# ULTRAVIOLET THREE AXIS ATTITUDE SENSOR

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Abstract

It is becoming increasingly obvious that satellite bus technologies, which have been developed for traditional larger satellite platforms, are not always suitable for use with smallsats. This is due to the intrinsic limitations in size, weight, available power, and cost associated with the latter. The problem is particularly obvious for attitude reference sensors of both the earth and star viewing type. In response to the lack of suitable sensors for this purpose, Honeywell is developing a system that determines three axis attitude through ultraviolet imaging of the earth's limb and adjacent stars. A non-conventional wide angle optics assembly and intensified CCD array are utilized for this purpose. Because of the intrinsic stability of the features being observed and the large number of pixels on which the scene is imaged, it should be possible to obtain accuracies on the order of .05 degrees with a very small and lightweight sensor configuration.

## I. Rationale for an Ultraviolet Sensor

Horizon sensors have typically operated in the infrared because of the stability of the limb in this wavelength region. They would seem to have severe intrinsic limitations with regard to smallsat applications due to their size and weight characteristics and relatively high cost. There are no suitable observables for yaw determination available to sensors of this type, and an additional sensor is thus required for this purpose. Visible wavelengths offer the possibility of lightweight imaging sensors which could obtain three axis information through simultaneous observation of the limb and stars. The limb in the visible, however, has a high degree of variability due to weather conditions, that introduces a large intrinsic error in location.

An ultraviolet sensor combines the advantages of a relatively small and inexpensive package which can observe both limb and stars with a limb stability that is comparable to that seen in the infrared. Because of the strong absorption of wavelengths below 3000Å by atmospheric ozone and oxygen, the sunlit limb is formed at altitudes well above terrestrial and meterological features, and is consequently not affected by them. This can be seen from the altitude distribution and spectral absorption profiles of ozone as shown in Figures 1 and 2. As the intensity profile is determined by Rayleigh scattering it is quite predictable, and depends entirely on the solar radiance and the altitude profiles of atmospheric constituents. The general appearance of the sunlit limb in the wavelength region of interest is seen in Figure 3. The night limb radiance derives from emissions of atmospheric gases at higher altitudes, and has also been found to be well defined within the wavelength region of interest. The ultraviolet also proves to be an advantageous waveband for stellar observations.

## II. Principle of Operation

The Earth Reference Attitude Determination System (ERADS) sensor determines roll, pitch and yaw through observation of a number of terrestrial features and certain stars in a narrow band of the ultraviolet. Pitch and roll are derived from observing the maximum intensity altitude of Rayleigh scattered sunlight during daylight conditions, and

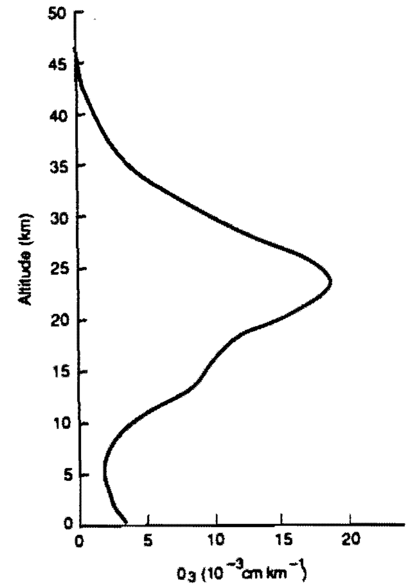


Figure 1. Altitude Distribution of Ozone

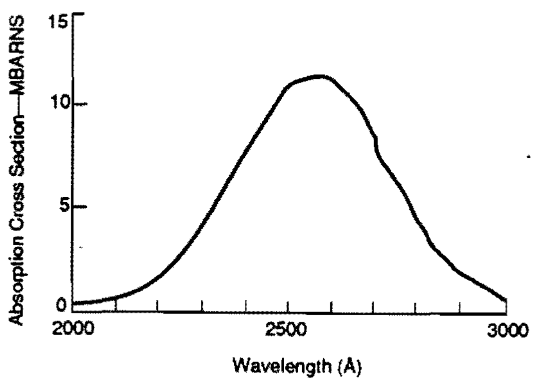


Figure 2. Absorption Cross Sections of Ozone

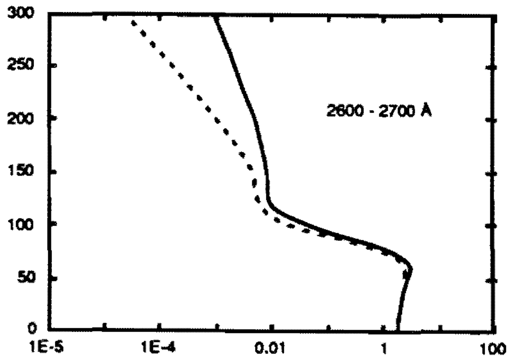


Figure 3. Limb Intensity Profile (maximum noon brightness)

of the nightglow at night. These maxima occur at about 55 km and 91 km above hard earth respectively, and little if any variation in altitude has been observed. During the transition period from day to night, or vice versa, a methodical progression in the location of the maximum between these two altitudes occurs. The entire earth limb is viewed simultaneously, and nadir determined from a mean center of the maximum intensity point at all azimuths. Because the entire earth is within the field of view, no alignment of the sensor on the limb is necessary, and highly elliptic orbits can be accommodated with no adjustment.

Yaw is determined from the location of one or more of a small catalog of stars with a significant ultraviolet output. We have found that stars of the solar type or hotter of visible magnitude 4.5 or brighter can be seen by the ERADS sensor. This group includes at least 400 examples; as the ERADS sensor views about 4% of the entire sky at one time, the mean number of stars available at any time is 16. It appears that in all possible configurations at least one star will always be in the field of view.

Radiometric Considerations

A number of theoretical and experimental data sources on the day and night limbs have been examined, and were found to be in close agreement. The noon limb is the brightest object observed, and the faintest catalog stars are the least bright. The dynamic range required to cover this range of intensities is approximately 8000 to 1, well within the capabilities of the sensor. The sun will also on occasion enter the field of view. When this occurs the voltage on the phototube and the integration time will be reduced to allow viewing of the sun and noon limb.

## III. Sensor Configuration

The ERADS sensor will view the region from the earth's surface to 10 degrees above. In order to image these large field angles, a combination of a reflective field reducer and a spherical lens is used. A center aperture stop is used with the lens. Because the refractive surfaces are concentric to the stop, the only third order Seidel aberrations present are spherical aberration and Petzval curvature. Spherical aberration is minimized by using sapphire, which has a very high refractive index. The curved image surface is matched to the Petzval curvature, so the compact lens is useful over a wide field of view. Not only is the system much more compact than a flat field wide field of view system, but the illumination is greatly improved. Illumination falls off as the fourth power of the cosine of the angle leaving the exit pupil for flat field systems. By using the curved image surface, which is also concentric to the stop, the beams are all at normal incidence to the image surface. Thus, the illumination only falls off as the cosine, which is due to the obliquity of the pupil at higher angles.

The curved surface of a fiber optic field flattener is placed at the curved image surface. It is coated with a medium for conversion of the ultraviolet to visible light for transmission through the fiber bundle. The image is then transmitted through an image intensifier tube to the megapixel CCD array.

Since the sensor is viewing the earth's limb with a total field of view that can exceed 150 degrees, the imaging qualities of the ball lens are somewhat stressed. Because of the obliquity of the wavefront at the aperture stop, the effective aperture at extreme angles is greatly reduced, and there are higher order aberrations present. Also, the field flattener mapping from a nearly hemispherical image surface to a flat one greatly increases the footprint of the detector pixels at the outer edges of the image. Therefore, a reflective mirror array is used before the spherical lens to map the extreme field into a more moderate field of view. This reduces the effects of oblique spherical aberration and pixel distortion. Six to eight facets are used rather than a continuous mirror (which would be a portion of a linear axicon.) A continuous mirror would preserve mapping, but introduces a great amount of astigmatism, which reduces resolution. The faceted mirrors preserve wavefront quality, but introduce mapping distortion tangential to the limb. There are regions of ambiguity and missing data in the image at each mirror seam due to this mapping distortion. Because of the centroiding nature of the attitude determination algorithms, this distortion is not deterimental to overall sensor performance. A reflective mapper is used because a transmissive mapper would reduce resolution dramatically due to chromatic aberration.

The sensor optical configuration is shown in Figure 4. The resulting image spot is on the order of the pixel dimensions.

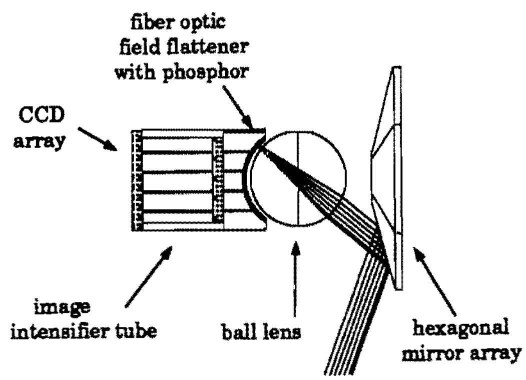


Figure 4. Optical Layout of Sensor

Because of the wide field of view, no scanning or alignment of separate sensors will be required. Since the maximum intensity altitude of the limb is defined as the horizon, no absolute calibration is required. As this feature is being determined at so many locations around the limb, the effects of sensitive variations between pixels are minimized.

The image intensifier tube will be gated to extend the tube lifetime and provide a shutter for the CCD. Reduction of the accelerating voltage can also be used to increase dynamic range.

## IV. Sensor Parameters

The following characteristics of the sensor can be summarized as follows:

| | |
|---|---|
| Field of view | 133-143 degrees |
| Collecting aperture | 1 square centimeter |
| IFOV | .04 degrees |
| Spectral band | <3000A |
| Lens material | sapphire |
| Optical efficiency | 0.5 |
| Detector | Intensifier tube/ 1024x1024 CCD |
| Weight | 1.2 Kg |
| Power consumption | 4.3 Watts - 8 peak |
| Pitch uncertainty | <0.1 degree |
| Roll uncertainty | <0.1 degree |
| Yaw uncertainty | <0.2 degree |
| Volume | 2000 cubic centimeters |

## V. ERADS Attitude Determination

The ERADS sensor provides a wide angle image of the earth and surrounding space allowing multiple distinct reference objects to be identified for attitude determination and navigation functions. This unique feature allows the ERADS system to provide a complete attitude determination solution with a single solid state sensor, replacing the traditional combination of scanning earth sensor, sun sensor and inertial rate sensor. The ERADS sensor can be mounted both as a direct earth imaging sensor as well as side mounted in a single or dual sensor configuration depending on spacecraft mounting constraints and mission requirements.

### Real Time Image Processing

Functionally, the ERADS attitude determination system works much like an imaging star tracker. Camera frames are processed at a nominal rate of 2Hz for attitude determination purposes, although the camera control logic allows both the frame rate and integration interval to be varied on the fly by the ERADS software. Once the frame integration is complete, the pixels are digitized and transfered to the Image Data Store Module (IDSM) and stored in SRAM and an interrupt is sent to the Integrated Control Processor (ICP) to indicate that the frame is ready for processing. The ERADS frame processing software module is triggered by the interrupt and the focal plane is processed to locate objects of interest. Observation vectors are processed from both point sources such as ultraviolet stars, as well as extended bodies such as the earth, sun and moon.

### Stars

Stars are processed by centroiding subframe windows to locate individual stars and then processing the located stars against an onboard star catalog for autonomous star identification.
The identification algorithm uses a multiply-linked star database to rapidly identify configurations of stars by position and magnitude.

### Earth

The limb of the earth in the ultraviolet shows a distinctive bright band which varies only as a function of solar zenith angle and that remains very stable with no discernible seasonal variations typical of IR type earth sensors. This bright band is located to process a section of the limb,which is then compared against an onboard earth limb model to estimate the center of the earth. This nadir reference vector is then passed on to the attitude determination algorithm.

### Vector Attitude Determination

The ERADS imaging sensor provides multiple observation vectors that can be processed by standard optimal attitude determination filters to provide full three axis attitude data. The basic algorithm used by ERADS for attitude determination is the QUEST quaternion estimation algorithm developed by Shuster and Oh. This algorithm compares multiple vector measurements with reference vectors to provide a best estimate of the quaternion representing the frame rotation from the reference frame to the measurement frame. In order to provide three axes of attitude knowledge, at least two vectors are required. If the earth is present in the sensor field of view, the nadir vector is always used for the first vector, the second and subsequent vectors are obtained from near stars (there is an average of sixteen in the FOV at any time), the terminator, the sun, or the moon. Sun, moon and satellite orbital ephemerides are carried onboard to provide reference vectors for the QUEST algorithm.