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PINHOLE CAMERAS AS SENSORS FOR ATOMIC OXYGEN IN ORBIT; APPLICATION TO ATTITUDE DETERMINATION OF THE LDEF

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SUMMARY

Images produced by pinhole cameras using film sensitive to atomic oxygen provide information on the ratio of spacecraft orbital velocity to the most probable thermal speed of oxygen atoms, provided the spacecraft orientation is maintained stable relative to the orbital direction. Alternatively, as described here, information on the spacecraft attitude relative to the orbital velocity can be obtained, provided that corrections are properly made for thermal spreading and a co-rotating atmosphere. The LDEF orientation, uncorrected for a co-rotating atmosphere, was determined to be yawed 8.0° ± 0.4° from its nominal attitude, with an estimated ± 0.35° oscillation in yaw. The integrated effect of inclined orbit and co-rotating atmosphere produces an apparent oscillation in the observed yaw direction, suggesting that the LDEF attitude measurement will indicate even better stability when corrected for a co-rotating atmosphere. The measured thermal spreading is consistent with major exposure occurring during high solar activity, which occurred late during the LDEF mission.

INTRODUCTION

A requirement to study the LDEF attitude was identified and a pinhole camera was developed for this purpose as part of Experiment A0114 (refs. 1-3). The atomic oxygen sensitive pinhole camera uses the fact that oxygen atoms dominate the atmosphere in low-Earth orbits, and formation of a nearly

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collimated beam of oxygen atoms passing through a pinhole in a satellite front surface occurs as a result of the orbital velocity being greater than the most probable Maxwell-Boltzmann speed of the oxygen atoms. Thus, the range of incidence angles of atoms to satellite surfaces is very limited, as shown by the angular distribution curves for two different temperatures in fig. 1 and described in greater detail elsewhere (ref. 4). The same maximum oxygen atom intensity was used for both temperatures to illustrate how the intensity spreads into the wings for higher temperatures. A thin film of material (silver in this case), which is sensitive to atomic oxygen, then forms an image of the impact spot.

The temperature of the thermosphere depends upon solar activity; the 700 K temperature in fig. 1 is characteristic of a solar minimum and the 1500 K is closer to a solar maximum. LDEF altitude was high during the solar minimum of September 1986 (initially deployed at 480 km in April 1984) where oxygen density was lower and had decayed by the time solar maximum was reached in June 1989 (recovery occurred at 310 km in January 1990). Most of the exposure in the pinhole camera, occurred close to solar maximum when the altitude was lower, the oxygen density was greater, and the angular distribution for atom incidence was widest. As will be described later, a well-defined spot was measured on the pinhole camera's silver sensor surface. Although overall darkening from overexposure (scattered atoms within the camera) was observed, this spot has been interpreted as being from the direct incidence beam and was used to determine the orientation of the LDEF relative to the orbital velocity.

MEASUREMENTS

The pinhole camera consisted of a 0.3 mm thick stainless steel hemisphere 3.25 cm (1.28 in.) radius, polished on the concave surface and coated with vacuum-evaporated silver. Silver was used because it discolors from formation of oxide (ref. 5). The pinhole had a conical shape with an included angle much wider than the maximum atom incidence angle and terminated as knife edges at a pinhole diameter of 0.5 mm (0.020 in.). The pinhole was positioned at the center of the silvered hemisphere. As shown in fig. 2, the exposure at any point on the hemisphere will depend upon the solid angle subtended by the pinhole from that point and the point's angular displacement from the orbital direction, i.e., the atom fluence as a function of angle from the velocity vector as shown in fig. 1. For orientations within 10° of the orbital direction, the solid angle subtended by the pinhole is constant within 2%; the predominant effects of pinhole size and thus solid angle are to reduce the overall fluence, or exposure, and increase resolution by reducing pinhole size.

Thus, the spot produced behind the pinhole should be centered with the LDEF's velocity vector and the spot's intensity should correspond to the distribution shown in fig. 1. Any variation in the attitude of the LDEF's velocity vector relative to the atmosphere would cause the spot to wander, producing a nonspherical, larger than normal, spot compared to that produced by thermal spreading of the beam.

Two techniques were used to determine the spot center and its shape: the first technique involved measurements taken directly from an enlarged photograph of the hemisphere taken on-axis with a 120 mm format camera and a 80 mm macro lens, and the second technique involved digitizing a 512 x 512 pixel CCD video camera image of the hemisphere and processing it to obtain both the spot and hemisphere centers and the spot geometry. Both techniques gave similar results.

DISCUSSION

Assuming that misalignment of the pinhole camera relative to the LDEF frame was negligible (machined surfaces and robust structures offer assurance of this), an LDEF orbiting with nominal attitude should have produced a spot centered on the hemisphere and uniformly round. The actual spot, as shown in fig. 3, was off-center, as would be produced by $8^\circ \pm 0.4^\circ$ clockwise yaw viewed from the space end. The spot was elliptical (major axis 14.8° and minor axis 14.1°, as subtended from the pinhole), with the major axis in the satellite yaw direction. It is noted that a yaw of 8° should have narrowed the spot in the yaw direction, not widened it as observed; thus, an oscillation in atom incidence along the yaw direction is the likely cause. This originally led us to conclude that the LDEF oscillated in the yaw direction (i.e., about its long axis), but it has been brought to our attention (Bourrassa, private communication, 1990) that a co-rotating Earth's atmosphere interacting with an inclined orbit produces an oscillation in the angle of incidence of oxygen atoms at the surface. We have verified that the oscillation occurs in the yaw direction, as observed, but the maximum range should be about $\pm 1.5^\circ$, not the estimated $\pm 0.35^\circ$ obtained from the ellipticity measured on the spot. While the center of the spot is rather well defined and is believed to be the average orientation for the LDEF, oscillations, thermal spreading, and other influences on exposure, such as multiple scattering must be separated. Some considerations are:

1. The exposure of the silver was an integrated effect which occurred over 5 3/4 years, over a wide range in oxygen atom temperature, and with an excess background from multiply-scattered atoms. However, most of the oxygen exposure was received during the last six months of the flight.

2. We have not been able to depth profile the exposed silver film, particularly across the spot. Although a nearly circular bulleye pattern suggests a profile similar to those in fig. 1, we have not yet devised a satisfactory technique for measuring optically opaque profiles.

3. Without a depth-composition profile it is not possible to fit the oxygen exposure to a known temperature distribution and there is some uncertainty as to the exact limits of the spot diameter (i.e., where the spot ends and the background takes over); however, it appears that rings on the spot represent equal thicknesses of oxide and provide the measured ellipticity. The minor axis of the spot could represent temperatures as high as 1500 K if assigned FWHM in fig. 1.

4. An oscillating structure and the apparent oscillation caused by an inclined orbit and rotating atmosphere do not yield the same angular flux distribution in a pinhole camera. An oscillating structure sweeps rapidly through the zero displacement and pauses at the extreme angular displacement; The opposite is true for the rotating atmosphere effect. Thus, a mechanical oscillation has a larger integral effect on spot diameter for the same number of degrees of oscillation. We are calculating these profiles with atmospheric oscillations included. Further study is needed to accurately determine the LDEF's range of oscillation.

Analysis by x-ray diffraction of the black powder flaking from much of the camera interior confirmed that it was Ag_2O. For reasons yet unknown, the primary exposed spot was more stable than the rest of the background exposed surface; this assisted our investigation.

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FIGURE CAPTIONS

Fig. 1. Intensity of oxygen atoms versus incidence angle, cap-theta, in degrees from the orbital ram direction for two equilibrium temperatures of the atoms.

Fig. 2. Schematic of pinhole camera with off-centered spot due to yaw of the LDEF and showing thermal spreading about the spot center due to the effect shown in Fig. 1.

Fig. 3. Photograph of exposed silver hemisphere from pinhole camera; overall dark flaking area is interpreted as overexposure from multi-scattered atoms, and the spot, which is more stable, is believed to be from direct incidence.

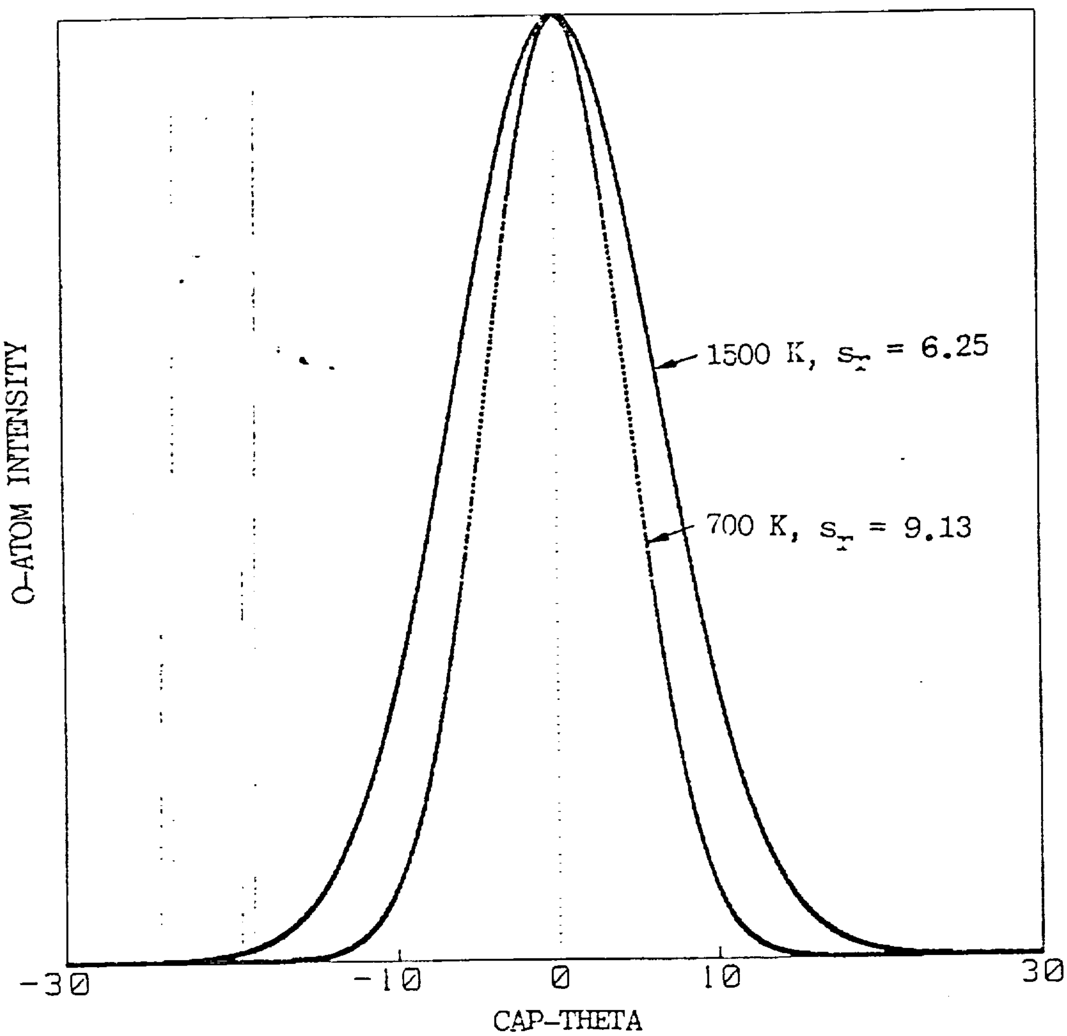
1500 K, s_r = 6.25
700 K, s_r = 9.13
O-ATOM INTENSITY
-30
-10
0
10
30
CAP-THETA

Fig. 1

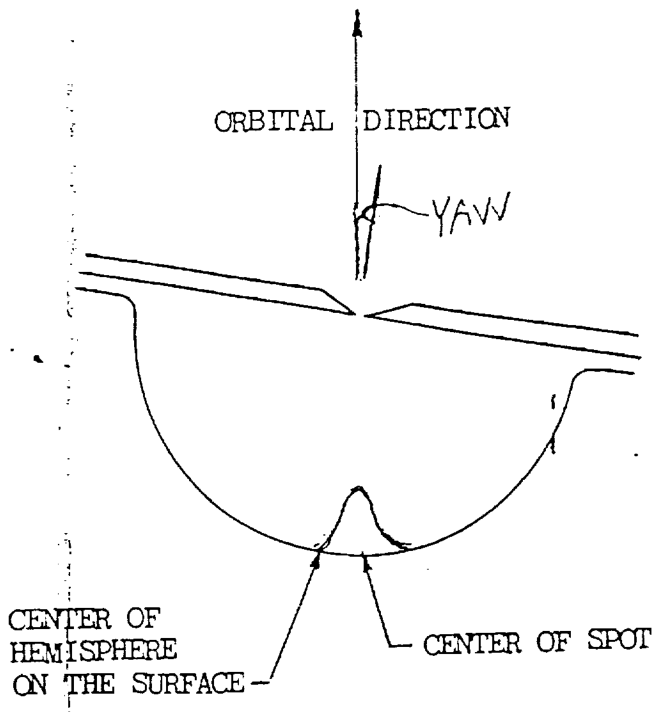
ORBITAL DIRECTION
YAW
CENTER OF HEMISPHERE ON THE SURFACE
CENTER OF SPOT

Fig. 2

Fig. 3