regions, and transient disturbances such as flares, respectively[12]. As an approximation, Ts may be estimated from the following relation:

$$Ts = 120000F^{0.75} \qquad (8)$$

which is more or less the average of the Allen curve and Van de Hulst curve given in Reference 13.

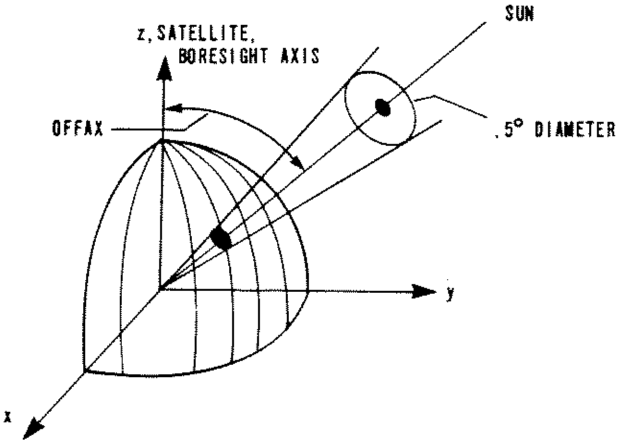


FIGURE 4: THE SUN'S SOLID ANGLE (SHADED) AND THE OFF-AXIS ANGLE OFFAX: Z-AXIS POINTED TO THE SATELLITE.

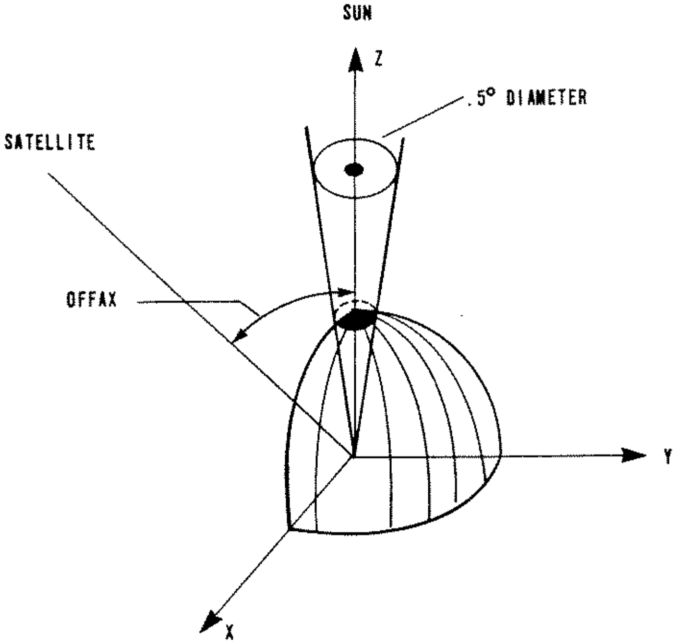
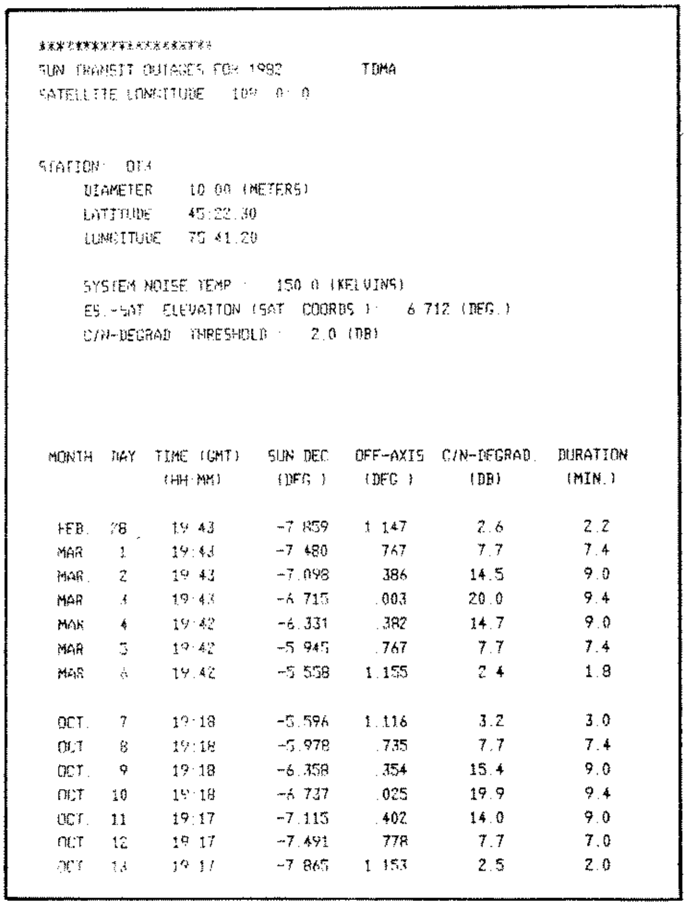


FIGURE 5: THE SUN'S SOLID ANGLE (SHADED) AND THE OFF-AXIS ANGLE OFFAX: Z-AXIS TO THE SUN.



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SUN TRANSIT OUTAGES FOR 1982          TDMA
SATELLITE LONGITUDE   109: 0: 0


STATION:  OT3
     DIAMETER     10.00 (METERS)
     LATITUDE     45:22.30
     LONGITUDE    75 41.20

     SYSTEM NOISE TEMP :    150.0 (KELVINS)
     ES.-SAT  ELEVATION (SAT  COORDS.):   6.712 (DEG.)
     C/N-DEGRAD  THRESHOLD :    2.0 (DB)



 MONTH  DAY  TIME (GMT)   SUN DEC   OFF-AXIS  C/N-DEGRAD.  DURATION
              (HH:MM)     (DEG.)    (DEG.)      (DB)       (MIN.)

  FEB.  28    19:43       -7.859    1.147        2.6         2.2
  MAR    1    19:43       -7.480     .767        7.7         7.4
  MAR.   2    19:43       -7.098     .386       14.5         9.0
  MAR    3    19:43       -6.715     .003       20.0         9.4
  MAR    4    19:42       -6.331     .382       14.7         9.0
  MAR    5    19:42       -5.945     .767        7.7         7.4
  MAR    6    19:42       -5.558    1.155        2.4         1.8

  OCT.   7    19:18       -5.596    1.116        3.2         3.0
  OCT    8    19:18       -5.978     .735        7.7         7.4
  OCT.   9    19:18       -6.358     .354       15.4         9.0
  OCT   10    19:18       -6.737     .025       19.9         9.4
  OCT.  11    19:17       -7.115     .402       14.0         9.0
  OCT   12    19:17       -7.491     .778        7.7         7.0
  OCT   13    19:17       -7.865    1.153        2.5         2.0
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TABLE 1: A SAMPLE PRINTOUT ACCORDING TO STATION (OTTAWA 3) AND SERVICE (TDMA) FOR 1982.

The C/N-degradation in dB at the demodulator input can then be computed from the following:

$$\Delta(C/N) = 10\log\left[(Tsys + Ta)/Tsys\right] \quad (9)$$

where Tsys is the equivalent system noise temperature at the receiver input in the absence of a sun transit. Tsys includes the equivalent noise temperature of uplink noise, noise generated in the transponder, intermodulation and interference noise, downlink noise, and noise generated by the earth station receiver, all referred to the receiver input.

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SUN TRANSIT OUTAGES FOR 1983
SATELLITE LONGITUDE  104 30  0



OCT  15

TIME (GMT)  STATION   SERVICE  C/N-DEGRAD.
 (HH MM)                         (DB)

   18:35      WHE      CBCRTV     8.7
   18:37      TUK      CBCRTV    16.3
   18:38      BUY      BCTEL      4.6
   18:38      TKK      AGTTR      9.6
   18:40      CA2      GBLFTV      .9
   18:40      CA2      LRTDMA     1.2
   18:40      CA3      CMFAX      2.0
   18:40      SHR      NWTTR     14.1
   18:40      HYR      NWTTR      8.8
   18:40      LMA      CANCOM      .2
   18:41      YKE      CBCRTV    13.3
   18:41      HID      NWTTR     14.1
   18:42      SDT      NWTTR     12.8
   18:42      COF      NWTTR     10.3
   18:42      COE      AGTTR     10.3
   18:43      KYE      SASKTR     6.3
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     •
     •
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TABLE 2: A SAMPLE PRINTOUT ACCORDING TO ASCENDING ORDER OF THE SUN TRANSIT PEAK TIME ON OCT. 15, 1982.

THE PROGRAMS

Based on the method described above, two programs, written in FORTRAN'77 and named SUNT1 and SUNT2, have been developed for use on an HP-1000 computer system. SUNT1 generates detailed information on sun transit predictions, and SUNT2 is used to handle cases of large data bases.

The solar disk temperature can be either specified or estimated from Eq. (8). The antenna gain pattern can be either supplied from a data file or computed from Eqs.(5) and (6). Other input data include: the year considered, the satellite's longitude, the maximum tolerable C/N-degradation (outage threshold), the downkink carrier frequency, the earth station data and service data. The last two can be entered manually or fetched from user-supplied data bases. The earth station data base contains names, codes, longitudes, latitudes and diameters of all earth station antennas. The service data base consists of names, codes and number of served earth stations for all services; and for each service, earth station identification indices in the earth station data base, and equivalent system noise temperatures.

The results can be printed out according to station and service and/or according to the ascending order of the sun transit outage peak time (time of the coplaner instant). Sample printouts are shown in Tables 1 and 2.

PREDICTION ACCURACY

Numerous sun transit outage measurements have been taken by Telesat Canada in the past. The most recent one is shown in Figure 6. As compared with the predictions, the differences in the times of the coplanar instant are within half a minute and those in the C/N-degraduation are within a few dB

The accuracy in the time of the coplanar instant is more than sufficient for our purposes. However, it could be improved further by employing a better model to predict the sun's position, a better model to describe the earth's geometry, and by taking into consideration the earth station's altitude and the earth station's pointing deviation for the nominal.

The discrepancy in the C/N-degradation is due mainly to the variation of the solar disk temperature, which is difficult to predict, and due to the assumption that the sun is 0.5° disk source of the constant temperature. This assumption is not accurate for cases involving high gain (narrow beamwidth) antennas since the brightness distribution over the solar disk is not uniform. This can be seen in Figure 7. Nevertheless, there is not much one can do to improve the accuracy of the C/N-degradaton

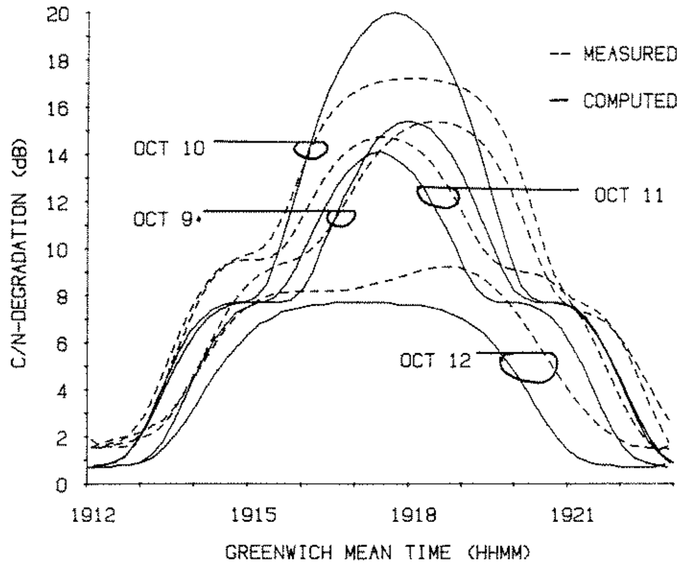

FIGURE 6: A SAMPLE OF SUN TRANSIT MEASUREMENT AND THE CORRESPONDING PREDICTION FOR THE TEN METER EARTH STATION OTTAWA 3 (POINTED TO THE ANIK-B SATELLITE) IN OCT., 1982

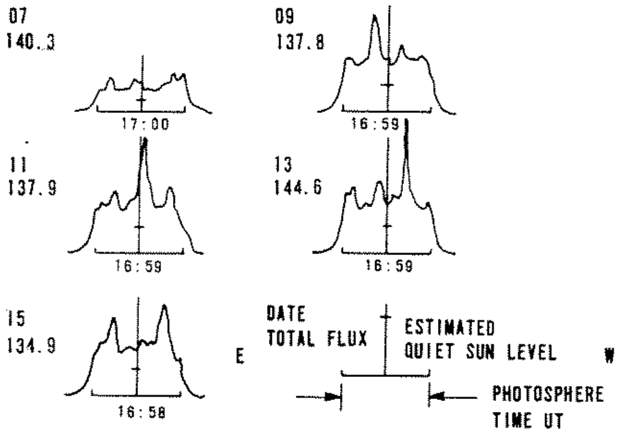

FIGURE 7: ONE DIMENSIONAL BRIGHTNESS DISTRIBUTION OVER THE SOLAR DISK IN OCT. 1982[14]

prediction, since the brightness distribution over the solar disk is measured and available in only one dimension[14] and cannot be extrapolated accurately more than a couple of days in advance.

CONCLUSION

A method and computer programs used do generate accurate sun transit predictions have been developed. Comparison with measurements have been performed. The accuracy in the prediction of sun transit outage peak is within half a minute and that of C/N-degradation is within a few dB.

ACKNOWLEDGMENT

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APPENDIX A: COMPUTATION OF AZ AND EL

AZ and EL, as illustrated in Figure 1, are the azimuth and elevation angles of the earth station with respect to the satellite. They should not be confused with the more familiar azimuth and elevation angles of the satellite with respect to the earth station. By convention here, AZ takes a negative value if the earth station is east of the satellite, and EL takes a negative value if the earth station is located in the southern hemisphere.

The earth has been modelled as a spherical ellipsoid. Thus the earth's radius, $\overline{OE}$, at the latitude of the earth station, ESLAT, may be calculated as follows:

$$\overline{OE} = R/\left[1 + e^2 \sin^2(ESLAT)/(1-e^2)\right]^{\frac{1}{2}} \qquad (A1)$$

where

R = equatorial radius of the earth
= 6378.16 km

e = eccentricity of the earth
= 0.08182

Resolving $\overline{OE}$ into components parallel and normal to the equatorial plane gives:

$$\overline{OI} = \overline{OE}.\cos(\text{ESLAT}) \qquad (A2)$$

and

$$\overline{EI} = \overline{OE}.\sin|\text{ESLAT}| \qquad (A3)$$

Let ESLON be the longitude of the earth station and SATLON be the longitude of the satellite and define their difference as A, so that:

$$A = |\text{ESLON} - \text{SATLON}| \qquad (A4)$$

and

$$\overline{IM} = \overline{OI}.\sin A \qquad (A5)$$

Define $\overline{OS}$ as the nominal radius of the geostatonary orbit, equal to 42164.2 km. Then,

$$\overline{SI} = |\overline{OS}^2 + \overline{OI}^2 - 2.\overline{OS}.\overline{OI}.\cos A|^{\frac{1}{2}} \qquad (A6)$$

Finally,

$$|AZ| = \arcsin(\overline{IM}/\overline{SI}) \qquad (A7)$$

$$|EL| = \arctan(\overline{EI}/\overline{SI}) \qquad (A8)$$

APPENDIX B: COMPUTATION OF SE, SK AND EK

From Figure 3,

$$\overline{SE} = (\overline{SI}^2 + \overline{EI}^2)^{\frac{1}{2}} \qquad (B1)$$

where $\overline{SI}$ and $\overline{EI}$ may be computed from equations (A6) and (A3), respectively.

Let SUNLAT be the sun's latitude at the noncoplanar instant, and SUNLONc and SUNLON, the sun's longitude at the coplanar and noncoplanar instants, respectively. Define α as the difference between the sun's longitude at the two instants, so that

$$\alpha = |\text{SUNLON} - \text{SUNLONc}| \qquad (B2)$$

Then,

$$\overline{SJ} = \overline{SI}/\cos\alpha \qquad (B3)$$

and

$$\overline{SK} = \overline{SJ}/\cos(\text{SUNLAT}) \qquad (B4)$$

Also,

$$\overline{KJ} = \overline{SJ}.\tan|\text{SUNLAT}| \qquad (B5)$$

and

$$\overline{IJ} = \overline{SI}.\tan\alpha \qquad (B6)$$

Finally,

$$\overline{EK} = \{\overline{IJ}^2 + |\overline{EI} + \text{sgn}(\text{SUNLAT}.\text{ESLAT})\overline{KJ}|^2\}^{\frac{1}{2}} \qquad (B7)$$

where

$$\text{sgn}(x) = \begin{cases} 1 & x \geq 0 \\ -1 & x < 0 \end{cases}$$

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