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REPLY

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Chubb (1986) concludes that the transient decreases in the earth's ultraviolet dayglow intensities as reported by Frank et al. (1986a) are instrumental artifacts. His conclusion is based upon examination of published images that exhibit examples of these localized decreases, otherwise known as "atmospheric holes." Frank and co-workers (1986a) previously summarize their extensive analyses of the inflight performance of the imaging photometer. These latter authors conclude that the decreases in dayglow intensities are a geophysical phenomenon on the basis of results of these analyses that required several years of effort. These intensity decreases are interpreted in terms of an influx of small comets into the earth's upper atmosphere (Frank et al., 1986b). In addition several observational results support the interpretation of this striking feature of the dayglow intensities in terms of a geophysical phenomenon. The variations of the occurrence rates of these atmospheric holes as functions of latitude and local time are qualitatively similar to those for radar meteors, including the appearance of a maximum in the early afternoon at low latitudes (Frank et al., 1986a). The occurrence rates of atmospheric holes also display an annual variation that is well-correlated with the non-shower, or sporadic radar meteor rates (Frank et al., 1986c). It is not possible for the present authors to reasonably attribute these observational findings to an instrumental artifact. In the following discussion we offer two additional results, i.e., the apparent motions of the atmospheric holes across the sunlit atmosphere and the increase of angular diameter of the atmospheric holes as seen from low altitudes over the atmosphere.

With examination of thousands of images of atmospheric holes in the earth's dayglow we find that the majority of these intensity decreases are seen in one pixel when the spacecraft is at its high altitudes, ~ 15,000 to 23,000 km. For atmospheric holes with dimensions of greater than one pixel, the additional pixel occurs most frequently in an adjacent scan line, i.e., the pixels are obtained during successive spacecraft rotations. Such an atmospheric hole is seen in the image displayed in Figure 1. Here we recall that an image is gained pixel by pixel by employing the rotation of the spacecraft and a stepping mirror in the instrument. That is, a single vertical line of the image in Figure 1 is telemetered during each spacecraft rotation period of 6 seconds. The mirror is then rotated such that the photometer field-of-view is turned by 0.25° for the scan line during the next spacecraft rotation. This situation is further clarified in Figure 2. Shown are two consecutive scan lines for a small section of the image. If the object, in this case, a water vapor cloud above the earth's atmosphere, is moving with appropriate direction and speed, a decrease in intensity observed in one scan line can be observed in the following scan line. It is thus of interest to determine whether or not such events exhibit an organized apparent motion across the earth's sunlit hemisphere.

The low occurrence rate for these events in consecutive scan lines requires an evaluation of the possibility that these events are random, i.e., independent events occurring in adjacent pixels of the two consecutive scan lines. For this study we use ~ 2,900 images that are certified to be free of scan-line misalignment due to small timing errors from the spacecraft nadir pulse generator. The earth's limb as it appears in the images is used for this certification. Twenty events with the greatest intensity decreases in adjacent scan lines are used from this image set. These atmospheric holes are selected such that their mean intensity decrease corresponds to a decrease in photometer count rates of 5.8 σ, where σ is one standard deviation. The total number of pixels for dayglow measurements is $\sim 1.5 \times 10^7$. The probability of observing an atmospheric hole with intensity decrease corresponding to $\gtrsim 5.8\ \sigma$ is 2×10^{-4} (Frank et al., 1986a; see Figure 1). Because any one of four pixel positions adjacent to the first pixel with a 5.8-σ decrease, i.e., two pixels each for the preceding and following scan lines, can yield the adjacent pixel pair, the probability of observing such a random event is $4 \times (2 \times 10^{-4})^2 = 1.6 \times 10^{-7}$. Thus for the total of $\sim 1.5 \times 10^7$ pixels the number of random events is $(1.5 \times 10^7) \times (1.6 \times 10^{-7}) \simeq 2$, or a factor of ~ 10 less than the observed event rate.

The results of this study of the apparent motion of the atmospheric holes across the earth's sunlit hemisphere are given in Figure 3. It is important to note that one-half of the image set is taken with the mirror scanning in one direction, the other half of the image set in the opposite direction (see Figure 2). The orientation of the spacecraft spin axis is such that the center scan line is located at nearly fixed longitude in earth-centered, solar-ecliptic coordinates. These coordinates are used in Figure 3. The atmospheric holes are projected onto a reference earth-centered sphere at 300 km above the earth's surface. Mirror rotation is to the left or right in Figure 3 and is indicated by the thick arrows. The dawn terminator is positioned at 270° longitude, dusk at 90°. Latitudes southerly of ~ - 40° are not sampled with this image set. The twenty adjacent-pixel events shown in Figure 3 are labeled according to their image file number. The thin arrows are the observed direction of motion as determined from the pixel center points. These vectors are particularly sensitive to small errors in scan line positions

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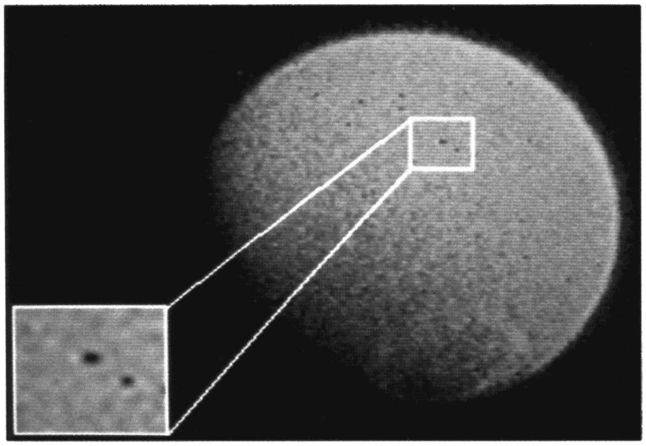

Figure 1. Image of the earth's ultraviolet dayglow, primarily in the atomic oxygen emissions at 130.4 nm, as taken with an imaging photometer on board Dynamics Explorer 1. An atmospheric hole that is detected in two adjacent scan lines is shown near the center of the inset, the other atmospheric hole is seen only in one scan line. This image is taken from altitude 23,000 km and geographic latitude and longitude -48° and 35°, respectively, at 0709 UT on October 10, 1982.

during image reconstruction whereas the determination of eastward or westward motion solely with the mirror (thick arrows) is insensitive to such errors.

The apparent motions of the atmospheric holes as shown in Figure 3 exhibit two features. First the apparent motion for 16 of the 20 atmospheric holes is directed from local evening to morning. Note that from the binomial distribution the probability $P(n|x)$ of x successes in n trials is $n!(1/2)^n/(x!(n-x)!)$. $P(20|16)$ is then 4.6×10^{-3} and can be compared with $P(20|10) = 0.18$. Secondly the remaining 4 atmospheric holes, for which the motion is directed from morning to evening, are located in the local morning sector. Frank et al. (1986b) previously interpret the atmospheric holes in terms of water vapor clouds from the disruption of small comets in the vicinity of the earth. The water vapor absorbs the earth's ultraviolet dayglow emissions, along the line of sight from the spacecraft to the radiant screen of the atmosphere. The comets are inferred to be in prograde elliptical orbits around the sun with perihelia in the vicinity of 1 A.U. (Frank et al., 1986b, c, d). Because a large fraction of the comets in such orbits are expected to overtake the earth, i.e., apparent motion from local evening to morning, the above findings

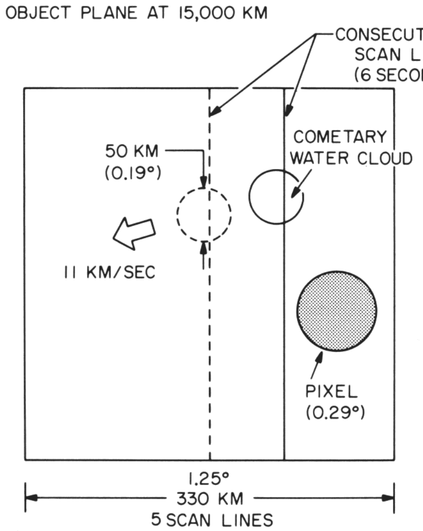

Figure 2. Diagram for the interception of two pixels, each in adjacent scan lines, by a water vapor cloud moving with apparent velocity 11 km/sec at a distance from the spacecraft of 15,000 km.

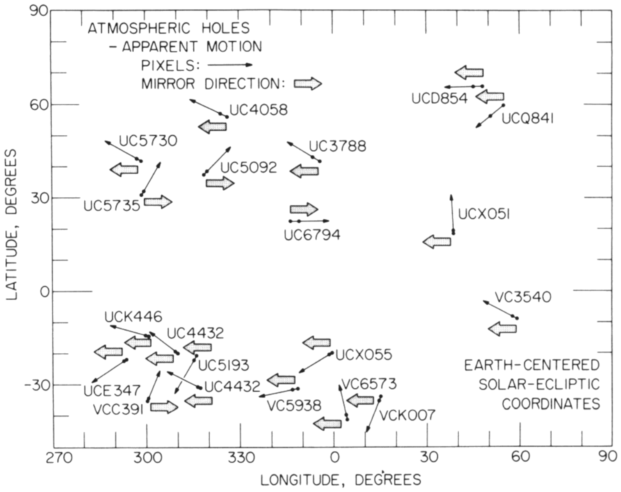

Figure 3. Summary of the directions of the apparent motions for 20 atmospheric holes. The positional coordinates are earth-centered solar ecliptic latitude and longitude.

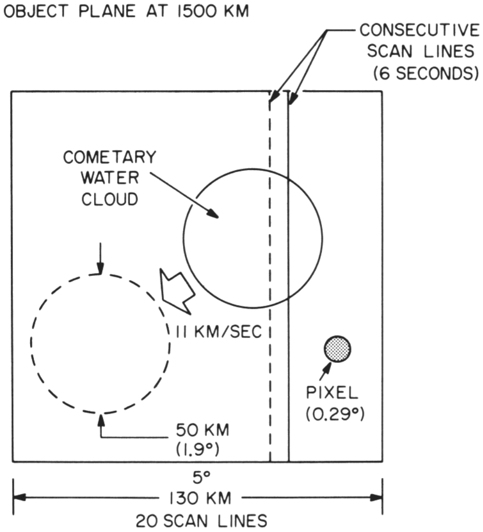

Figure 4. Diagram for observation of water vapor clouds at low altitudes. At 1,500 km the angular size is sufficiently large to give a string of darkened pixels during a single scan line. During the next scan line, one spacecraft rotation later, the cloud is located beyond the photometer's field-of-view.

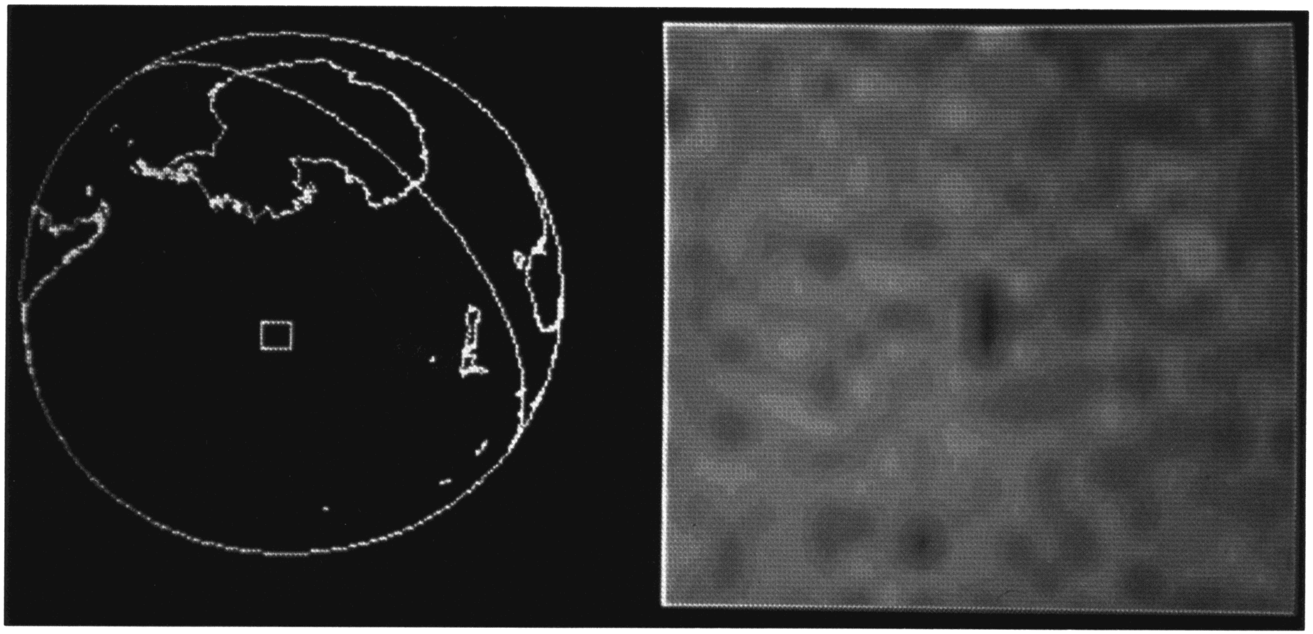

Figure 5. Example of an atmospheric hole observed at low altitudes with Dynamics Explorer 1. The area corresponding to this image as projected to 300 km above the earth's surface is shown in the global map on the left-hand side of the figure. This image is taken from altitude 1,170 km and geographic latitude and longitude -64° and 217°, respectively, at 1838 UT on October 15, 1981.

of such apparent motions of the atmospheric holes support the interpretation offered by Frank and co-workers. The further observation that the apparent motions of a few atmospheric holes in the morning sector are directed from morning to evening is evidence for earth-sweeping of some of the small comets, i.e., their azimuthal speeds around the sun are less than the earth's orbital velocity. For example, a prograde elliptical orbit with perihelion at 0.8 A.U., aphelion beyond Jupiter's orbit and inclination of 35° satisfies this latter condition. Thus the gross characteristics of the apparent motion of the atmospheric holes are generally consistent with expectations from the infall of small comets from prograde orbits.

The technique that is employed above in the determination of apparent motion is severely restricted by the spin-scan imaging. In order to detect an atmospheric hole in two adjacent scan lines, the angular motion is restrained to 750(± 200) μrad/sec. Part of this restraint is imposed by the minima of the composite point-spread function between pixels of an image. This angular motion corresponds to apparent speeds, in the plane perpendicular to the line-of-sight from the spacecraft, of ~ 4.8, 9.6 and 14 km/sec at distances of 1, 2 and 3 R_E, respectively. Few, if any, examples of atmospheric hole detection in three or more scan lines are expected due to further confinement of the window for angular motion and to the curvilinear trajectories in the earth's gravitational field. No such examples are found to date. The restraints on apparent angular motion also preclude the possibility of detection of atmospheric holes associated with small comets in retrograde orbits because orbital speeds are in the range of ~ 30 to 70 km/sec and thus too large to be detected in two consecutive scan lines. Similarly the ratio of the numbers of small comets in prograde orbits that are swept up by the earth to those that overtake the earth cannot be readily determined. The observations are not normalized with respect to the spatial sampling density. Nevertheless the observations support the existence of these two latter classes of trajectories.

At high altitudes, ~ 15,000 to 23,000 km, atmospheric holes with dimensions greater than one pixel occur most frequently for two pixels in adjacent scan lines as noted above. The apparent angular dimensions as seen from these altitudes are $\lesssim 0.3°$. At low altitudes the apparent angular dimensions of the atmospheric holes are expected to increase. The geometry of viewing atmospheric holes with the spin-scan photometer at low altitudes is summarized in Figure 4. A water vapor cloud with diameter of 50 km is assumed to be at a distance of 1,500 km from the spacecraft position. The speed of the cloud in the plane perpendicular to the line of sight is taken to be 11 km/sec for illustrative purposes. The solid angle for a single pixel is also shown. Consecutive pixels with decreases of responses due to the occluding water vapor cloud are expected for a single scan line. At these altitudes the water cloud is moving with sufficient angular speed that it is beyond the field-of-view of the next scan line, i.e., 6 seconds later. Thus consecutive darkened pixels occur in the same scan line at these altitudes and provide an instantaneous cut through the occluding cloud, in direct contrast to the situation at high altitudes where darkened pixels appear in adjacent scan lines and are due to motion of the water vapor cloud (see Figure 2).

An example of a sighting of a large atmospheric hole from a spacecraft position at low altitude, ~ 1,200 km, is shown in Figure 5. Three consecutive samples of dayglow intensities corresponding to pixel responses 3.3, 4.1 and 3.6 σ, respectively, below the surrounding averages are found in a single scan line as the photometer field-of-view passes over the atmospheric hole. As expected, decreases of intensities are not found in the adjacent scan lines. If this series of pixels is a random event then the probability of occurrence is ~ 4 x 10^{-8} event/pixel, or approximately once every 10^6 seconds of elapsed time at low altitudes. The distribution of occurrence rates of atmospheric holes for individual pixels as a function of the decrease in responses is used to calculate this random event rate (cf. Figure 1 of Frank et al., 1986a). Because the spacecraft orbit is eccentric with initial perigee altitude 570 km and apogee altitude 23,300 km the time available for searching for atmospheric holes from a spacecraft altitude range of 1,000 to 2,000 km is limited. For the present survey, the total time at these altitudes is ~ 800 minutes from a set of ~ 130 orbits. During these 4.8 × 10^4 seconds, two atmospheric hole sightings with three consecutive darkened pixels in a single scan line are found, an occurrence rate that is a factor of ~ 40 greater than that expected from random events.

The probability of sighting an atmospheric hole diminishes rapidly with decreasing spacecraft altitude. At an altitude of 20,000 km, an atmospheric hole is observed approximately every 10 scan lines, or 1 minute of elapsed time. A rough estimate for the occurrence frequency at low altitudes is gained by noting that the effective area for detection of water vapor clouds crossing the field-of-view for a scan line with fixed angular dimension varies approximately as h^2, where h is the distance from the spacecraft to the top of the earth's atmosphere at altitude ~ 300 km. That is, the water vapor clouds traverse a triangular area bounded at its apex by the spacecraft position, the adjacent sides by the field of view corresponding to a scan line and at the base by the atmospheric oxygen distribution. This order-of-magnitude estimate for the occurrence period at a spacecraft altitude of 1,500 km, for example, becomes $(20,000)^2/(1,500-300)^2 \times 60$ seconds/event ≃ 1.7 x 10^4 seconds/event. The observed average period, not statistically well-determined from 2 events, is ~ 2.4 x 10^4 seconds/event, and is similar in magnitude to that expected from high-altitude observations.

In addition to these two large atmospheric holes, a greater flux of atmospheric holes with lesser dimensions, one and two pixels in apparent angular size in a scan line, are also observed at these low altitudes. This distribution of smaller atmospheric holes is well beyond the resolution of the imaging photometer when viewing from higher altitudes.

The spatial dimensions of the two large water clouds observed from low altitudes are in the range 15 to 20 km if their positions are at ~ 300 km above the earth's surface. The expected diameter is ~ 50 km. A sufficient set of examples is not available to determine whether (1) the field-of-view slices through the cloud along an off-center cut (cf. Figure 4) or the maximum dimensions of the clouds are ~ 15 to 20 km. In this regard we note here an important limitation of the present observations in determining the evolution of the water vapor clouds with altitude. Images of the atmospheric holes provide only the apparent angular size and the position of the occluding cloud as seen against a screen of atmospheric ultraviolet dayglow. The altitude of this cloud is not directly determined. Our interpretation is based upon the assumption that the comet disrupts and vaporizes at the lowest possible altitude, ~ several thousand kilometers (cf. Frank et al. 1986b). It is possible that the water vapor clouds observed when the spacecraft is near apogee are positioned at altitudes of 5,000 to 10,000 km. In this case, and with the assumption that the total vaporization rate of water snow remains constant as the material moves toward the atmosphere, the apparent angular diameter of the cloud as seen from high altitudes becomes sufficiently small at lower altitudes that it is not seen in the images. The size of the water cloud as a function of altitude may be partially resolved by their detection in the geocorona (cf. Frank et al., 1986a). In the geocorona a rough estimate of the distance from the cloud to the spacecraft is obtained because the cloud is seen when only a fraction of an optical depth of atomic hydrogen is present along the line of sight. A better assessment of the evolution of the size of the cometary water cloud as a function of altitude may eventually allow a determination of the mass spectrum of the small comets or their fragments from the distribution of sizes of the water vapor clouds as seen at low altitudes, ~ 1,000 to 2,000 km.

On the basis of thorough examination of the electronics for the imaging photometer and of the inflight telemetry Frank et al. (1986a) previously conclude that the occurrence of atmospheric holes is not due to an instrumental artifact. Features of the atmospheric holes that further support this conclusion are (1) a dependence of occurrence rates upon local time and latitude that is qualitatively similar to that for radar meteors, (2) annual variations in the occurrence rates that are proportionally similar to those for non-shower, or sporadic radar meteors, (3) apparent motions as seen from high altitudes, and (4) increase of angular size when viewed from low altitudes.

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