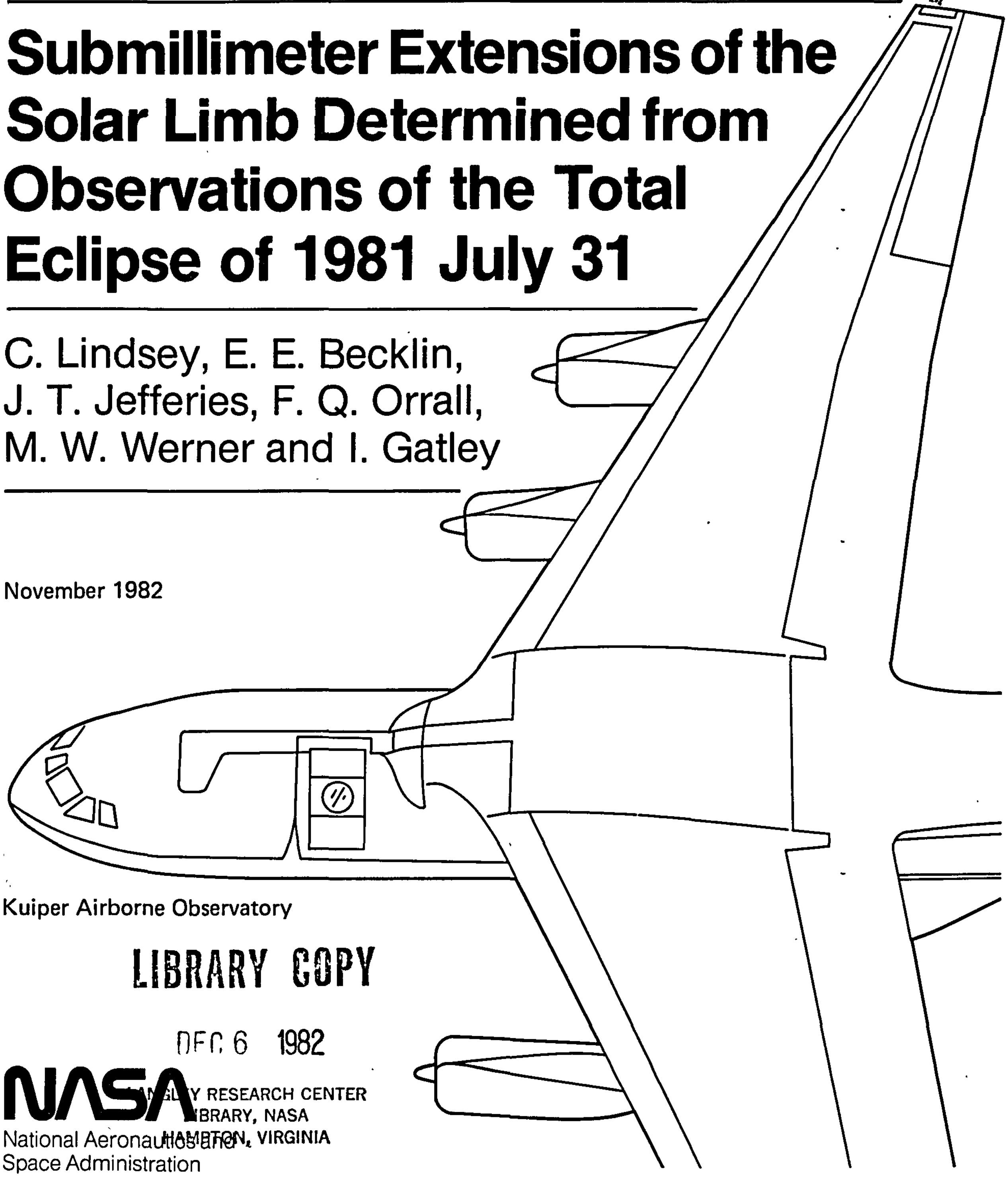
NASA Technical Memorandum 84306

Airborne Astronomy Program
Medium Altitude Missions Branch
Preprint Series 001

Submillimeter Extensions of the Solar Limb Determined from Observations of the Total Eclipse of 1981 July 31

C. Lindsey, E. E. Becklin,
J. T. Jefferies, F. Q. Orrall,
M. W. Werner and I. Gatley

November 1982



Kuiper Airborne Observatory

NASA
National Aeronautics and
Space Administration

NASA Technical Memorandum 84306

Airborne Astronomy Program
Medium Altitude Missions Branch
Preprint Series 001

Submillimeter Extensions of the Solar Limb Determined from Observations of the Total Eclipse of 1981 July 31

C. Lindsey
E. E. Becklin
J. T. Jefferies
F. Q. Orrall, Institute for Astronomy, University of Hawaii
M. W. Werner, Ames Research Center, Moffett Field, California
I. Gatley, United Kingdom Infrared Telescope

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

N83-14047 #

Ap. J. Lett.

SUBMILLIMETER EXTENSIONS OF THE SOLAR LIMB DETERMINED FROM OBSERVATIONS OF THE TOTAL ECLIPSE OF 1981 JULY 31

C. Lindsey, E. E. Becklin, J. T. Jefferies, and F. Q. Orrall

Institute for Astronomy, University of Hawaii

M. W. Werner

NASA-Ames Research Center

and

Ian Gatley

United Kingdom Infrared Telescope

Received September 1982

Accepted for publication in Astrophysical Journal Letters

ABSTRACT

We present first results of observations of a lunar occultation of the solar limb made from the Kuiper Airborne Observatory in the 30, 50, 100, and 200 μm continuum during the total solar eclipse of 1981 July 31. We find the solar limb to be extended at the longer wavelengths up to 1000 km higher than predicted from smooth plane-parallel chromospheric models. Results at both second and third contact show the infrared limb extensions to be approximately 0".8, 1".5, 2".5, and 3".0 above the visible limb in the 30, 50, 100, and 200 μm bands, respectively. A possible interpretation proposes chromospheric fine structure inhomogeneities of greater density than presently incorporated in models of the middle chromosphere.

DEDICATION

We dedicate this work to David A. Barth, the chief pilot of the KAO during the eclipse observation, who tragically lost his life while test-flying an aircraft a few weeks after the successful completion of our program. Our observations required operation of the aircraft at its performance limit, and we therefore depended very much on his skill. We were very fortunate not only in having the benefit of his outstanding ability, but also for the real pleasure of his personal acquaintance during his involvement with our program.

I. INTRODUCTION

Observations in the infrared continuum provide a powerful LTE probe of the temperature and density structure of the solar atmosphere. The 30 to 200 μm continuum is of particular importance, since it originates from the temperature minimum, where nonradiative heating becomes important (cf., Thomas and Athay 1961).

The obstacles to making good solar observations at these wavelengths are that 1) the earth's atmosphere is opaque to most of the 30 to 300 μm range, and 2) diffraction severely limits angular resolution. Because of these difficulties, few solar observations exist in this entire spectral band.

The Kuiper Airborne Observatory (KAO) is uniquely suited to overcome both these problems, since it can fly a 0.9 m telescope to altitudes above 10 km, where atmospheric extinction of infrared radiation is only a few percent (cf. Cameron et al. 1971) . Furthermore, the occultation of the solar limb during an eclipse permits a determination of the solar limb intensity profile with high angular resolution. Smearing and displacement of the lunar shadow due to Fresnel diffraction are of the order

$$\Delta\theta \lesssim \left(\frac{\lambda}{\text{Distance to Moon}}\right)^{1/2} , \qquad (1)$$

which is less than 0".1 for wavelengths, λ, less than 200 μm. The practical limit to resolution is imposed by the roughness of the lunar limb, whose height distribution has a width of the order 1".

The overall eclipse experiment was designed to determine the intensity profile of the quiet solar limb. In this first report we present a determination of the extensions of the infrared limbs above the visible limb. These results, obtained by timing the occultations at all wavelengths, show the solar limb at 200 μm to be extended up to three arc seconds beyond the visible limb. This extension is substantially greater than that computed for prevailing chromospheric models in which the low chromospheric temperature minimum region is homogeneous, smooth, and in approximate hydrostatic equilibrium.

The observations we describe were made from the KAO at an altitude of 13 km over the north Pacific Ocean, close to the Kurile Islands, north of Japan, during the total solar eclipse of 1981 July 31. Both 2nd and 3rd contact occultations were observed in well-defined broad passbands centered near 30, 50, 100, and 200 μm. All four passbands were monitored simultaneously at the same position on the limb.

A full analysis of the infrared intensity profiles will be presented in subsequent papers.

II. PROCEDURE

The KAO telescope is a 0.9-m Cassegrain with f/17 secondary optics. For solar observations, a filter of 6 mm thick high-density polyethylene was installed over the primary mirror to reject visible light and prevent overheating of the telescope optics. This filter introduced optical aberrations that smeared the instrumental beam width to ~100" at 200 μm and to ~130" at 30 μm.

The detector system was a dichroic cryogenic four-channel photometer (cf., Gatley et al. 1977). In this system incoming radiation enters a 4 mm (60") common focal-plane aperture, and is partitioned by dichroic beamsplitters into four well-defined passbands centered near 30, 50, 100, and 200 μm, with fractional width $\Delta\lambda/\lambda \sim 0.3$. These bands are detected separately by four gallium-doped germanium bolometers. The infrared flux in the same region is thus monitored simultaneously in all four passbands.

Two-beam chopping was used to compensate for variable sky and telescope emissivity and to eliminate low-frequency electronic noise in the detector system. In this technique the secondary mirror of the telescope is rocked at 30 Hz in a square-wave mode, so that the focal plane aperture alternately samples beams 2' apart. The detector outputs are fed into phase-switched amplifiers, which extract the signal difference and thus continuously register the infrared flux difference between the two beams. We define the "positive beam" and the "negative beam" according to the sign of the signal voltage produced by an infrared source in the respective beam.

In normal two-beam chopping the difference signal due to an unresolved source in one beam is sensitive to guiding errors. To solve this problem a 0.5 Hz triangular wave of 5' amplitude was superimposed on the normal square-wave oscillation of the secondary mirror. This has the effect of sweeping both beams across the solar limb crescent, once each second.

This procedure is illustrated in Figure 1 for the occultation approaching second contact (a). As the negative beam sweeps across the limb crescent (cf. profile b), a negative signal (two-beam difference) results, closely followed by a positive deflection as the positive beam follows behind. The resulting profile is shown in (c). The ordinate range of this profile serves as a measure of the solar intensity in the band swept by the beams.

The telescope was gyro-stabilized with a 1 Hz rms guiding jitter estimated at 2" and a guiding drift of 2"/sec. A visual pointing reference was provided by a bore sighted guide telescope. The triangular-wave scan was centered onto the projected point of second contact on the solar limb, where it was maintained for a full 20 seconds after visual second contact. The telescope was then moved across the moon to the projected point of third contact, where the foregoing sequence (in reverse) was repeated.

The occultation rate, as viewed from the moving aircraft, was calculated 0".46/sec. The total duration of visual totality was 88 s.

III. RESULTS

Figure 2 shows the 30 and 200 μm two-beam scan profiles across the solar limb crescent from about 15 seconds preceding to 10 seconds following visual second contact. Profile 2(a) provides the positions of the center-point between the beams as they are scanned across the crescent. Profile 2(b) shows the resultant 200 μm signal difference.

A 200 μm signal difference for the lunar limb is clearly present after the solar contribution has disappeared. This profile during totality was used to generate a representation of the lunar contribution throughout the occultation 2(c), which was subtracted from the 200 μm profile (a) to represent the profile of the solar contribution alone (d). The 30 μm occultation profile is shown in (e).

The differences between the upper and lower envelopes of the two-beam difference plots define an occultation curve for the segment of the solar crescent scanned by the beams. These amplitudes are plotted in Figure 3 for 30 and 200 μm, at both second and third contact. The 50 and 100 μm occultation curves fall between the 30 and 200 μm profiles. The lower, abscissa zeros are the points of visual second and third contact as determined by a video tape record of the guide telescope image.

Note that the 200 μm occultation curve at second contact extrapolates to zero 2" above the 30 μm curve. The 30 μm curve in turn extrapolates to zero ~1" above the visible limb. The 200 μm limb is therefore a full 3" above the visible limb. This result is confirmed at third contact. We contend that such large limb-extensions cannot be produced artificially. Neither Fresnel diffraction nor sudden limb-brightening can conspire to extend the moment of occultation significantly.

Note that the occulation curves are approximately linear approaching contact. This indicates a relatively flat intensity profile approaching the extreme limb. The slope of the 200 μm profile at third contact is ~15% greater than at second contact. This indicates a locally brighter limb, possibly associated with weak calcium plage near the point of third contact (cf. Hale regions 17754 and 17761).

The times of visible second and third contact were determined from a video tape record of the visual reference monitor used for guiding. Because of the increased vidicon gain during totality, our determination of the time of visible third contact was made with three times better precision than the time of second contact. The separation of the 30 μm limb above the visible limb at third contact was measured at $0''.8 \pm 0''.2$. This value is also adopted for second contact, because of better timing of visual third contact. The limb extensions for all wavelengths for both second and third contacts are listed in Table 1.

IV. DISCUSSION AND CONCLUSIONS

The submillimeter limb extensions determined by our occultation observations increase progressively with wavelength from 0".8 (580 km) above the visible limb at 30 μm to 3" (2200 km) at 200 μm. These heights are respectively 900 km and 2500 km above the base of the photosphere (defined by τ [5000 Å] = 1 viewed at disk center), which lies 340 km below the visible limb. These results are not easily understood in terms of smooth hydrostatic-equilibrium model chromospheres made to fit radiometric measures of the solar continuum, including all of the models of Vernazza, Avrett and Loeser (VAL 1981). The only known important submillimeter continuum opacity sources in the solar chromosphere are free-free absorption in (e, p) and (e, H) collisions. These increase approximately as λ^2, and so are much greater for the longer wavelengths. At low chromospheric heights in the VAL models, temperatures are much less than 6000 K and hydrogen is almost entirely neutral, so that (e, H) absorption dominates. Above 1200 km, hydrogen ionization exceeds 1%, generating strong (e, p) absorption, which dominates from thence upward. We calculate the 200 μm limb heights due to free-free opacity to be less than 1500 km for all of the VAL models, approximately 1000 km below the observed height.

It is hard to see how a simple modification of the smooth models can provide the extra chromospheric opacity needed to raise the 200 μm limb the additional 1000 km required by the observations. Such a discrepancy strongly indicates the existence of dense fine-structure inhomogeneities in the middle chromosphere that depart from gravitational-hydrostatic equilibrium.

The sense of our results was somewhat to be anticipated from earlier results at longer wavelenghts. Beckman, Lesurf, and Ross (1975) claim a limb extension of 4" at in 400, 800, and 1200 μm Horne et al. (1980) observed a limb extension of the order of 8" at 1300 μm. These extensions have been attributed to chromospheric spicules (Beckman and Clark 1978), seen in Hα images of the solar limb. Our observations must relate to similar but denser lower-lying fine structure.

Our results establish the existence of material of significant submillimeter opacity at heights exceeding 2500 km above the base of the photosphere. An important hypothesis is that the fine-structure material responsible for the extended limbs corresponds to the 6000 K hydrogen ionization plateau, so prominent in all of the VAL models. The onset of hydrogen ionization in this temperature region could provide strong (e, p) absorption to make the fine structure opaque to submillimeter radiation.

The 200 μm disk-center brightness temperature is only 4500 K (Rast et al. 1978). Consequently, opaque 6000 K fine structure should brighten the limb considerably. A colder limb would require cooler and much denser fine structure to generate the observed submillimeter limb extensions. A resolution of this matter will depend on careful analysis of our data to determine the absolute limb brightness temperatures at the longer wavelengths.

We applaud the entire KAO staff for their extreme hard work, competence and enthusiasm, which made this special and difficult program a success. The Astrophysical Experiments Branch at NASA-Ames gave exemplary technical support. The staff and personnel of Yakota Air Force Base in Japan gave us special hospitality and a comfortable and convenient working situation. Marie K. McCabe provided us with valuable support from the Mees Solar Observatory. Our Japanese colleagues at Kyoto University and the University of Tokyo provided us with important updates on solar activity and strong support in making our operation in Japan possible. We regret that space does not allow us to thank all those who worked so hard on this extremely difficult project. This work was supported in part by NASA grants NAG 2-59, NGL 12-001-011, and NASW-3159, the Royal Observatory of Edinburgh and by the NASA-Ames Research Center.

TABLE 1

Submillimeter Limb Extensions

λ	Second contact	Third contact
0.5 μm	0".0 ± 0".5	0".0 ± 0".2
30 μm (ref)	0".8 ± 0".0	0".8 ± 0".0
50 μm	1".4 ± 0".2	1".7 ± 0".2
100 μm	2".2 ± 0".2	2".7 ± 0".2
200 μm	2".9 ± 0".2	3".2 ± 0".2

REFERENCES

Beckman, J. E., Lesurf, J. C. G., and Ross, J. 1975, Nature, 254, 38.

Beckman, J. E., and Ross, J. 1978, in Far Infrared Astronomy, ed. M. Rowan-Robinson (Oxford: Pergamon Press), p. 79.

Cameron, R. M., Bader, M., and Mobley, R. E. 1971, Appl. Optics 10, 211.

Gatley, I. I., Becklin, E. E., Werner, M. W., and Wynn-Williams, C. G. 1977, Ap. J., 216, 277.

Horne, K., Hurford, G. J., Zirin, H., and de Graauw, T. 1980, Ap. J., 244, 340.

Orrall, F. Q., Becklin, E. E., Jefferies, J. T., Lindsey, C., Werner, M. W., and Gatley, I. I. 1982, BAAS, 13, 880.

Rast, J., Kneubuehl, F. K., and Mueller, E. A. 1978, Astr. Ap., 68, 229.

Thomas, R. N., and Athay, R. G. 1961, Physics of the Solar Chromosphere (New York: Interscience), p. 17.

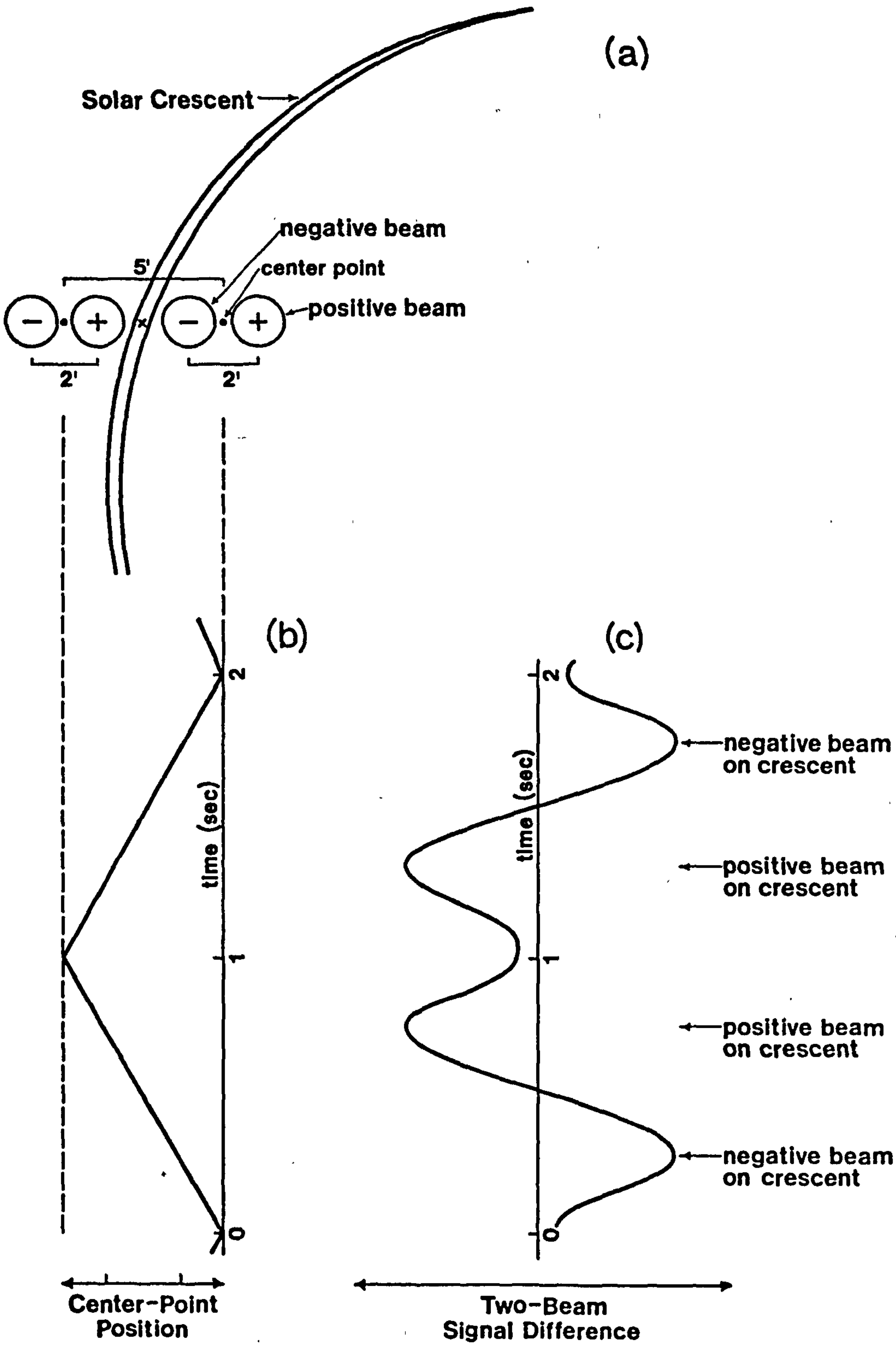
Vernazza, J. E., Avrett, E. H., and Loeser, R. 1981, Ap. J. Suppl., 45, 635.

FIGURE CAPTIONS

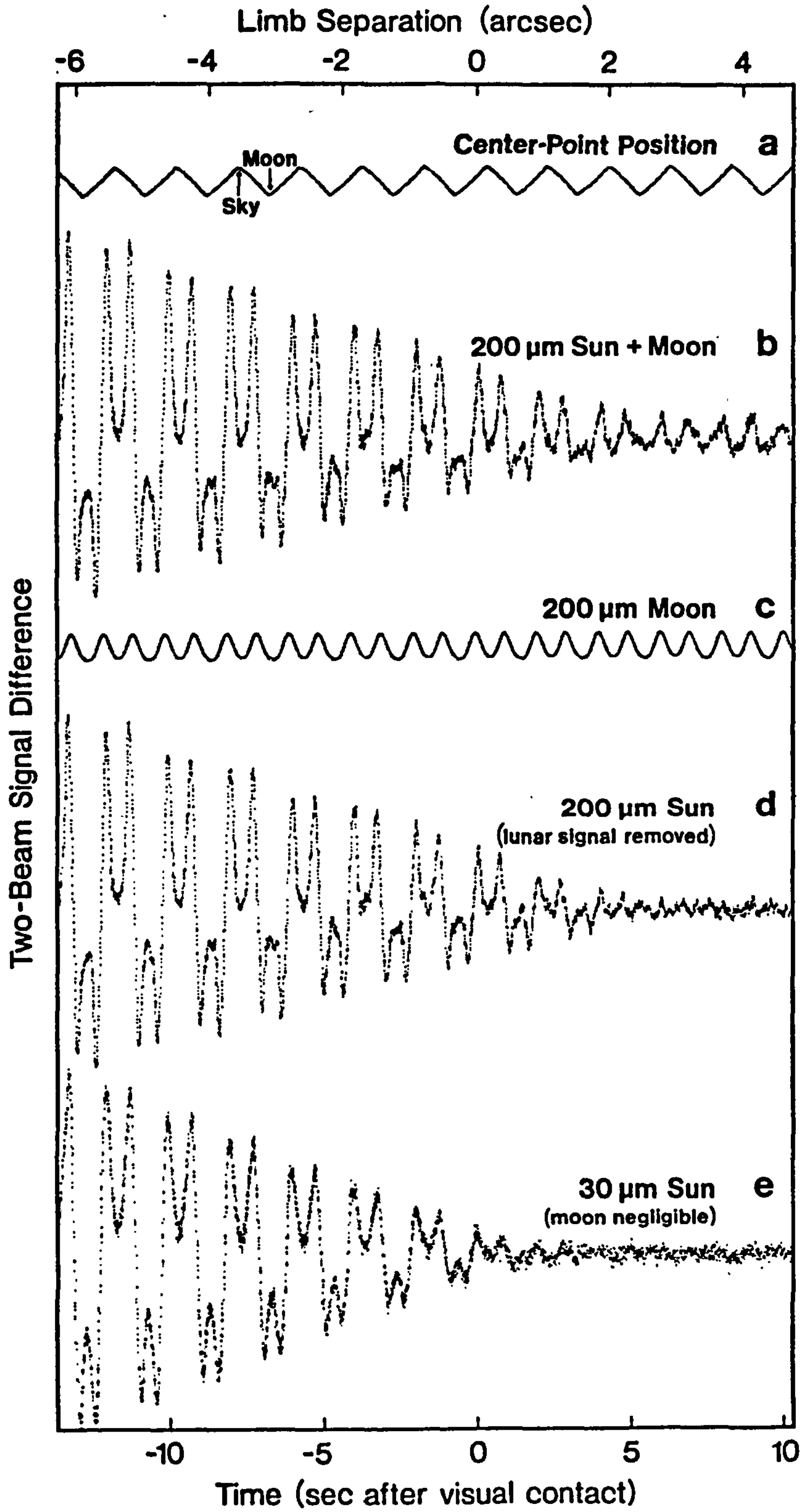
FIG. 1.—Schematic diagram of two-beam chopping-scanning mode used for observing the solar limb crescent (a) — see text for details.

FIG. 2.—Two-beam difference profiles across the solar limb crescent at 30 and 200 μm during the 2nd contact limb occultation — see text for details.

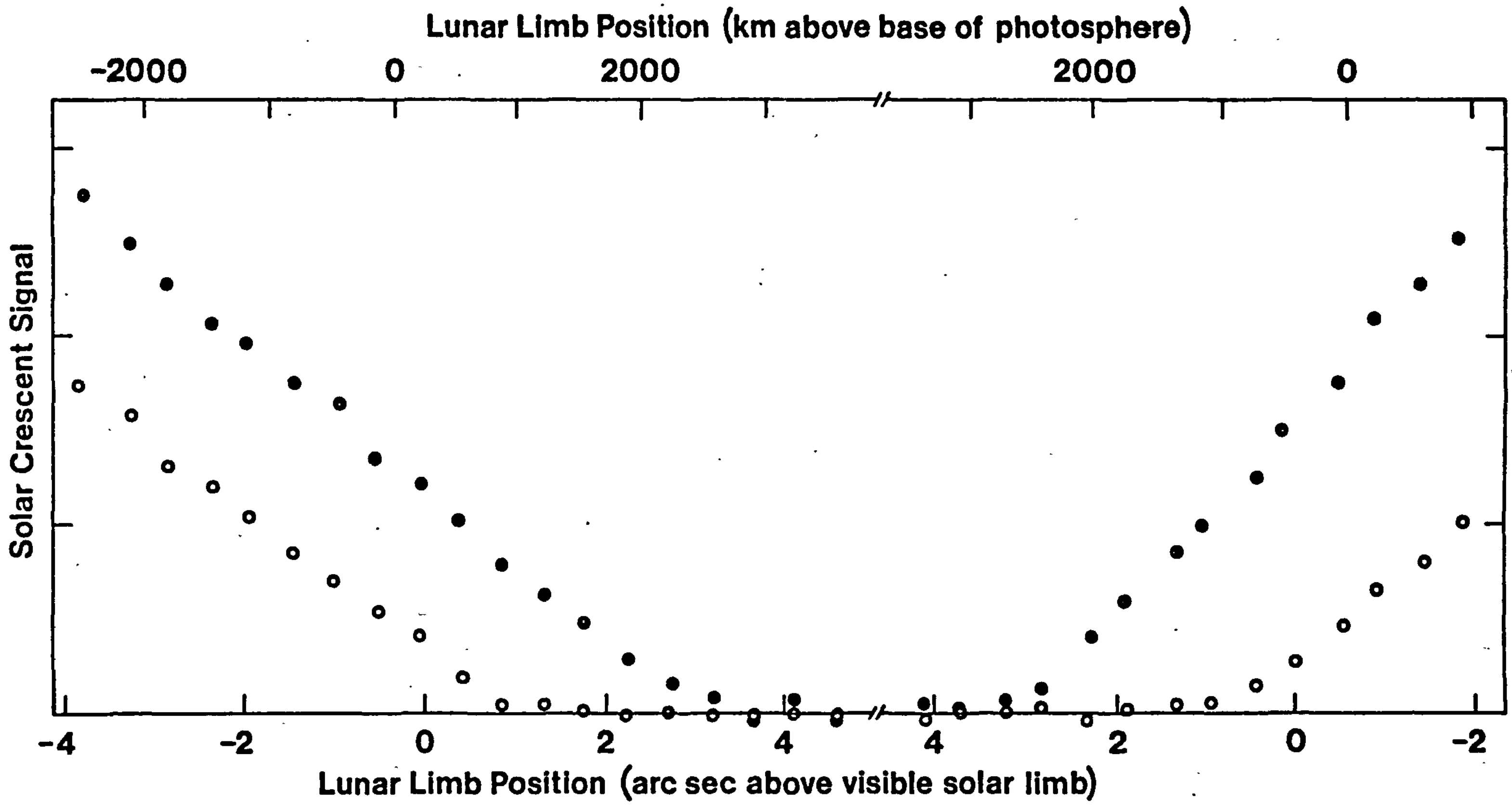
FIG. 3 —Occultation curves at 30 and 200 μm at second and third contact. The bottom abscissa zeros represent the points of visual contact. The upper abscissa zeros reference the base of the solar photosphere (340 km below the visible limb.



(a)
Solar Crescent
negative beam
center point
positive beam
5'
2'
2'
(b)
time (sec)
0
1
2
Center-Point
Position
(c)
time (sec)
0
1
2
negative beam
on crescent
positive beam
on crescent
positive beam
on crescent
negative beam
on crescent
Two-Beam
Signal Difference



Limb Separation (arcsec)
-6
-4
-2
0
2
4
Center-Point Position
a
Moon
Sky
200 μm Sun + Moon
b
200 μm Moon
c
200 μm Sun
(lunar signal removed)
d
30 μm Sun
(moon negligible)
e
Two-Beam Signal Difference
-10
-5
0
5
10
Time (sec after visual contact)


Lunar Limb Position (km above base of photosphere)
-2000
0
2000
2000
0
Solar Crescent Signal
-4
-2
0
2
4
4
2
0
-2
Lunar Limb Position (arc sec above visible solar limb)

1. Report No.
NASA TM-84306

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
SUBMILLIMETER EXTENSIONS OF THE SOLAR LIMB DETERMINED FROM OBSERVATIONS OF THE TOTAL ECLIPSE OF 1981 JULY 31

5. Report Date
November 1982

6. Performing Organization Code

7. Author(s)
C. Lindsey,* E. E. Becklin,* J. T. Jefferies, F. Q. Orrall,* M. W. Werner,** and Ian Gatley†

8. Performing Organization Report No.
A-9154

9. Performing Organization Name and Address
*Institute for Astronomy, University of Hawaii, Honolulu, Hawaii
**Ames Research Center, Moffett Field, Calif. and
†United Kingdom Infrared Telescope, Hilo, Hawaii

10. Work Unit No.
352-02-03

11. Contract or Grant No.
NAG-259, NGL 12-001-011, and NASW-3159

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes
Preprint Series #1. Supported by NASA grants. Point of Contact: L. C. Haughney, Ames Research Center, Moffett Field, Calif. 94035, M/S 211-12, (415) 965-5339, FTS 448-5339

16. Abstract

We present first results of observations of a lunar occultation of the solar limb made from the Kuiper Airborne Observatory in the 30, 50, 100, and 200 μm continuum during the total solar eclipse of 1981 July 31. We find the solar limb to be extended at the longer wavelengths up to 1000 km higher than predicted from smooth plane-parallel chromospheric models. Results at both second and third contact show the infrared limb extensions to be approximately 0".8, 1".5, 2".5, and 3".0 above the visible limb in the 30, 50, 100, and 200 μm bands, respectively. A possible interpretation proposes chromospheric fine structure inhomogeneities of greater density than presently incorporated in models of the middle chromosphere.

17. Key Words (Suggested by Author(s))
Submillimeter observations
Solar limb
Solar eclipse

18. Distribution Statement
Unlimited

STAR Category - 92

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	20	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161