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REFINEMENTS ON THE PINHOLE CAMERA MEASUREMENTS OF THE LDEF ATTITUDE

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ABSTRACT

The results from the UAH pinhole camera have been reanalyzed to include the effects of corotation of the atmosphere with the Earth as well as satellite oscillation. Previous results[1] from the instrument showed that the satellite had stable attitude offsets in yaw of 8.0° and 1.0° in pitch; these offsets are unchanged by the present analysis. The primary impact zone of oxygen, i.e. the directly exposed spot on a silver detector, had a ratio of major to minor axes equal to 1.05, which was interpreted as being caused by a small oscillation of ±0.35° (with precision ±0.15°). The present analysis shows that the observed effect can largely be accounted for by atmospheric corotation, but that an additional oscillation in yaw of the order of a degree cannot be excluded. The sensitivity of the pinhole camera to satellite oscillations is shown to decrease nonlinearly with decreasing magnitude of the oscillation and to vary inversely with the gas temperature.

INTRODUCTION

As a satellite in low-Earth orbit moves through the atmosphere, the velocity distributions of gas molecules striking its surfaces may be calculated if the satellite velocity, air bulk velocity and gas temperature are known. The predominant species in the atmosphere at altitudes of principal interest (200-500 km) is the ground-state oxygen atom. The velocity distributions of these atoms relative to orbiting surfaces need to be known for detailed calculation of satellite lift and drag, erosion of carbonaceous materials, satellite glow, etc.. We have used the method of Nocilla[2] to combine the orbital velocity with the Maxwell-Boltzmann distribution of molecular speeds to reproduce certain erosion morphologies observed on polymer surfaces exposed to atomic oxygen on Shuttle flight STS-8.[3] Details of the method given in reference 3 are not reproduced here. Our prior analyses, as have most, did not account for effects due to a corotation of the atmosphere with the Earth. The rotational speed of a point on the Earth's surface at the equator is 492 m s^{-1}. Ignoring weather perturbations, the bulk of the air moves in the same direction at the same angular velocity as the surface of the Earth beneath it. This bulk motion is maintained into the upper atmosphere, but the actual velocity may not be known within 10%. In our analysis we have assumed the same angular velocity about the Earth's axis for all regions. The pinhole camera of the LDEF Experiment A0114 imaged the drifting Maxwellian velocity distribution as a spot on a silvered hemisphere, and because of overexposure also appears to have a very large background from multiply scattered atoms, as previously described.[4] The refinements that we now introduce are: (1) inclusion of a corotating atmosphere, and (2) simulation of the exposed spot in the pinhole camera by integrating atom intensities over an orbit while oscillations occur. The physical yaw oscillation of the LDEF had a longer period than the corotation period of 91.836 minutes and, when combined with the corotation effect, resulted in a wavefunction that was the sum of the two. Lacking greater details, and since the experimental results do not permit separation of such effects, the total oscillation was approximated by a simple cosine function with same phase but larger amplitude than the corotation effect alone.

PROCEDURE

Several assumptions were made as approximations: the pinhole was treated as a source of atoms with intensity given by a Nocilla-type distribution[2] for a given speed ratio; a constant speed ratio was assumed for one orbit and the intensities were determined for a number of locations in that orbit and averaged, while assuming a sinusoidal oscillation with a period the same as the orbital period; the exposed spot in the pinhole camera was assumed to be an image of this "resultant intensity" and several physical features of the spot were associated with contours of the same flux level. Such contours would be circles centered on the point of maximum flux for a constant ram direction. These contours would become elongated along any axis associated with an oscillation. Since gravity-gradient restoring torques for the LDEF have been reported as being 2 orders of magnitude higher than restoring torques for a yaw displacement, we have assumed pitch oscillation to be negligible compared to yaw oscillation.

Intensities were averaged for various numbers of orbital positions, up to 365 per orbit. Contours associated with such intensities with no oscillatory effects were compared to contours of intensities resulting when various peak-to-peak oscillations were assumed in the yaw of the LDEF. Any resultant asymmetries in the contours were expressed as the ratio of the major to minor axes; these ratios were compared to each other and to that measured for the "outer contour" of the spot in the pinhole camera. The intensities were plotted in three dimensions and as 2-dimensional cross sections in the yaw and pitch planes and in various spherical and rectangular representations to better visualize the results.

RESULTS

Using averaged orbital parameters for December 6, 1989, we obtained a peak-to-peak oscillation in the incident atom directions due to a corotating atmosphere equal to $\pm 1.853°$, in agreement with Bourassa, et al..[5] These parameters are summarized in Fig.1. Average atom intensities were obtained for a number of hypothetical cases of the LDEF orbiting with its leading surface C-9 having different fixed yaws relative to the ram direction, different peak-to-peak oscillations in the yaw, different numbers of intensities used in the average (number of equally spaced locations in one orbit), and other parameters. The intensity was determined in 3-dimensions and plotted in spherical coordinates, as shown in Fig. 2. This figure shows the example of a beam entering through a pinhole with a fixed 8° yaw. The beam's intensity is also shown in Fig. 2 on a hemisphere, simulating the exposure of the silver in the pinhole camera to oxygen. The intensity plot is also shown in two views in Fig. 3; Figure 3(b) most accurately represents the photographed hardware 3(c) from which spot measurements were made. This photograph, and its enlargement 3(d), show that at some lower level of atom intensity, the spot contours are obscured by background from multiply scattered atoms. Intensities in Figs. 2 and 3 were computed for a speed ratio of 7.139, which corresponds to a temperature of 1000 K and includes corotation of the Earth's atmosphere. Other results for the higher temperature limit and different assumed oscillation amplitudes are shown in Table I. The simulation of a large angle oscillation of $\pm 10°$ produced an average intensity with large elongation in the yaw direction of about $\pm 6°$ compared to the pitch direction, as shown in Fig. 4. In contrast, for smaller oscillations such as the $\pm 1.85°$ associated with a corotating atmosphere, the elongation is much smaller, about $\pm 0.2°$. Actual values are temperature dependent, as can be seen in the table. The effect of higher temperature is to spread the intensity distribution and lower its maximum and to reduce the influence of oscillation on elongating the major axis of the spot compared to the minor axis (decreases sensitivity of the pinhole camera to satellite oscillation). This smaller effect is shown in Fig. 5 as yaw and pitch profiles and in Fig. 6 as contours having slightly elongated yaw dimensions.

These computed results are compared in Table I to the experimental data. The measured spot had angular dimensions of 14.8° and 14.1°, or expressed differently, the major axis was ±0.35° wider than the minor. Using the worst case temperature (1600 K) it can be seen that a total oscillation of ±3° provided a good fit. On the other hand, the oscillation of ±1.853° associated with the corotation almost satisfies the measured value within stated errors. A total oscillation of ±4° is clearly inconsistent with the measurements.

CONCLUSIONS

The measured values of spot ellipticity of the AO114 silver pinhole camera are, within errors, consistent with the ±1.853° oscillation caused by atmospheric corotation and a 28.5° inclination orbit. A better fit is given by a total oscillation of ±3° including the ±1.853° corotation contribution; while ±4° gives too large an effect. While we have not attempted to account properly for the differences in period and phase for the two components, our best estimate of the yaw oscillation of the LDEF satellite about its stable 8° offset is ±1°(±1°).

The analysis has shown that the pinhole camera becomes more sensitive to angular motion at larger angular amplitudes and lower gas temperatures.

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5. Bourassa, R. J.; Gillis, J. R.; and Rousslang, K. W.: Atomic Oxygen and Ultraviolet Radiation Mission Total Exposures For LDEF Experiments, *Proc. of LDEF First Post-Retrieval Symposium*, ed. by A. S. Levine, NASA CP-3134, Part 2, June 1991, pp. 643-661.

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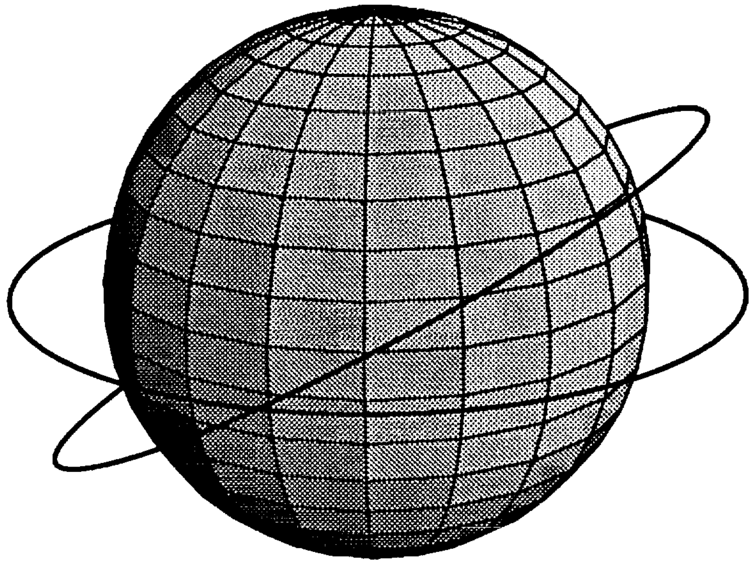
Table I. Calculated and Measured Atom "Average" Intensity (Spot) Parameters

	Assumed Temperature (K)	Speed Ratio[a]	Assumed[b] Yaw Oscillation (Degrees)	Contour Width Yaw[c] (Degrees)	Ratio Major to Minor (Yaw:Pitch) Axes	Elongation (Yaw-Pitch) (Degrees)
SIMULATIONS						
Corotation Effect of ±1.853°	1000 1600	7.139 5.645	±1.853 ±1.853	14.46 14.36	1.026 1.018	±0.18 ±0.13
Large Oscillation of ±10°	1000 1600	7.139 5.645	±10 ±10	27.0 23.4	1.92 1.59	±6.5 ±4.7
3° Oscillation (Nearly Equal to Measured Effect)	1000 1600	7.139 5.645	±3 ±3	15.2 14.7	1.08 1.04	±0.55 ±0.32
4° Oscillation (Excessive)	1600	5.645	±4	15.3	1.09	±0.60
EXPERIMENT DATA						
From Pinhole Camera Spot Contour Having 14.1° Pitch Width	----	----	----	14.8	1.05	±0.35 ±0.15

[a] Ratio of orbital speed, relative to a corotating atmosphere, to the most probable thermal speed of the impinging atoms

[b] Simple sinusoidal oscillation about zero yaw is assumed with the peak-to-peak amplitudes shown.

[c] Yaw widths were determined on contours having pitch widths of 14.1° to match the contour measured for the spot in the pinhole camera.



AVERAGE LDEF ORBITAL PARAMETERS FOR DECEMBER 6,1989*

INCLINATION: 28.52°

ORBITAL SPEED: 7.690 km s^{-1}

TEMPERATURE: 1008 K to 1587 K

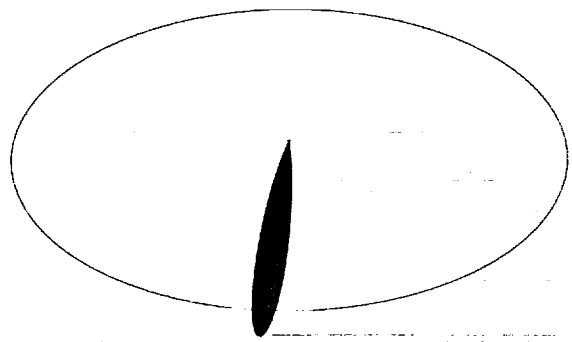
ALTITUDE: 364 km

COROTATING ATMOSPHERE'S SPEED:
0.4918 km s^{-1} @ equator @ altitude & 0.4321 km s^{-1} for component parallel to orbit

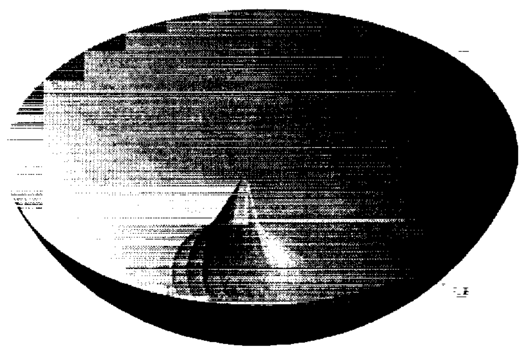
PEAK-TO-PEAK OSCILLATION DUE TO COROTATION:
+ 1.853° with the maximum negative at the ascending node and the maximum positive at the descending node

Figure 1. Average orbital parameters used in the calculations.

* From Bourassa and Gillis[6]



(a)



(b)

Figure 2. (a) Beam of oxygen atoms passing through a pinhole as computed for 8° yaw;
(b) same intensity beam imaged on hemisphere to simulate exposure of silver.

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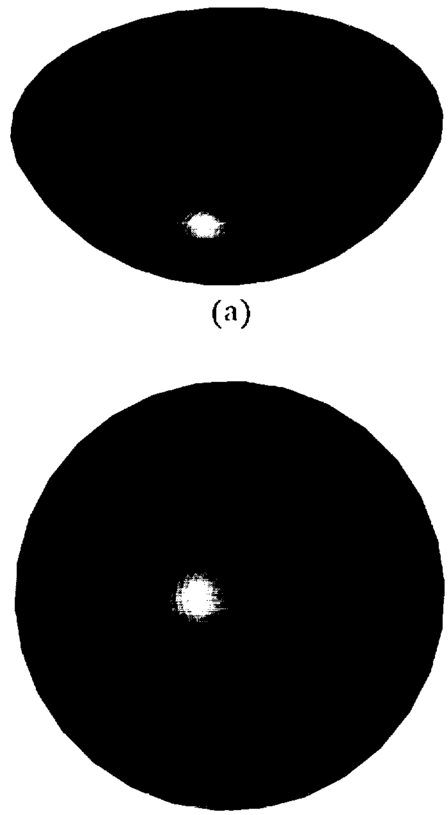
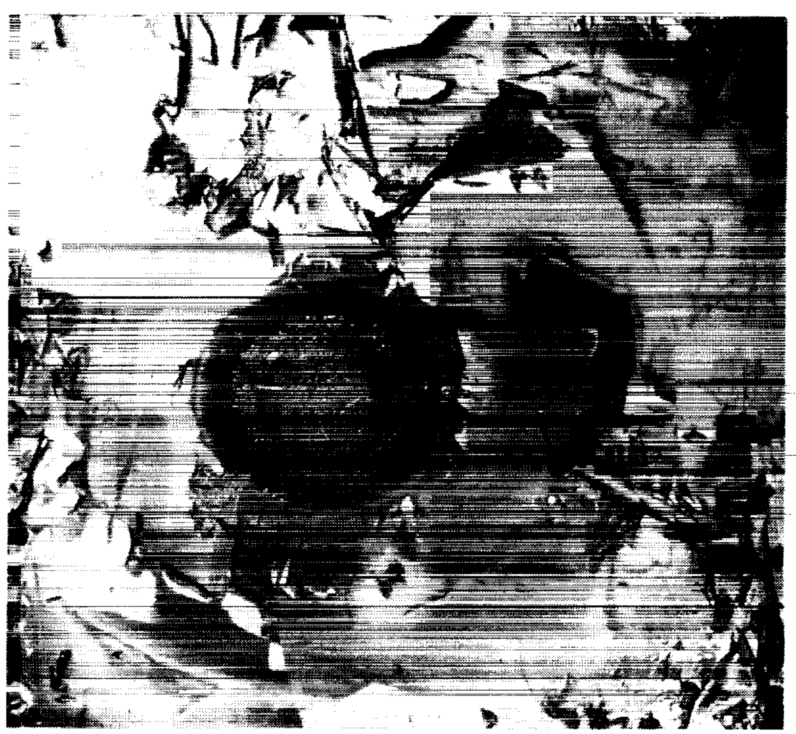


(a)

(b)

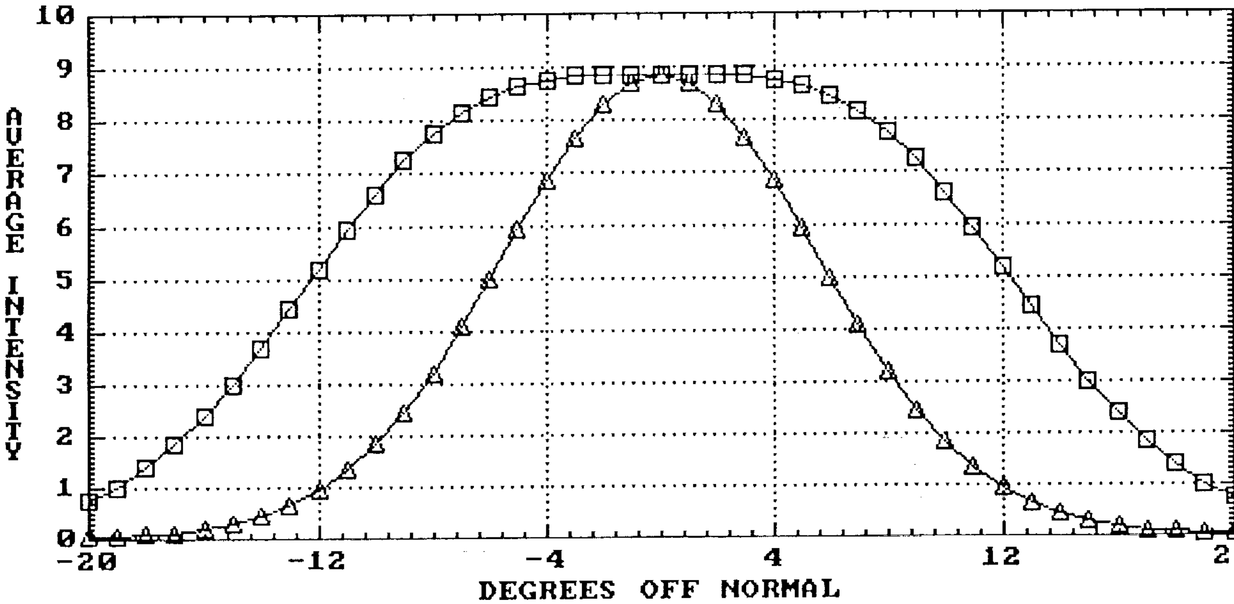
Figure 5. (a) A different representation of the intensity imaged on the hemisphere (b) the same intensity viewed as the pinhole camera photograph

(c)



(d)

(c) photograph of the exposed pinhole camera, showing spot and background;
(d) enlarged region of photograph near the exposed spot.



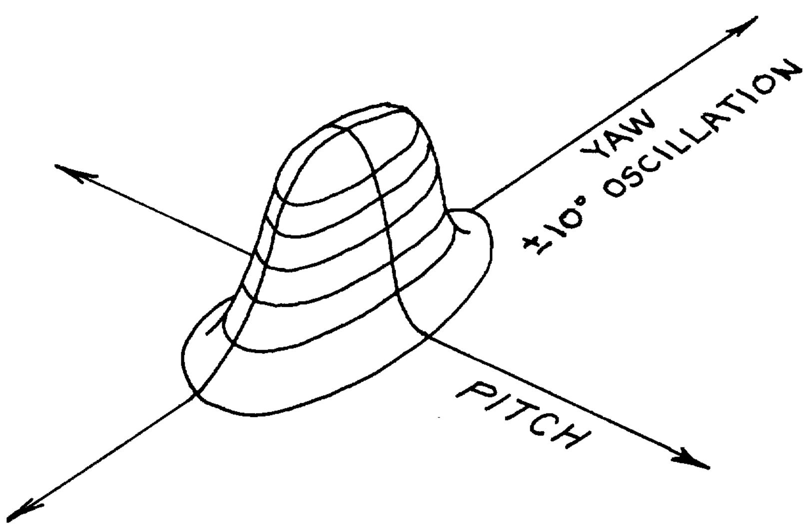


Figure 4. (a) Yaw (□) and pitch (△) profiles of average oxygen atom intensities in terms of degrees off normal of a surface that oscillated ±10°while pointing in the orbital direction;

(b) 3-d representation of profiles in (a), illustrating the elongation in yaw.

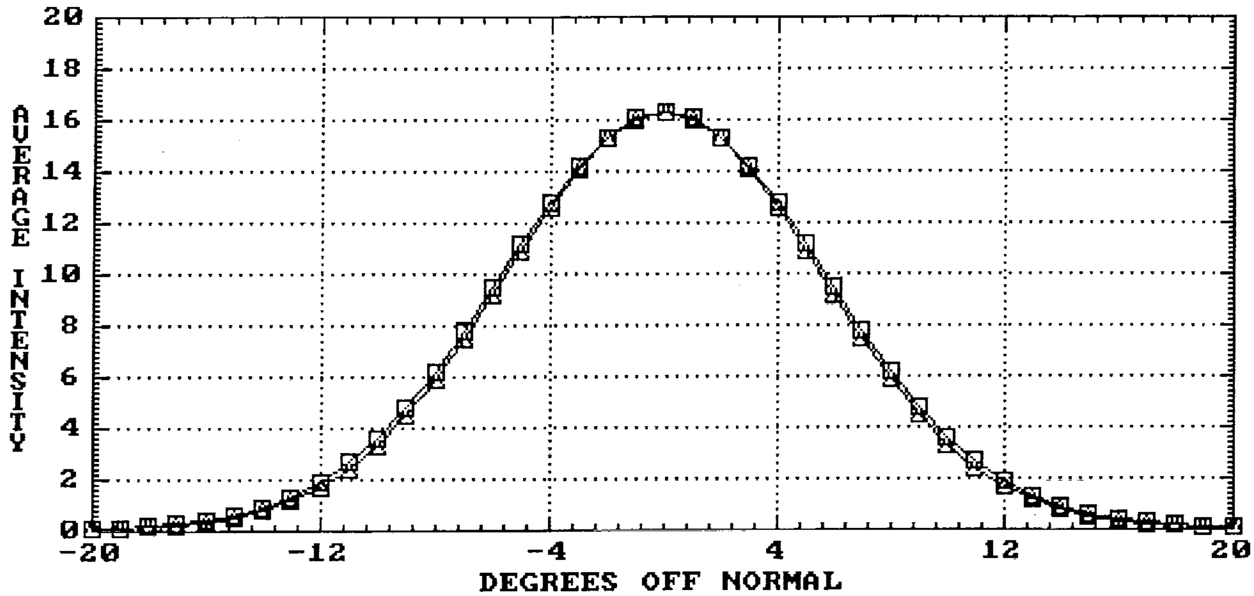


Figure 5. Yaw and pitch profiles, as in Fig. 4(a), but for ±1.853° oscillation in yaw.

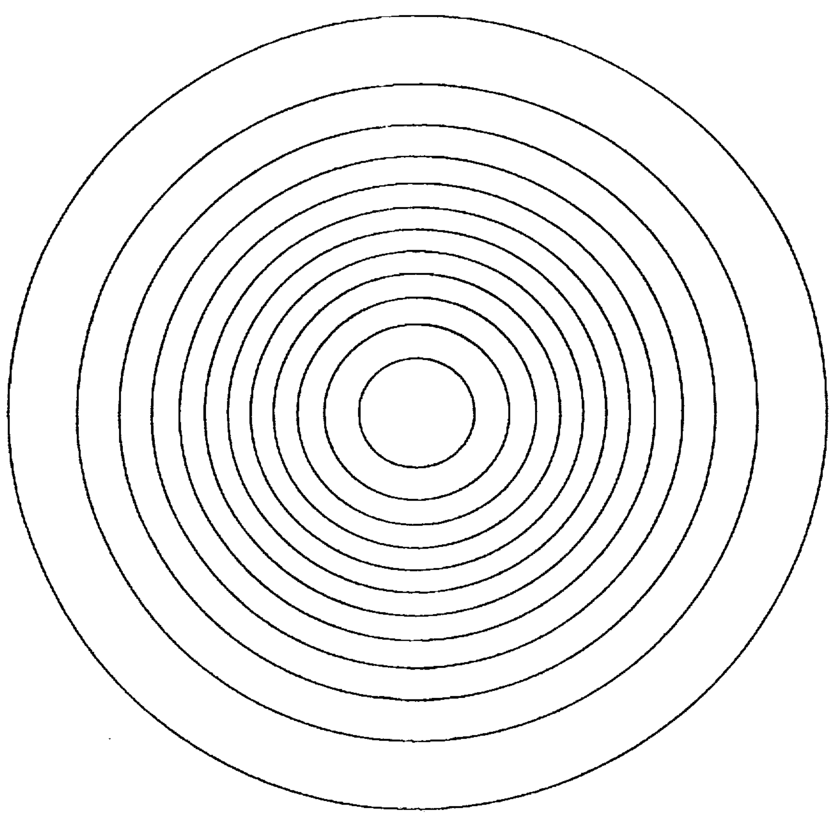


Figure 6. Contours taken from an atom intensity representing ±1.853° oscillation in yaw; the major axes in yaw direction are slightly larger than minor for all contours.