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**LYMAN ALPHA SMM/UVSP ABSOLUTE CALIBRATION
AND GEORONAL CORRECTION**

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TABLE OF CONTENTS

	Page
1. DEFINITIONS.....	1
2. CALIBRATION.....	4
3. SLIT PROFILE.....	5
4. THE GEOCORONAL CORRECTION FOR LYMAN ALPHA	6
5. CONVOLUTION OF GEOCORONAL FEATURE.....	11
6. ABSOLUTE CALIBRATION OF DETECTOR 1 AT LYMAN ALPHA	13
7. FUTURE WORK	15
REFERENCES.....	16

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TECHNICAL MEMORANDUM

LYMAN ALPHA SMM/UVSP ABSOLUTE CALIBRATION AND GEOCORONAL CORRECTION

1. DEFINITIONS

This report defines the instrument quantum efficiency K_s^d , where the index d refers to detector number and s to slit number. This can be considered as the product of two functions

$$K_s^d = K_d Q_s \quad ,$$

where Q_s is a factor which is different for different slits. It has been assumed that

$$Q_2 \equiv 1 \quad ,$$

i.e., slit 2 as the reference slit.

By definition, the function K_d does not depend on slit but only on detector and time and will be expressed as K_d (doy) where doys is a floating point number of days. Further K_d and probably Q_s also depend on wavelength.

Thus, K_d can be considered as the ratio between detected photons, N , and the number of incident photons, N_i . The number of photons with frequencies between $\nu - \frac{\Delta\nu}{2}$ and $\nu + \frac{\Delta\nu}{2}$, which enter the instrument during the gate time t_e , is given by:

$$N_i = t_e a \omega \int_{\Delta\nu} \frac{I_\nu d\nu}{h\nu} \quad ,$$

where h is the Planck constant, I_ν the radiation intensity, a the area of the observed solar surface, and ω the solid angle which corresponds to the entrance of the instrument as seen from the Sun.

The frequency can be taken out of the integral. The constant can be calculated from the quotient of the telescope collector area ($A = 66.4 \text{ cm}^2$ [1]) and the square of the distance to the Sun ($R^2 = 2.238E26 \text{ cm}^2$) to give

$$\omega = 2.967E-25 \text{ ster} .$$

The area of the observed solar surface can be expressed in square arc seconds as

$$a = s \left(\frac{2 \pi R}{360 \times 3600} \right)^2 = s \times 5.26E15 \text{ cm}^2 ,$$

so,

$$\omega a = s \times 1.56E-9 \text{ cm}^{-2} \text{ ster} ,$$

and,

$$\frac{a\omega}{hc} = 7.86E6 \text{ s} .$$

So for the number of incident photons, one writes (with λ in cm)

$$N_i = t_e s 7.86E6 \lambda \int_{\Delta \nu} I_\nu d\nu .$$

One may replace $\int_{\Delta \nu} I_\nu d\nu$ with $\int_{\Delta \lambda} I_\lambda d\lambda$, provided the domains $\Delta \nu$ and $\Delta \lambda$ are equivalent. For $\text{Ly}\alpha$

$$N_i = t s 95.5 \int_{\Delta \nu} I_\nu d\nu .$$

Since for slit 2 all lines (including $\text{Ly}\alpha$) are unresolved, i.e., much sharper than the slit, the maximum counts for that slit are proportional (linear response is assumed) to the integrated intensity in all cases. This is the main reason for using slit 2 as the reference slit. And since $s = 1'' \times 1''$, then

$$K_d = K_2^d = \frac{N_{\max}}{t_e \cdot 7.86E6 \cdot \lambda \int_{\Delta \nu} I_\nu d\nu} ,$$

and for Ly α

$$K_d = \frac{N_{\max}}{t_e \cdot 95.5 \int_{\Delta \nu} I_\nu d\nu} .$$

When using other slits and unresolved lines, one can use similar formulae for K_s^d but considering different s and λ .

When using other slits for resolved lines (not 1 or 2), slits which have widths comparable to the line width, and for which the counts reflect the line profile (even when convolved), one can also calculate the integrated intensity by adding the counts at all scanning positions. But depending on the step size (n) and the effective slit width, one is counting many times the same photons (at the same frequencies) or missing some of them. In order to correct for this effect, one multiplies the counts by the multiplicity factor:

$$m = \frac{n \delta \lambda}{\Delta \lambda_{\text{eff}}}$$

where $n \delta \lambda$ is the wavelength displacement corresponding to each step. So one can write

$$K_s^d = \frac{n \delta \lambda}{t_e \cdot s \cdot 7.86E6 \cdot \lambda \cdot \Delta \lambda_{\text{eff}}} \cdot \frac{\sum N}{\int_{\Delta \nu} I_\nu d\nu} .$$

For Ly α one has

$$K_s^d = \frac{n \delta \lambda}{t_e \cdot s \cdot 95.5 \cdot \Delta \lambda_{\text{eff}}} \cdot \frac{\sum N}{\int_{\Delta \nu} I_\nu d\nu} .$$

If one wants to obtain the absolute values of K_S^d , one can use the values for the integrated intensities of the quiet Sun. See for example Vernazza and Reeves [2] which give $\int I_\nu d\nu$ for many lines in the UV region of the spectrum.

2. CALIBRATION

Once the quantum efficiency has been determined, it can be used to calibrate, in absolute units, the profiles of resolved lines as well as the rasters. Assuming that I_ν^c is the intensity convolved with the slit response function (ϕ_ν) normalized to 1, one has:

$$I_\nu^c = \int_{\Delta\nu} \phi_\nu I_\nu d\nu \quad \text{or} \quad I_\lambda^c = \int_{\Delta\lambda} \phi_\lambda I_\lambda d\lambda \quad ,$$

with

$$\int_{\Delta\nu} \phi_\nu d\nu = \int_{\Delta\lambda} \phi_\lambda d\lambda = 1 \quad .$$

Then, if one assumes that I_ν^c does not vary over a $n\delta\lambda$ interval (which is not always the case), one finds for each step in wavelength

$$N_i = t_e s \ 7.86E6 \ \lambda \ \Delta\nu_{\text{eff}} \ I_\nu^c \quad ,$$

or

$$N_i = t_e s \ 7.86E6 \ \lambda \ \Delta\lambda_{\text{eff}} \ I_\lambda^c \quad ,$$

where

$$\Delta\nu_{\text{eff}} = \frac{\nu \ \Delta\lambda_{\text{eff}}}{\lambda} = \frac{c}{\lambda} \cdot \frac{\Delta\lambda_{\text{eff}}}{\lambda} \quad .$$

The coefficients C_ν and C_λ are defined by the formula

$$N = C_v I_v^c = C_\lambda I_\lambda^c ,$$

where

$$C_v = K_s^d t_e s 2.36E17 \frac{\Delta \lambda_{\text{eff}}}{\lambda} ,$$

and

$$C_\lambda = K_s^d t_e s 7.86E6 \lambda \Delta \lambda_{\text{eff}} ,$$

(with λ in cm and $\Delta \lambda_{\text{eff}} I_\lambda$ in $\text{erg cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$).

If using λ in \AA and I_λ in $\text{erg cm}^{-2} \text{s}^{-1} \text{ster}^{-1} \text{\AA}^{-1}$, one has

$$I_v = 3.33E-19 \lambda^2 \cdot I_\lambda .$$

For $\text{Ly}\alpha$

$$I_v = 4.93E-13 I_\lambda .$$

3. SLIT PROFILE

The only remaining problem is the definition of ϕ_λ and $\Delta \lambda_{\text{eff}}$ which can be obtained from the observed profile of a very thin line or a sharp edge, assuming one knows both integrated and peak intensity as well as the original line shape. The shape is not necessary if the original full width is much smaller than $\Delta \lambda_{\text{eff}}$. To obtain the function ϕ_λ , one can analyze the profile of a sharp unresolved line with $n\delta\lambda \ll \Delta \lambda_{\text{eff}}$. Under those conditions the observed profile is just the slit profile ϕ_λ . The slit effective width was taken from the table by Woodgate et al. [1]. The slit profiles seem to be well represented except for slits 1, 2, 18, 19, and 22 by the expression

$$\phi_{\lambda} = \begin{cases} \frac{2}{\pi \Delta \lambda_{\text{eff}}} \cos^2 \left(\pi \frac{\Delta \lambda}{\Delta \lambda_{\text{eff}}} \right) & \text{for } |\Delta \lambda| < \frac{\Delta \lambda_{\text{eff}}}{2} \\ 0 & \text{for } |\Delta \lambda| > \frac{\Delta \lambda_{\text{eff}}}{2} \end{cases}$$

For slits 1, 2, 18, 19, and 22, some theoretical diffraction curve may be used.

The formula for the slit profiles can be used for deconvolution procedures, but one must remember that deconvolution is sometimes tricky and mathematically the solution of the problem is not unique. For this reason, it is more reliable to convolve the theoretical profile and then compare with the observed profile.

4. THE GEOCORONAL CORRECTION FOR LYMAN ALPHA

For the geocoronal correction of the Lyman alpha profiles, it is assumed that the intensity received by the instrument is related to the intensity, I_{ν}^{\odot} , from the Sun, by the formula

$$I_{\nu} = I_{\nu}^{\odot} \exp(-\phi_{\nu} \tau)$$

where

$$\phi_{\nu} = \exp \left(- \left(\frac{\Delta \lambda}{\Delta \lambda_{\text{D}}} \right)^2 \right),$$

and ϕ_{ν} is the profile of the geocoronal absorption coefficient. τ is the optical thickness of the geocorona at the center of the feature and $\Delta \lambda_{\text{D}}$ is the Doppler width of the geocoronal absorption coefficient. For the conditions in the geocorona, the profile is well represented by a gaussian profile.

This approach assumes that emissivity is negligible, which is true for solar observations, but is a poor assumption when observing very faint objects. Further, it assumes that the Doppler width is constant throughout the geocorona.

In the above formula, one has to consider also that both parameters τ and $\Delta\lambda_D$ can be functions of time, latitude, and longitude due to temporal and spatial changes in the geocorona. Also differential velocities can affect the present assumptions.

The value of τ to be used has to be considered a function of the zenith angle θ_0 , i.e., of the angle between the direction to the Sun and the Earth radius through the spacecraft position.

The details of that function depend on the geometric model or the geocorona. It should be stressed that the dependence of τ with μ_0 ($\mu_0 = \cos\theta_0$) is not well represented by the formula

$$\tau = \tau_0 / \mu_0$$

because it can only be good for values of μ_0 close to 1 and for a very thin geocorona, which is not the actual case.

The model of the geocorona can be expressed as the function $\kappa(h)$ where κ is the absorption coefficient at the center of the feature and h is the height (along the Earth radius).

A model consisting of a constant value of κ , which is zero except between h_0 and h_1 , where h_0 is the spacecraft altitude, and h_1 some other parametric value, was tried first.

Since there are two experiments (V02345 and V02347) in which profiles have been obtained at various zenith angles, the authors have compared the variation of the feature depth with μ_0 and found that the model does not agree with the observations.

Then a different model which seems to fit the observations was used. The model assumes an exponential variation of κ , viz.

$$\kappa = \kappa_0 \exp\left(-\left[\frac{h-h_0}{H}\right]\right),$$

where κ_0 is the absorption coefficient at height h_0 above the Earth's surface and H is the scale height. This expression applies to the density in a hydrostatic, isothermal atmosphere.

A value of $h_0 = 550$ km was used in the calculations and it was assumed that SMM was in a circular orbit at that height.

With dz being the element of distance from the SMM to the Sun, and $\mu = \cos \theta$ the projection factor at height h for the ray with respect to the direction of the local radius, one has

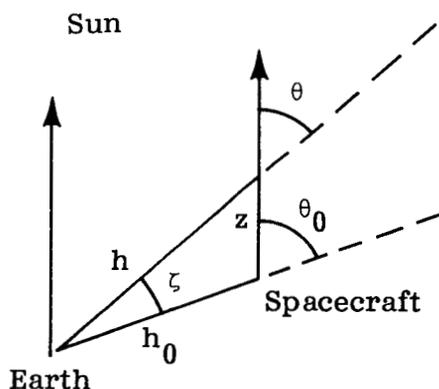
$$\tau = \int_{z_0}^{\infty} \kappa dz = \int_{h_0}^{\infty} \kappa \frac{dh}{\mu} \quad , \quad \text{valid for } \theta \leq 90 \quad .$$

Considering spherical geometry, μ is a function of h . From geometrical considerations

$$\frac{\sin(\pi - \theta_0)}{h} = \frac{\sin \theta}{h_0} = \frac{\sin \zeta}{z} \quad .$$

It follows that

$$\sin \theta = \frac{h_0}{h} \sin \theta_0$$



and that

$$\mu = \left(\frac{h_0}{h} \right) \left[\mu_0^2 + \frac{(h^2 - h_0^2)}{h_0^2} \right]^{1/2} \quad .$$

From the above expression, one sees that even when the formula of τ seems to be the standard, $\mu \neq \mu_0$ for all geometries except for the plane parallel case.

From the above expressions one has

$$\tau = \kappa_0 h_0 \int_1^{\infty} \exp \left(- \frac{(h-h_0)}{H} \right) \cdot \left(\frac{h}{h_0} \right) \frac{d \left(\frac{h}{h_0} \right)}{\left[\mu_0^2 + \frac{(h^2 - h_0^2)}{h_0^2} \right]^{1/2}}$$

or defining $x = \frac{h - h_0}{H}$ and $\beta = \frac{h_0}{H}$

$$\tau = \kappa_0 H \int_0^{\infty} e^{-x(1 + \frac{x}{\beta})} \frac{dx}{\left[\mu_0^2 + \frac{x}{\beta} \left(2 + \frac{x}{\beta} \right) \right]^{1/2}}$$

If $\mu_0 = 1$, one finds

$$\tau_0 = \frac{\kappa_0 H}{\mu_0} = \kappa_0 H$$

i.e., the optical thickness of the geocorona when observing along the Earth radius.

No analytic expression for the integral has been found. It was calculated numerically and then tabulated as a function $\frac{\tau}{\tau_0}(\mu_0, \beta)$. One interpolates in the table for the different cases.

The following values were obtained from the experimental data:

$$\Delta \lambda_D = 0.022 \text{ \AA} ,$$

$$\tau_0 = 0.63 ,$$

and

$$\beta = 2.33 .$$

For the SMM orbit, some parameters of neutral hydrogen are calculated:

$$\sigma = \frac{\pi e^2}{mc\sqrt{\pi}} \frac{f}{\Delta \lambda_D} = 1.68E-18 \left(\frac{\lambda}{\Delta \lambda_D} \right) = 9.28E-14 \text{ cm}^2$$

$$N_H = \frac{\tau_0}{\sigma} = 6.78E12 \text{ cm}^{-2}$$

$$H = 236 \text{ km}$$

$$T = \frac{m_H c^2}{2k} \left(\frac{\Delta \lambda_D}{\lambda} \right) = 1780 \text{ K}^\circ$$

$$n_H = \frac{N_H}{H} = 2.87E5 \text{ cm}^{-3}$$

$$m_m = \frac{kT}{m_H g_H} = 6.36$$

where σ is the atomic cross section at line center, f the oscillator strength, N_H and n_H are the neutral hydrogen atoms column and particle densities, T the kinetic temperature (of neutral hydrogen atoms), m_H the mass of hydrogen atoms, g the gravitational acceleration, c the velocity of light, k the Boltzmann constant, and m_m the mean mass of particles with respect to hydrogen.

From the above, one can correct the incident intensity for geocoronal absorption using the formula

$$I_\nu^\circ = I_\nu \exp(+\phi \tau) \quad .$$

The zenith angle can be calculated as suggested by Henze [3], from the standard routines of Shine [4], knowing the time of the observation of the feature. Care has to be taken for long scans because the time delay during the experiment is sometimes important.

The zenith angle cosine is given by the formula

$$\mu_0 = \cos \beta \cdot \cos \alpha$$

where β is the angle between the SMM orbital plane and the line of sight to the Sun and α is the angle around the orbit from the position of spacecraft orbital noon.

$$\alpha = 2\pi(t - t_n)/T$$

where T is the orbit period, t_n the time from orbital noon, and t the time of the observation.

A detailed study of the time variations of the geocoronal parameters was not performed, but it was apparent for the 1980 data that these parameters did not change significantly. However, after the SMM repair and the observations began again in 1984, the geocoronal parameters show larger variations, showing much deeper and perhaps even broader absorption and possibly a small turn to emission in the center of the Lyman alpha feature.

5. CONVOLUTION OF GEOCORONAL FEATURE

The above mentioned procedure for applying geocoronal correction is good only for slit 20 profiles, because in that case the slit width is smaller than the Doppler width of the feature. Since in the general case one has to correct some observed profile I_ν^c , one can write

$$I_\nu^c = \int_{\Delta\nu} \phi_\nu I_\nu d\nu = \int_{\Delta\nu} \phi_\nu I_\nu^0 \exp(-\phi_0 \tau) d\nu .$$

If one applies the Fourier or Laplace transform to this expression, considering that the transform of the convolution of two functions is the product of their transform, one has

$$\text{Trans } I_\nu^c = \text{Trans } \phi_\nu [\text{Trans } \exp(-\phi_\nu \tau) + \text{Trans } I_\nu^0]$$

and

$$\text{Trans } \phi_\nu \cdot (\text{Trans } I_\nu^0) = \text{Trans } I_\nu^c - \text{Trans } \phi_\nu [\text{Trans } \exp(-\phi_\nu \tau)] .$$

The correcting function is defined at a specific frequency as

$$F = \int_{\Delta\nu} \phi_\nu \exp(-\phi_\nu \tau) d\nu ,$$

and the corrected observed intensity I_{ν}^{co} is

$$I_{\nu}^{\text{co}} = I_{\nu}^{\text{c}} / F = \int_{\Delta \nu} \phi_{\nu} I_{\nu}^{\circ} d\nu .$$

The correcting function in turn can be obtained using the known slit profile and computing numerically the convolution. The complete expression is

$$F = \int_{\lambda - \frac{\Delta \lambda_{\text{eff}}}{2}}^{\lambda + \frac{\Delta \lambda_{\text{eff}}}{2}} \frac{2}{\pi \Delta \lambda_{\text{eff}}} \cos^2 \left[\pi \left(\frac{\lambda - \gamma}{\Delta \lambda_{\text{eff}}} \right) \right] \exp \left[\frac{-\tau}{\exp \left(\frac{\gamma - \lambda_0}{\Delta \lambda_{\text{D}}} \right)^2} \right] d\gamma ,$$

where λ_0 is the wavelength at the center of the geocoronal feature and λ is the wavelength at which one is evaluating the correction.

From this formula, one sees that if $\Delta \lambda_{\text{eff}}$ is smaller than $\Delta \lambda_{\text{D}}$, the correction procedure from the previous section holds, i.e., $F = \exp(-\phi_{\nu} \tau)$. If this is not the case, one has to calculate the function F for all wavelengths between $\lambda_0 - \frac{\Delta \lambda_{\text{eff}}}{2}$ and $\lambda_0 + \frac{\Delta \lambda_{\text{eff}}}{2}$.

If the position of λ_0 corresponds to one exact step, then one can write all the wavelengths in steps and get

$$F = \int_{g - \frac{l_{\text{eff}}}{2}}^{g + \frac{l_{\text{eff}}}{2}} \frac{2}{\pi l_{\text{eff}}} \cos^2 \left[\pi \left(\frac{g - y}{l_{\text{eff}}} \right) \right] \exp \left[\frac{-\tau}{\exp \left(\frac{y - g_0}{l_{\text{D}}} \right)^2} \right] dy$$

where

$$l_{\text{eff}} = \frac{\Delta \lambda_{\text{eff}}}{\delta \lambda} , \quad l_{\text{D}} = \frac{\Delta \lambda_{\text{D}}}{\delta \lambda} , \quad g = \frac{\lambda}{\delta \lambda} , \quad g_0 = \frac{\lambda_0}{\delta \lambda} .$$

Choosing $g_0 = 0$ (i.e., the zero wavelength in the geocoronal feature center) and defining

$$p = \frac{y}{\lambda_{\text{eff}}} = \frac{\gamma}{\Delta \lambda_{\text{eff}}} \quad \text{and} \quad v = \frac{g}{\lambda_{\text{eff}}} = \frac{\lambda}{\Delta \lambda_{\text{eff}}}$$

one has

$$F = \int_{v - 1/2}^{v + 1/2} \frac{2}{\pi} \cos^2[\pi(v - p)] \exp \left[\frac{-\tau}{\exp \left(p - \frac{\lambda_{\text{eff}}}{\lambda_D} \right)^2} \right] dp$$

The last integral is evaluated numerically for the integer values of g (steps in the wavelength drive) from $-$ to $+$ $\max(\lambda_{\text{eff}}/2, 2\lambda_D)$.

6. ABSOLUTE CALIBRATION OF DETECTOR 1 AT LYMAN ALPHA

The function K_d has been evaluated by studying the rasters of the lambda max experiments with slit 2 and detector 1 at the Lyman alpha line.

In those rasters, the experiments which show some quiet Sun close to the disk center have been selected. In the first observations it was usually impossible to find any image completely away from any active regions; in that case the images have been selected which show a portion of nonfacular areas and do not contain large filaments.

Some tracings along diagonals and across the raster centers have been plotted for all the rasters from which the average counts have been taken for the whole raster and all the tracings. Comparing all average values one can easily recognize the quiet Sun areas which show constant average counts for all tracings, and the active region images which show higher values at some tracings.

For the images containing active regions, average counts using selected portions of the rasters whose appearance was closer to the quiet Sun have been used.

The resulting values of quantum efficiency vary in steps with the time; that is, they are fairly constant for many days and then change suddenly in less than a few hours. All these steps (or degradation events), except the last case, seem to be correlated to the occurrence of large flares. It seems very likely that degradation could have occurred during the short time of a flare event. For large flares, the Lyman continuum intensity can rise by a factor of 5000 or more and the optical surfaces of the UVSP instrument may be adversely affected by this rapid and significant increase in UV radiation.

The initial efficiency was $K_1(0) = 1.3E-3$ which is close to the prelaunch estimate and is valid for the early experiments, up to doys = 61.11736. The next determination for doys = 67.98333 showed a new value $K_1(1) = 6.3E-4$. The exact time of the change in sensitivity was traced using other slits and active region observations. The change occurs close to the flare event at doys = 66.18194, so $t_1 = 66.18194$ is used.

The next step occurred between doys 80.64651 and 85.64306 and can be traced to the compact, energetic flare observed at doys = 80.64651. The time is then $t_2 = 80.64651$ and the efficiency after the event was $K_1(2) = 1.4E-4$.

Another step occurred on doys 89 and/or 90 in conjunction with the large flare observed in C IV line at 1548 Å. The efficiency after this event was $K_1(3) = 5.1E-5$.

The next change, and the largest one, took place between doys 97.4396 and 97.5056, so $t_4 = 97.50$ was used. This event seems to be correlated with a large flare from Active Region 2373 at noon on April 6, 1980. The new efficiency was $K_1(4) = 1.7E-5$.

The last change in sensitivity occurred between the last data from 1980 and the first from 1984 and can be related to slow degradation. For the 1984 and following data, the efficiency $K_1(5) = 8.8E-6$ is used.

The authors looked at detector quantum efficiency for detectors 3 and 4 for the time interval $103.365 < t < 103.799$ and obtained for this interval the following ratios:

$$K_3(t) / K_1(4) = 0.79 \pm 0.09$$

$$K_4(t) / K_1(4) = 1.19 \pm 0.06 \quad .$$

Since there are insufficient observations, a detailed study of the time dependence of K_3 and K_4 at the Lyman alpha wavelength was not performed. Data from other slits were used in order to obtain the coefficients Q_s . The best data were those from the 1984/1985 experiments, since they have quiet regions profiles taken with many slits. The values were also checked with earlier data to confirm the hypothesis of Q_s constant with time. The values obtained for Q_s are:

$$Q_4 = 2.0 \quad ; \quad Q_{12} = 1.0 \quad ; \quad Q_{19} = 1.5 \quad ; \quad Q_{20} = 1.5 \quad .$$

For various reasons (including change in solar activity, location of slit relative to line center, and change in sensitivity), the uncertainty in the value of Q_s may be as large as a factor of 1.5.

Another check on the consistency of the data comes from observations for $235.4076 < t < 235.6430$ using standard star Alpha Leonis on August 22, 1980 (Hayes and Shine [5]). For the different wavelength, the following was obtained:

$$K_{18}^4(t) = 3.0E-4 \quad \text{at} \quad \lambda = 1344 \text{ \AA} \quad .$$

7. FUTURE WORK

A comprehensive collection of the calibration details of the UVSP instrument on the Solar Maximum Mission spacecraft is in progress. Additional slit, detector, and wavelength data will be tabulated and details concerning the polarization measurements and absolute calibration at other wavelengths will be represented in this follow-on work. In addition, the behavior of the Lyman alpha line in various solar features will also be described in a follow-on paper. The discussions contained in this report were preliminary to the papers which are to follow.

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APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

for 

E. A. TANDBERG-HANSEN
Director, Space Science Laboratory