AN OPTICAL DEVICE FOR CORRECTING GEOSTATIONARY SATELLITE IMAGERY FOR EARTH CURVATURE EFFECTS:
MAKING METEOSAT IMAGERY OVER EUROPE AS GOOD AS IT IS OVER EQUATORIAL AFRICA

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Abstract

This paper discusses a new approach to meteorological remote sensing, introducing a family of optical devices for observing the earth and its atmosphere that can be used to correct for the loss of image resolution due to earth curvature effects. The proposed optical adapters are hardware modifications that would have to be designed into new remote sensing instruments before launch, and are best suited for use with two-dimensional CCD imaging arrays combined with fixed, relatively large-aperture, optical systems mounted on a three-axis stabilized spacecraft in geostationary orbit. In this configuration they offer the promise of essentially uniform resolution imagery over virtually the entire earth disk, enhancing the quality of space-based observations for use in numerical models or for applications involving integration into operational decision support systems. These image modifications are particularly valuable since they are applied before the observations are made and directly enhance the quality of the observation, and are not just a software remapping of the imagery after it is collected.

ENHANCING IMAGERY FROM GEOSTATIONARY ORBIT

This paper describes a new class of optical devices for observing the earth and its atmosphere that can be used to correct for the loss of image resolution due to earth curvature effects. The proposed optical adapters are a hardware modification that would have to be designed into new remote sensing instruments before launch. We term this adapter the GeoObs Adapter, reflecting its intended goal of enhancing geostationary earth imagery for geophysical observations and applications. The adapter, depending on the overall system design, could be a lens, mirror, or other optical device. The adapter could be a separate component within a satellite observing system, or in many cases its functionality could be incorporated into other existing optical components.

The optical image transformation is not merely an enlargement of the earth image, but rather a transformation that provides essentially constant image resolution across virtually the entire earth disk as seen from the satellite. The image transformation acts to "correct" the satellite imagery before it is collected and is not just a software algorithm or system for remapping imagery after it is collected.

For applications from geostationary orbit (GEO), these adapters are best suited for use in conjunction with 3-axis stabilized spacecraft, using large 2-D CCD imaging array detectors. Large CCD imaging sensors have become common in astronomy and space exploration, providing the critical imaging sensors for the Hubble Space Telescope, the Cassini spacecraft’s imaging cameras, and the upcoming James Webb Space Telescope (JWST). Two-dimensional CCDs are continually being improved and upgraded. The GeoObs Adapter is an optical system enhancement with no moving parts. Depending on the specific instrument design, imaging devices using this concept can generate VIS and IR multi-spectral imagery, or could be adapted for rapid-update (one minute or better), very high resolution imagery over Europe or other regional areas. This overall design is similarly well suited for lightning imaging detectors intended for large area coverage from geostationary orbit.
"Making Meteosat Imagery over Europe as Good as it is over Equatorial Africa"

Figure 1: An illustration of the enhanced imagery possible through optical stretching of the earth image to correct for earth curvature effects. The boxed areas over Europe represent equal resolution “windows,” highlighting the correction of the normal side-view perspective of Europe with a corresponding improvement in resolution.

In Figure 1, the left-hand image is just the normal, perspective view of the earth as seen from geostationary orbit. The original image is then transformed by the adapter to produce the image on the right. In this example the nadir resolution is unchanged, while a progressive radial “stretching” of the earth image away from nadir (anamorphic imaging) offsets the normal loss in image resolution due to earth curvature effects, providing full disk coverage out to 62.5 degrees away from nadir. In this particular simulation, the square CCD sensor mosaic has been rotated by 45°, permitting areas of extended coverage out to 70° from nadir and thereby providing uniform resolution imagery for all EUMETSAT member states, as well as producing equivalent imagery over all of Saudi Arabia and most of Brazil. In this example, European imagery would have the same resolution as would be available over equatorial Africa — a 2 to 3-fold improvement over traditional imaging devices with the same nadir resolution.

Figure 2 zooms in on Europe to emphasize the potential improvements in imagery that should be possible through use of the GeoObs Adapter by presenting simulated European imagery in three identical resolution windows. These smaller figures also illustrate two different approaches for implementing the proposed optical transformation the GeoObs Adapter. The left-hand panel is just the normal perspective view of Europe as seen from Meteosat. The right-hand panel, termed implementation #1, presents a detail from the example shown in Figure 1. This implementation preserves the resolution at nadir and maintains a constant radial resolution across the entire earth disk, but at the cost of a larger image and a correspondingly larger CCD. In this case the improved imagery would require a 2-D CCD with about twice the total number of pixels as would be needed for the original, unstretched image, reflecting a significant increase in the overall image resolution. This approach improves the resolution over central Europe by a factor of 2.5 to 3. A similar resolution increase over Europe could be provided without making use of the GeoObs Adapter by simply switching to a larger, higher-pixel count CCD. To do this, however, you would need to increase the size of the original 2-D CCD by nearly a factor of 10.
Three Views of Europe
shown in identical resolution windows

Figure 2: Three views of Europe shown in identical resolution windows. The left-hand panel is just the normal perspective view of Europe as seen from Meteosat. The two panels on the right illustrate the improved imagery provided with the GeoObs Adapter (see text for discussion).

The center panel shows an alternative implementation of the GeoObs Adapter, termed implementation #2. The essential feature of this implementation is a requirement to make use of the same size and resolution CCD sensor as could be used to view the entire earth without the adapter. In this case the adapter still transforms and corrects the image to provide uniform resolution imagery across the entire earth disk, but does so by introducing a modest loss in resolution in the center of the image (by a factor of 1.3 in this example), while still permitting a significant improvement in the resolution towards the edges of the earth disk.

The traditional view of Europe without the GeoObs Adapter shows the clear influence of earth curvature, with land features (most notably Great Britain and the United Kingdom) visually foreshortened. Both of the simulations using the GeoObs Adapter correct the imagery, looking more like images seen in an Atlas than the images we normally see from geostationary orbit. While implementation #2 shows a significant improvement in European coverage, implementation #1 is even more dramatic.

Figure 3 shows one-dimensional schematic illustrations that illustrate the required behavior of the GeoObs Adapter. In each schematic the top figure represents an equatorial slice through the earth with even angular intervals on the earth’s surface highlighted by alternating blocks of black and white. As seen from geostationary orbit (on the “raw earth image” side of the GeoObs Adapter), the alternating light and dark rectangular areas show the familiar pattern of foreshortening which is in turn reflected in the increasing size of the sensor footprint as you move away from nadir (bottom figure in the schematics). Implementation #1 invokes a simple stretching of the image to correct the foreshortening, resulting in a larger image and maintaining the original image resolution at nadir. Implementation #2 also stretches the original image to correct the foreshortening, but then shrinks the transformed image back to the dimensions of the original earth image. This results in a modest reduction in resolution at the center of the image, while permitting a significant improvement in resolution towards the edges of the earth disk, although not as much of an improvement as would be expected with implementation #1 (see Figure 2).

Figure 4 illustrates the stretching needed to correct for the normal foreshortening seen in imagery from geostationary orbit, and was used to define the stretching model used to generate figures 1 and 2. It must be emphasized, however, that while the correction for curvature effects was the initial goal of this design effort, there are many different stretching functions that can prove to be useful. As discussed briefly in Johnson (2006), for example, a slightly different mathematical formulation could be used to transform the image into an equal-area projection while maintaining the essential features shown in the current examples.
Figure 3: Schematic illustration of the required behaviour of an optical adapter that can correct for the foreshortening of the earth image as seen from a geostationary satellite. Two separate implementations of the GeoObs Adapter are shown, one which maintains the original image resolution at nadir (implementation #1) at the cost of a larger image and larger CCD sensing array, and the other (implementation #2) for which the stretched image is reduced in size to fit within the dimensions of the original image.

Figure 4: An example of the stretching required to correct for earth curvature effects.
Figure 5 shows simplified examples of the sort of mirror or lens that could provide the image stretching specified by Figure 4. In these illustrations, the radial distances from nadir are specified in a normalized coordinate system in which the apparent radius of the earth disk as seen from the satellite has been given the value of unity. Areas outside of 62.5 degrees offset from nadir (the red circle as shown in the normal perspective views of the earth in Figures 1 and 2) are identified by a darker gray shading, and the final image plane of the transformed image is identified by the thick horizontal line. In these illustrations, the final image plane is drawn for maximum coverage out to 62.5 degrees, but there doesn’t seem to be any reason to expect that optical systems of this sort could not be used to extend the coverage even further towards the edges of the earth disk, including the 70° limit shown in Figure 1.

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