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ESTIMATION OF ATMOSPHERIC ABSORPTION IN SOLAR RADIO DATA AT 3.75 GHz

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Abstract

Influences of the terrestrial atmospheric absorption are examined for the solar data recorded by the 3.75-GHz full-automatic radiopolarimeter at Toyokawa. The optical depth is estimated with an assumption of plane-parallel geometry to be in the range between 0.016 and 0.018 for the period from July through September, 1980. Comparison is made with values in earlier works and accuracy of the data is discussed.

1. Introduction

Measurements of solar radio flux densities at 9.4, 3.75, 2, and 1 GHz are being carried out every day by using full-automatic radiopolarimeters at Toyokawa. Time constant of the receiver system is about 0.3 sec. The flux data are sampled and digitized at an interval of 0.1 sec by a mini-computer, and sent to the host computer, where ten-second averaged flux is calculated and recorded on magnetic tapes. The equipments and the data acquisition system have been already described in detail by Torii et al. (1979) and Shibasaki et al. (1979).

Time	Comment
t1	Start of data acquisition
t2	Antenna beam begins to move from south to eastern horizon
t3	Sunrise
t4	Sunset
t5	Antenna beam begins to move from western horizon to south
t6	End of data acquisition

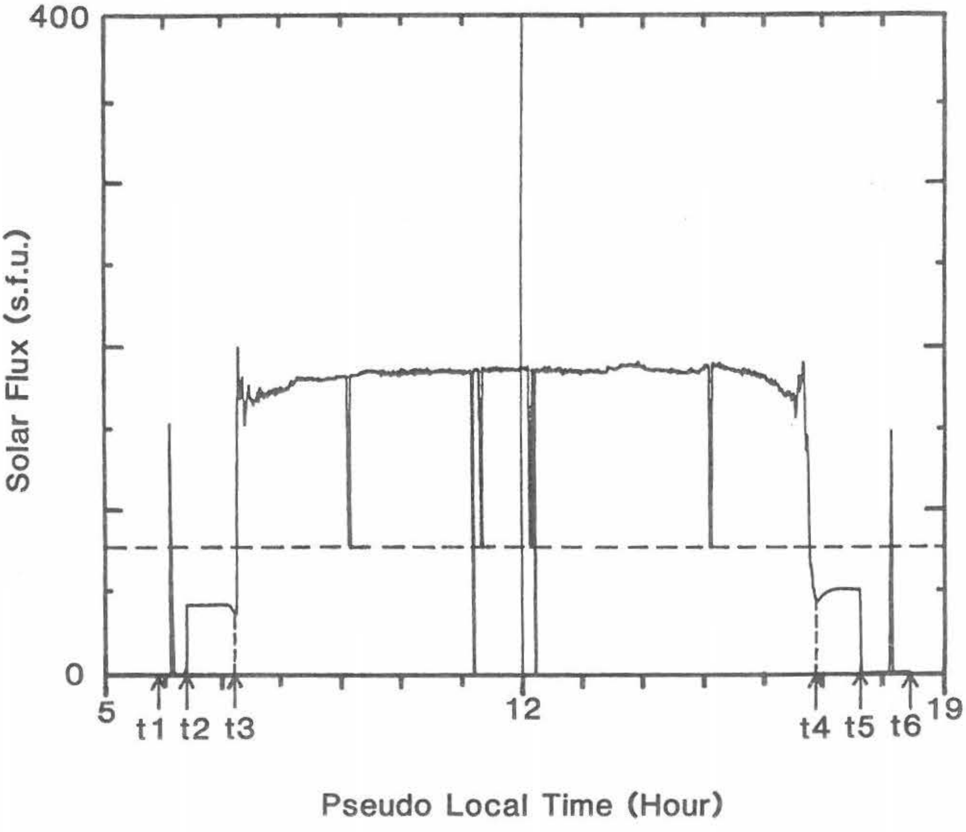


Figure 1. Example of single day data. The time t1 to t6 is explained in appended table. The dashed-line level corresponds to the atmospheric temperature, the abscissa is the pseudo local time at Toyokawa Observatory (see the text), and the time is from 5 hour to 19 hour. The ordinate is the flux density and the unit is 10^{-22} Wm^{-2} Hz^{-1} (s.f.u.). Gain check of receiver is carried out at 6, 9, 11, 12, 15, and 18 hours of JST.

As is seen in Figure 1, the output of the radiopolarimeter is lower at just after the sunrise and just before the sunset than the level near the noon. The oscillatory features appearing near the sunrise and sunset are due to the interference between the solar emissions one directly received by the antenna and the other reflected at the ground and then received by the antenna. The apparent depression of the solar flux densities in observations at low altitude of the Sun is mainly due to the atmospheric absorption.

Actually, the radiations received by the radiopolarimeter are not only the solar radio emissions but also the spillover of the antenna. Therefore it is important to establish the way correcting these influences for an effective use of radiopolarimeter data.

In Section 2, an example of observations is displayed and the influence of the atmospheric absorption on the data is explained. In Section 3, we describe a method to estimate the optical depth of the terrestrial atmosphere at 3.75 GHz from radiopolarimeter observations. The estimated value of the optical depth is in the range of 0.016 to 0.018. In the microwave region, Encrenaz et al. (1970) obtained 0.008 as a value of optical depth at the zenith by measuring the atmospheric emission and Cassiopeia A using a horn antenna at 1.415 GHz. This value is consistent with that determined from sky temperatures obtained by the experiment of Echo satellite at 2.39 GHz (Ohm, 1961). Theoretical values of the optical depth are summarized by Waters (1976), and can be simply calculated by the formulae obtained by Croom (1964) (Appendix 2).

In Section 4, we discuss the descrepancy between the value estimated by us and those of earlier work.

2. Atmospheric Absorption

An example of data (January 1st, 1980) is shown in Figure 1, where the abscissa is the pseudo local time at Toyokawa, which is given by 12 hours plus hour angle of a virtual Sun, which passes the central meridian with the true Sun but moves with the mean Sun, and the ordinate is the flux density. During the periods from the time t1 to t2 and from the time t5 to t6 in the Figure, the antenna is directed in the central meridian plane at the declination of the Sun. From the time t3 to t4 the antenna tracks the Sun automatically. The time t3 and t4 represent sunrise and sunset respectively. The gain check of receivers is carried out normally at 6, 9, 12, 15, and 18 hours of JST (Japan Standard Time) as shown in Figure 1.

The radio emission received by radiopolarimeter is composed of solar emission attenuated by the terrestrial atmospheric absorption, the terrestrial atmospheric emission, and the spillover of the antenna.

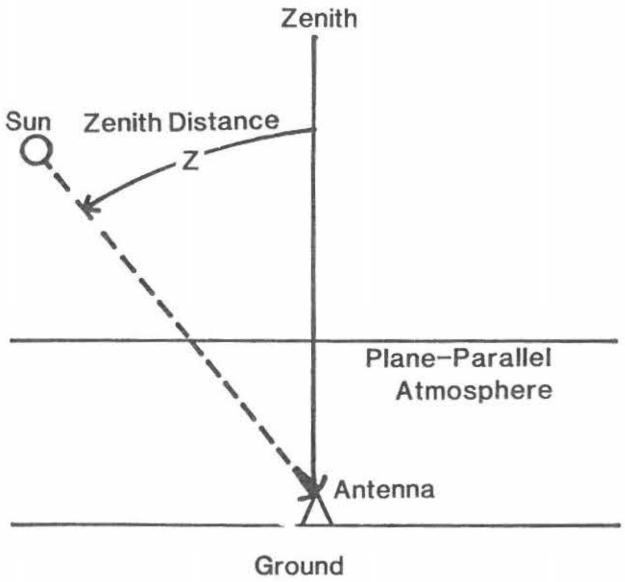


Figure 2. The plane-parallel atmosphere. This is assumed to obtain the optical depth in the direction of the Sun. The optical depth is given by τ secZ. Z is the zenith distance and τ is the optical depth in the direction of the zenith.

Assuming a plane-parallel atmosphere as is illustrated in Figure 2, the observed brightness temperature of the Sun is given by

$$T_{obs} = T_o \exp(-\tau \sec Z) + T_a \{1 - \exp(-\tau \sec Z)\} + T_g(Z), \quad (1)$$

where Tobs is an observed antenna temperature, To is an antenna temperature of the Sun at the top of the atmosphere, Ta is an atmospheric temperature, Tg(Z) is a spillover, τ is an optical depth in the zenith direction, and Z is the zenith distance.

It is considered that the spillover Tg(Z) is mainly a component of the ground radiation received from sidelobes of the antenna. When To is equal to Ta, the observed antenna temperature Tobs is given by

$$\text{Tobs} = \text{Ta} + \text{Tg(Z)}. \quad (2)$$

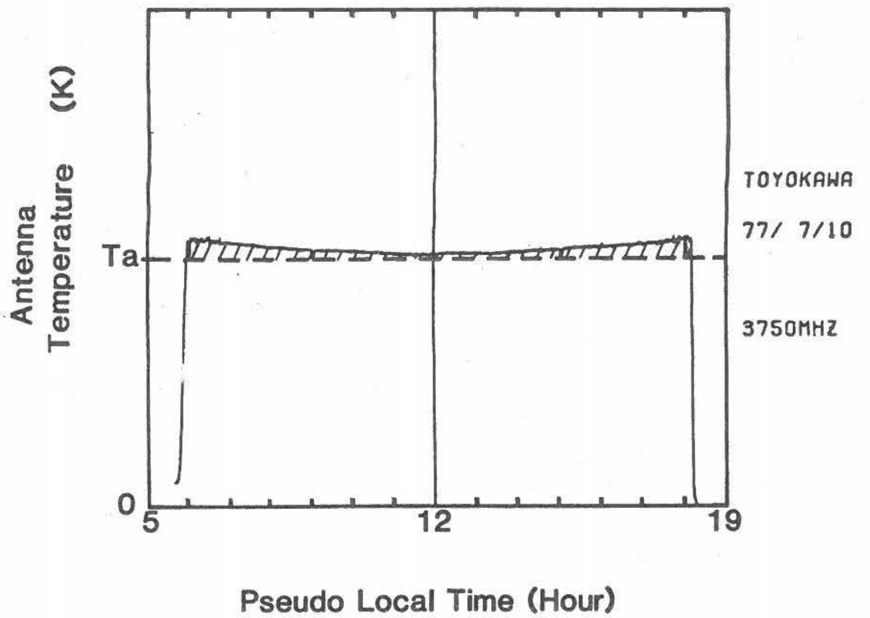


Figure 3. The data for which To is equal to Ta. The spillover Tg(Z) was calculated by this data. To is an antenna temperature of the sun at the top of the atmosphere and Ta is an atmospheric temperature. The hatched part corresponds to the antenna spillover, from which Tg(Z) is deduced.

During the period of sunspot minimum, the antenna temperature of the Sun is very close to Ta for the 3.75-GHz radiopolarimeter. On July 10, 1977 (Figure 3), the antenna temperature of the Sun was nearly equal to the atmospheric temperature and we can employ these data to get the spillover Tg(Z). In the following, we use Tg(Z) obtained in this way.

3. Estimation of Optical Depth

Using the observed valûe Tobs and from equation (1), the estimated value To' of the antenna temperature of the Sun is given by

$$To' = \{ Tobs - Ta - Tg(Z) \} \exp(\tau \sec Z) + Ta. \qquad (3)$$

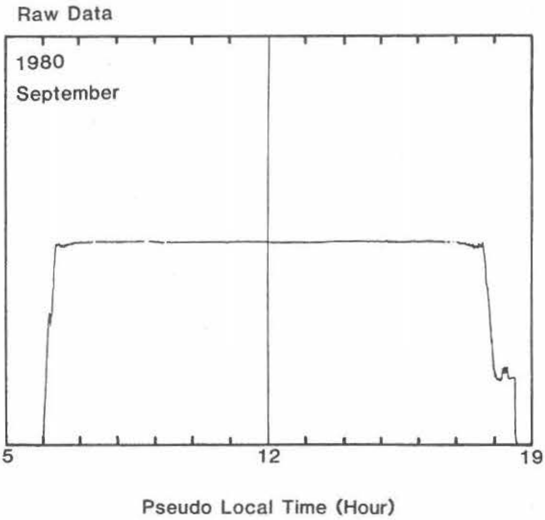
Estimation of the optical depth is, therefore, necessary.

Under an assumption that the solar radio flux (To) is stationary during the course of observations, To' in equation (3) is regarded as constant. The assumption can be justified for quiet days. An estimation of τ is made as follows.

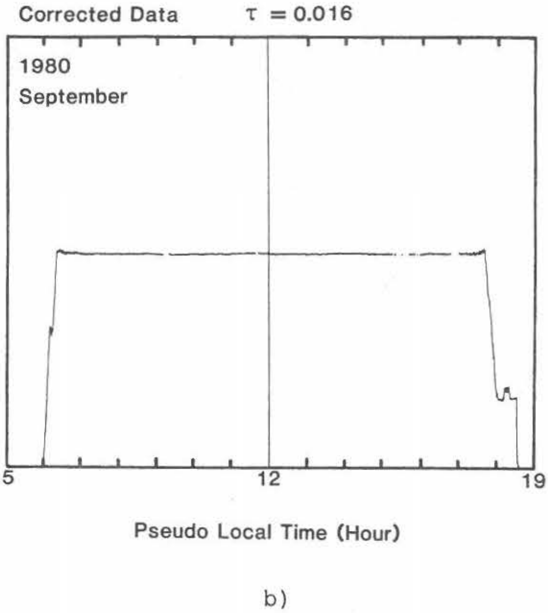
1) A trial value of τ is assumed and is substituted in equation (3) to obtain modified single day data.
2) The modified data is averaged for a month except bursts.
3) The averaged data is fitted by a quadratic equation of the pseudo local time by a least square method.
4) A correction to the assumed value of the optical depth is so determined that the quadratic coefficient of the fitted equation may converge to zero.
5) This correction is performed to the assumed value in the procedure 1), and then procedures 1) to 4) are repeated, until the correction reduces to less than 10^{-5}.

The solar radio data were surveyed from September, 1979 to September, 1980. The data from July, 1980 to September, 1980 were chosen and then the above procedure is carried out. In this period, the solar activity was relatively low and the variation of the receiver gain was small. The estimated values of the optical depth are 0.017, 0.018, and 0.016 for July, August, and September in 1980 respectively. The raw data and corrected data averaged for a month in September, 1980 are respectively shown in Figures 4 a) and 4 b).

In Figure 5, the raw data and the corrected data on November 28, 1979 is shown. The depression is seen after sunrise and before sunset in the raw data. In the corrected data, however, the degree of depression is much reduced.



a)



b)

Figure 4. Raw data and corrected data in September, 1980. a) is raw data and b) is the data corrected with the estimated optical depth of 0.016. Both data are averaged for a month except bursts.

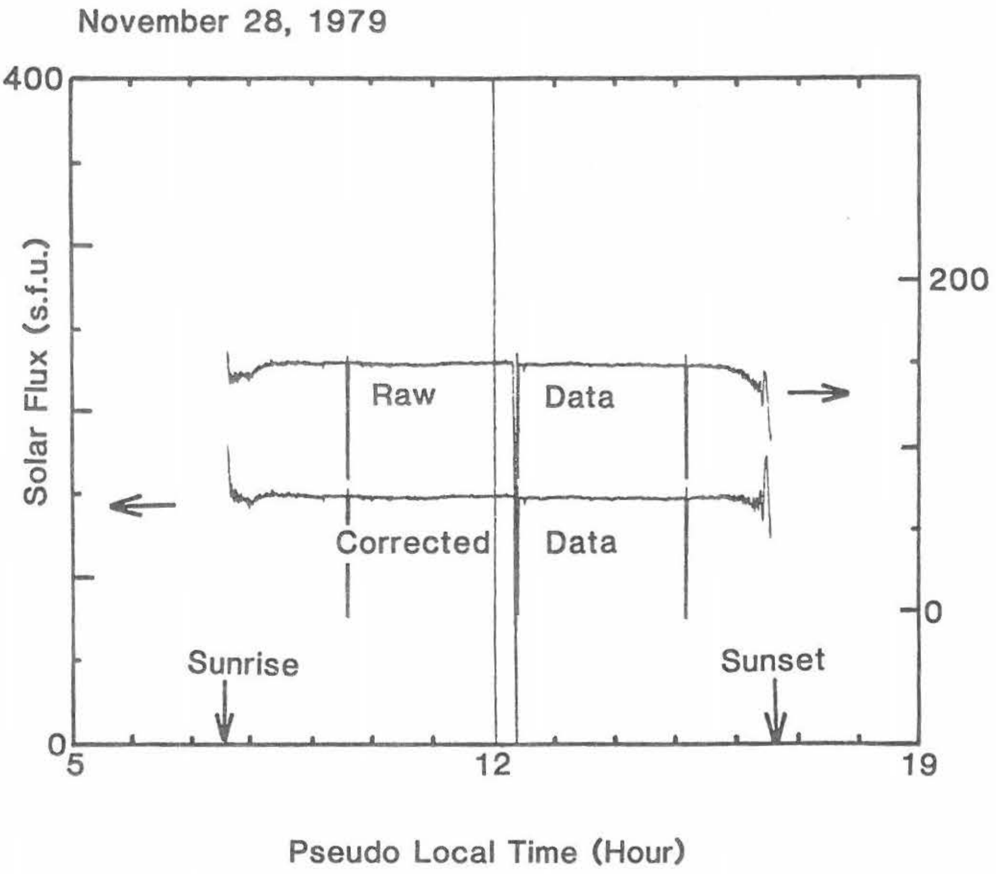


Figure 5. Raw data and corrected data on November 28, 1979. This data is corrected with the estimated optical depth of 0.016.

4. Summary and Discussion

As is described in the preceding Section, the estimated value is in the range from 0.016 to 0.018, and as mentioned previously, 0.008 is obtained for the optical depth by the experiments at the 1.415 GHz and 2.39 GHz (Ohm 1961; Encrenaz 1970).

Theoreticaly, at 3.75 GHz the optical depth is equal to 0.007 with the absorption coefficient formulae derived by Croom (1964) (Appendix 2). The discrepancy between the estimated value and those by the earlier measurments and the theoretical value may be due to the gain instability of our receiving system and errors in estimation of the spillover Tg(Z).

From these investigations we may conclude that the present method gives a way for getting true solar flux density corrected for the influences of the atmospheric absorption and spillover within an accuracy of 1 %. A better calibration of gain variation will give more correct estimation of the atmospheric absorption and spillover, and will give a better accuracy in the estimation of true solar flux density at low altitude.

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Appendix

1. Error of the optical depth between the plane-parallel atmosphere and the spherical atmosphere

Geometry of the plane-parallel atmosphere and the spherical atmosphere is shown in Figure A and the each path length in the direction of the Sun is given by

$$Lz = L\sec Z,$$

$$Lz' = \sqrt{r^2\cos^2 Z + 2rL + L^2} - r\cos Z,$$

where Lz is a path length in the plane-parallel atmosphere, Lz' is a path length in the spherical atmosphere, L is a path length in the direction of the zenith, Z is a zenith distance, and r is the radius of the Earth.

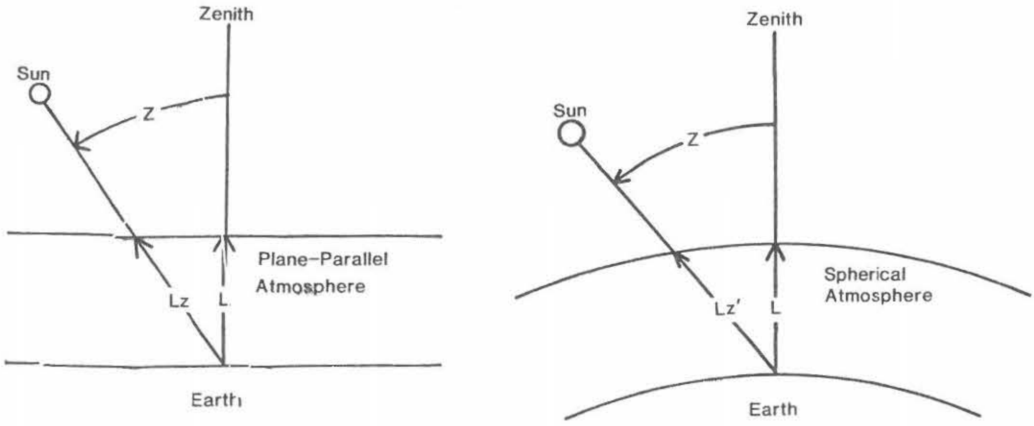

Figure A. Plane-parallel atmosphere and spherical atmosphere. For both cases path lengths are calculated and compared.

F(Z) is the ratio of the difference between Lz and Lz' to Lz', and is given by

$$F(Z) = \frac{\sec Z}{\sqrt{(r/L)^2\cos^2 Z + 2r/L + 1} - r/L\cos Z} - 1,$$

where r is equal to 6400 Km and L is equal to 8 Km because it is considered that L is equal to the scale height of the atmosphere. The calculated values of F(Z) are listed in Table A-1.

Table A-1. Zenith distance vs. F(Z). F(Z) is shown in the text and is the ratio of the difference between Lz and Lz' to Lz'. Lz' is the path length in the plane-parallel atmosphere, and Lz is the path length in the spherical atmosphere.

Zenith distance (°)	65	70	75	80	85	88
F(Z) (%)	0.21	0.35	0.65	1.48	5.78	29.63

2. Simple approximated formulae for calculation of the optical depth

The terrestrial atmospheric absorption at 3.75 GHz is mainly due to absorption lines of oxygen and water vapour. The former has a complex of resonance lines centred at a wavelength of 0.5 cm (60 GHz) and the latter has a resonance line at a wavelength of 1.35 cm (22.2 GHz) and resonance lines in the millimeter region (especially 183.3 GHz). The contribution of the line absorption is extended down to the order of 1 GHz because of pressure broadening.

The optical depth in the direction of the zenith is given by

$$\tau = \int_0^\infty (k+k')\,dh,$$

where k is absorption coefficient of oxygen, k' is absorption coefficient of water vapour, and h is height in km. In the following computation, the integration has been made up to the height of 20 km.

A simple approximated formulae of k and k' is given by Croom (1964) as

$$k = \begin{cases} 6.39/10^3 \exp(-0.195h) - 2.02/10^6\,\lambda^2 \exp(-0.458h) \\ \qquad \text{for } 10>h \text{ and } 3>f>1, \\ 0.345(0.018+0.025/\lambda^2)\exp(-0.195h) \\ \qquad \text{for } 10>h \text{ and } 10>f>3, \\ 5.15/10^2(0.018+0.025/\lambda^2)\exp\{-0.318(h-10)\} \\ \qquad \text{for } 20>h>10 \text{ and } 10>f>1, \end{cases}$$

$$k' = 3.48\rho/(10^4\lambda^2)(1/A+1/B+3.43)\exp(-0.221h),$$

where

$$A=(1/\lambda-1/1.35)^2,$$
$$B=(1/\lambda+1/1.35)^2,$$

and λ is wave length in cm, h is height in km, ρ is density of water vapour in gm/m^3, and f is the frequency in GHz.

Table A-2. Calculated values of the optical depth at 9.4, 3.75, 2, and 1 GHz. The optical depth is in the direction of the zenith.

Frequency (GHz)	9.4	3.75	2	1
τ	0.009	0.007	0.007	0.006

The calculated value of the optical depth is listed in Table A-2 for ρ is equal to 8exp(-0.548h). At 3.75 GHz, computations give

$\int_0^{20km} k\, dh$ is equal to 0.0073 and $\int_0^{20km} k'\, dh$ is equal to 0.0001.

The contribution of the water vapour is one order of magnitude less than that of oxygen. Thus the dependence of the atmospheric absorption on weather condition is expected to be negligible.

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