Remote Sensing of Atmospheric Emissivity over Mauna Kea Using Satellite Imagery

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Overview

As part of a program to assess environmental monitors that may be helpful in the operation of the Gemini telescopes, a comparison was made between the atmospheric water vapor content as measured by the CSO τ meter currently running on the summit of Mauna Kea and GOES satellite imagery made at a wavelength of ~7 µm. One of the basic purposes for such a comparison is to determine if satellite imagery can be used to detect and even *forecast* dry atmospheric conditions that are optimal for infrared astronomical observations. In a queue based operational system like that planned for Gemini, advance knowledge of key environmental parameters which fundamentally effect telescope performance and the selection of observing programs would simplify operations and improve data quality. While predicting or even "now casting" seeing is still in its infancy (Murtagh, Aussen, and Sarazin 1995, *PASP*, **107**, 702), slowly changing atmospheric conditions that can be monitored through satellite imaging can be taken into consideration when observations are planned or executed. For years satellite imagery has been used to monitor clouds as they pass near observatories. This technical note illustrates the use of mid-infrared satellite imaging to also monitor atmospheric emissivity conditions near observatories.

Background Information on the GOES Satellites

The GOES weather satellites image the earth on a regular and frequent basis at a number of visible and infrared wavelengths. One of the atmospheric bands these satellites use is sensitive to the water vapor content of the upper atmosphere. The primary meteorological driver for such imaging is the need to track relatively high altitude winds. In essence, 7 µm images record the radiation emitted from the low level atmosphere outward into space. Regions of high water vapor in the upper atmosphere are seen in absorption against the lower warmer layers. Such images detect high altitude (jet stream) atmospheric flows that often have only large scale structural correlation with near infrared satellite imagery of condensed water vapor (clouds). It follows that a site like Mauna Kea might be high enough that the dominant overhead water vapor component in the atmosphere under clear sky conditions is the same water vapor seen in absorption in satellite imaging. Accordingly, the basic hypothesis being checked here is if the CSO τ meter, on Mauna Kea, is detecting the same amount of water vapor that is seen in GOES 7 µm imagery. One of the key questions about this hypothesis is understanding how far down in the atmosphere 7 µm satellite imagery probes, i.e., does it probe only down to layers well above the summit, allowing water vapor above the summit that effects observations to go undetected by satellite imagery? Or does it probe well below the summit, leading to GOES measurements that are confused by water vapor that the summit sensor does not detect? And if satellite imagery does probe down to he optimal level in the atmosphere, are there unforeseen complications that inhibit the use of satellite imaging for such a test?

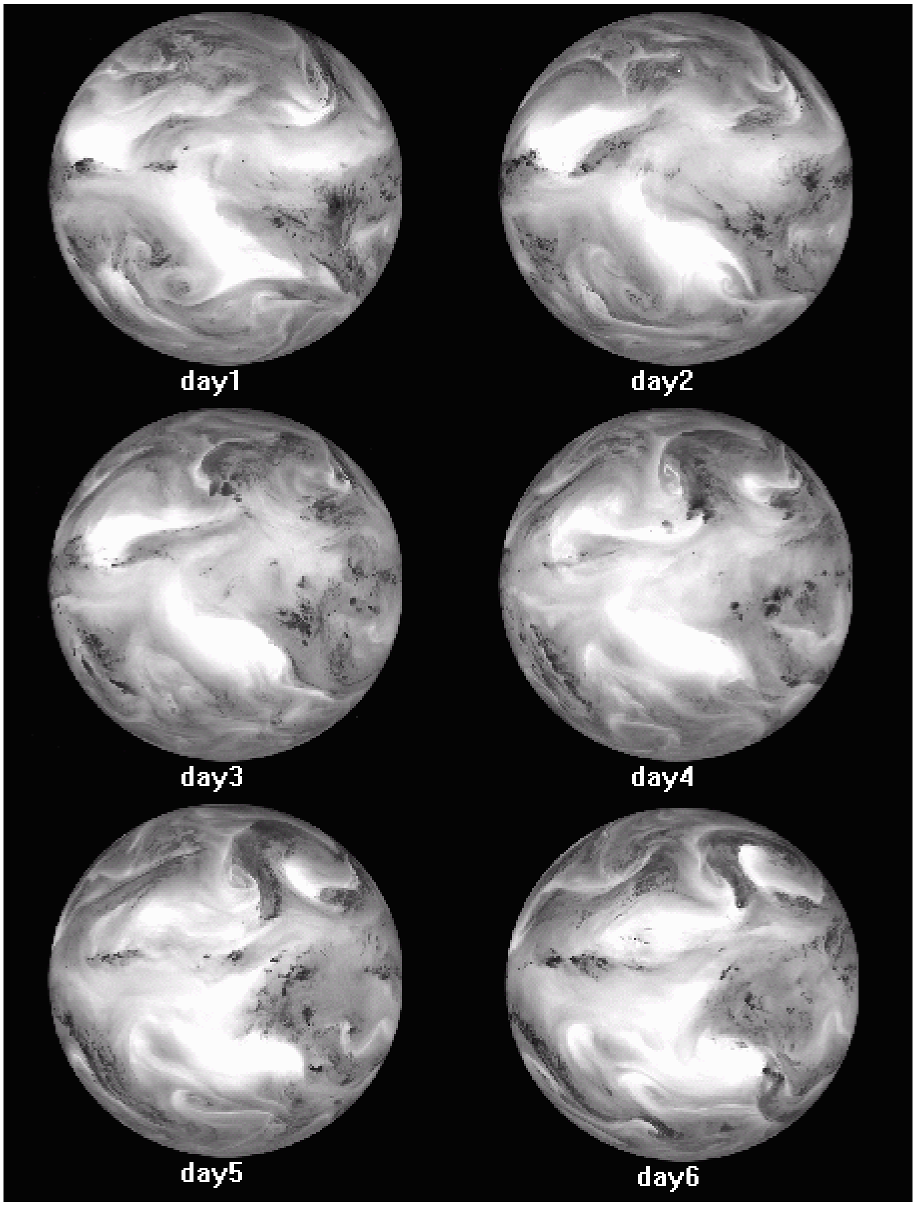


Figure 1 - Six consecutive days of 7 µm GOES-8 imagery of the upper atmosphere are shown. In this rendition white areas correspond to water vapor “holes” in the upper atmosphere, where underlying thermal radiation is escaping into space. Note how slowly large scale water vapor structures move in the upper atmosphere.

Starting in January 1995 one of the most recent additions to the GOES “family”, GOES-8, started providing global water vapor imaging of the western hemisphere (centered on 90° W Long.) on a regular basis at 7 µm. These images are available on an ftp server operated by NASA (ftp address is explorer.arc.nasa.gov /pub/Weather/). Figure 1 shows a sequence of such images, recorded 24 hours apart. White areas correspond to “holes” in the earth’s atmosphere where thermal radiation is escaping into space due to a lack of overlying water vapor. Note how the white patches move rather slowly, along with the rest of the upper atmosphere. This explains why periods of good thermal-infrared astronomy conditions tend to last for at least a few days at a time. In order to provide better Pacific coverage with GOES-8 coming on-line, GOES-7 was moved in January 1995 to a position over 135° W Longitude, which places Hawaii well into the imaged disk. Like GOES-8, GOES-7 water vapor imagery is posted on an internet ftp server roughly every ~3 hours. Though Hawaii is visible in GOES-8 images, GOES-7 measurements were used for this study to minimize limb brightening effects. It is trivial to locate Hawaii in the GOES-7 images since a graphic overlay is provided by several

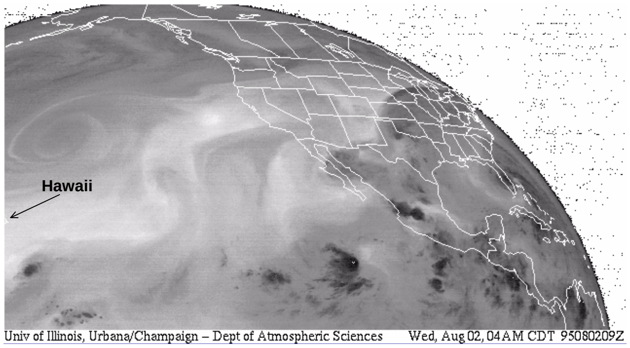


Figure 2 - A typical GOES-7 water vapor image with graphic overlay depicting North America and Hawaii is shown. Such frames were digitized and used to estimate water vapor over the Big Island in this analysis.

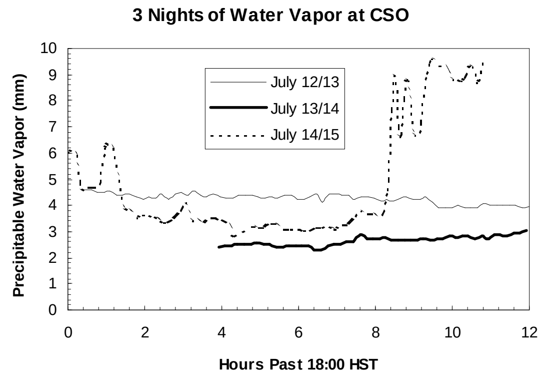


Figure 3 - Several typical nights of CSO τ data is shown. The strong and rapidly varying peaks during the third night in this sequence presumably is due to clouds passing through the radiometer's beam.

sites. Figure 2 is an example of a GOES-7 water vapor image used in this study, showing North America to the right and Hawaii along the extreme left edge of the frame.

Background Information on the CSO τ Monitor

An NRAO built radiometer has been in operation on Mauna Kea since ~1990 as part of a site characterization program for the new submillimeter array (SMA) scheduled to be built on Mauna Kea in the near future. The monitor is currently run jointly by SAO and CSO and is used to help characterize site conditions for radio telescopes on Mauna Kea. Masson (1992, IAU Colloquim 140, "Astronomy with Millimeter and Submillimeter Wave Interferometry") lists the relation between the 225 GHz atmospheric opacity and precipitable water vapor (PWV) over Mauna Kea as

$$\tau_{225} \approx 0.01 + 0.04\,PWV$$

where PWV is in millimeters and the 0.01 offset is due to oxygen. For unsaturated conditions the simple relation

$$\varepsilon \approx X_\lambda (1 - e^{-PWV\,\sec(Z)})$$

can be used to estimate atmospheric emissivity, where X_λ has been derived from Mauna Kea data (X_λ ~ 0.021 at ~10 µm) and is roughly constant across major atmospheric windows. Long term statistics derived with this monitor show significant diurnal and seasonal trends. During the day the well-known inversion layer that typically remains below the summit can, with heating, rise above the summit. Winter storms also tend to elevate the average PWV. The data recorded as part of this study essentially all correspond to ~5-6 AM HST in order to minimize contamination of CSO τ measurements by the local inversion layer. All measurements reported here were made during May to August 1995. Furthermore, relative humidity measurements recorded at the same time as the CSO τ measurements helped prevent spurious results from local ground fog from confusing the results.

Correlation Study

The study consisted of simply downloading GOES-7 images every few days and, at the same time, recording the current CSO τ meter measurements from Mauna Kea (kindly provided via a Gemini account on the JAC computer network). The GOES-7 images were translated via commercial software from their native JPEG format into FITS images before being read into SAOimage for detailed examination and identification of the precise location of the Big Island. A near-infrared high resolution image of the Big Island was downloaded at the same time to (1) determine if the summit of Mauna Kea (which is easily resolved in these images; see Figure 4) is clear and (2) if there is a relatively clear patch of ocean just east of the Big Island that can be used in the water vapor image analysis. The summit humidity was also recorded through the JCMT weather station. These important steps assure that (1) CSO τ data are not taken when local high humidity significantly influences measurements and (2) GOES-7 water vapor measurements are not contaminated by mid-level clouds that are not easily seen in the water vapor images yet are evident in near-infrared images, which probe all the way down to the surface of the ocean. The depth to which the water vapor images probe the atmosphere was not well known hence, in order to minimize the noise that underlying clouds can have on GOES-7 measurements, spots on the ocean surface (which has a relatively uniform thermal contribution to these images) were always used. With the precise location of a clear area near the Big Island determined (typically within ~100-200 miles of Hilo) the average signal value in a 6 pixel diameter aperture along this line of sight was evaluated. No complex transformation of measured image brightness into some other parameter was attempted in this, a first order assessment of GOES-7/CSO correlation. In principle, if CSO τ measurements and GOES-7 image brightness are related, a simple plot of PWV as measured at the CSO against GOES-7 measurements should exhibit a correlation. Figure 5(a,b) shows the results, which is derived from 26 days of data spanning a wide variety of PWV conditions that occurred during a ~3 month period in 1995. Figure 5(a) shows all of the data, including

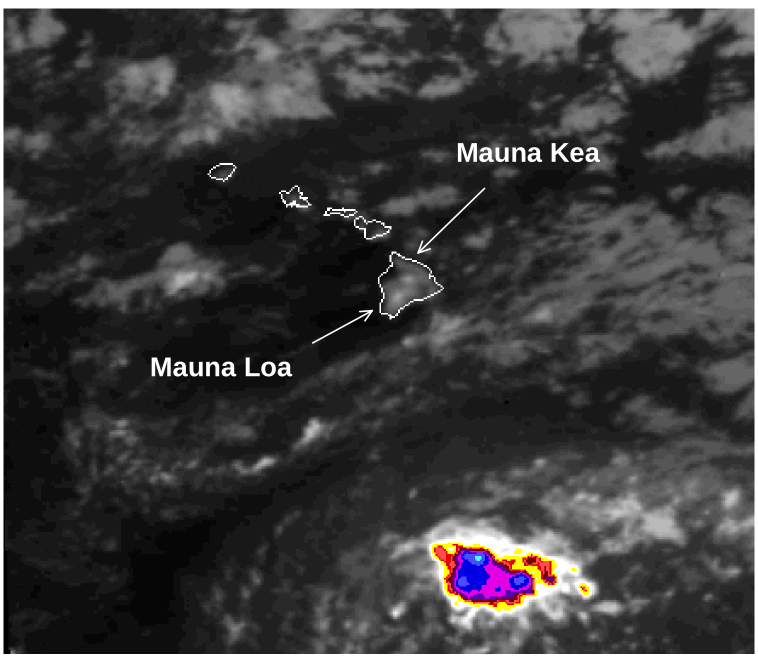
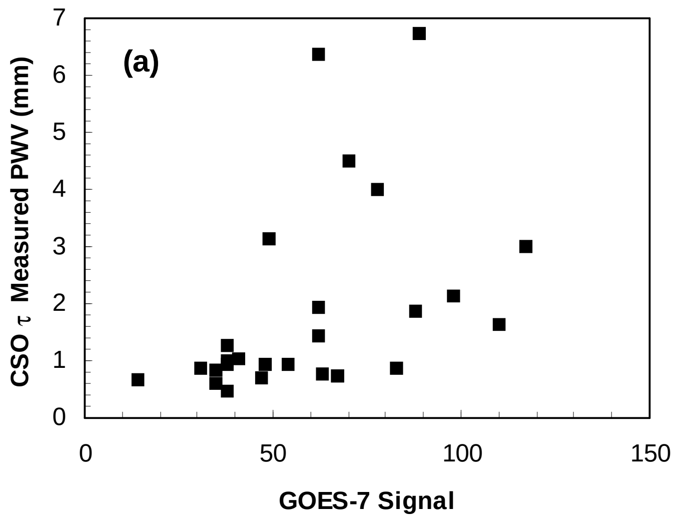


Figure 4 - A near-infrared GOES-7 image of the Hawaiian Islands is shown. The resolution is adequate to see the relatively cool tops of Mauna Kea and Mauna Loa on a regular basis at night in these images, which were used to identify a clear patch off-shore of the Big Island that could be used to sample GOES-7 mid-infrared imaging.



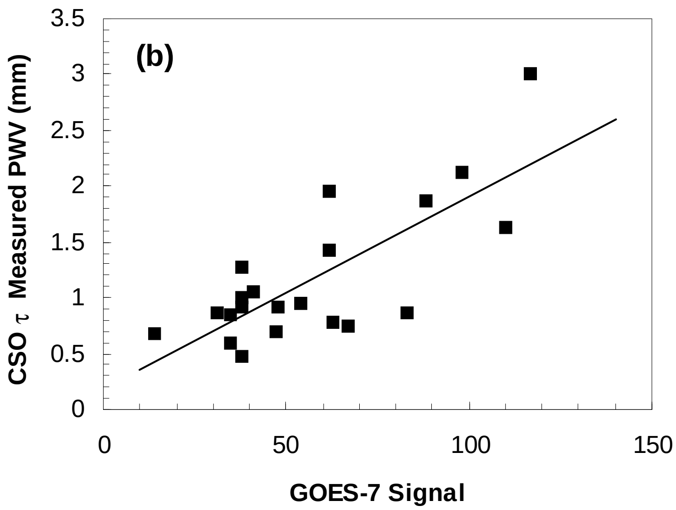


Figure 5(a,b) - Above (a) shows the complete data set comparing CSO measurements with GOES-7 data. This includes points known to be effected by ground fog or unusually high humidity conditions. Below, in (b), only points corresponding to clear skies and moderate to low summit humidity (RH < 60%) are shown. When anomalous conditions are excluded from the analysis a fairly well defined correlation between CSO and GOES-7 data emerges. The CSO τ meter appears to go non-linear compared to GOES-7 images for saturated conditions.

mornings in which local ground fog (RH >90%) was noted or a tropical depression (the remnants of a hurricane) was very close to the Big Island yet no clouds appeared to be in the CSO beam or over the summit according to near-infrared images. Figure 5(b) shows the same data but with the previously mentioned anomalous points removed. Clearly some care must be used to make such remote measurements since the CSO τ meter goes into a non-linear relationship with GOES-7 measurements under extremely high PWV conditions which do not necessarily correspond to clouds over the summit. A simple linear fit to the points in Figure 5(b) is shown, which has the form:

$$PWV(mm) = 1.72 \times 10^{-2}\, GOES + 0.19$$

The Pearson correlation coefficient for this data set is 81%. Note that the previously mentioned relation between CSO raw data and PWV has been incorporated in this fit. The correlation between these measurements demonstrates that, barring local high humidity that cannot be sensed from space easily, satellite 7 µm imagery can be used to determine water vapor conditions above Mauna Kea to an accuracy of ~25%.

The real potential for this relationship lies not in trying to replace a ground based monitor with satellite data, rather the key here is that time-lapse sequences of satellite images should make it possible to predict near-term PWV conditions. The typical sizes of low water vapor patches in the upper atmosphere range from hundreds to thousands of miles across. While it remains a challenge to predict with confidence water vapor conditions under transitional conditions, there are periods in which extremely large patches of dry air remain over Hawaii and these satellite images can certainly be used to determine when such large patches are overhead. A detailed attempt at predictive models is beyond the scope of this first-order analysis of the problem. Nonetheless, the prospects for using such remote sensing for queue optimization within Gemini's future operations looks promising.

At this early stage satellite imagery is probably best described as complimentary to ground based measurements. Specifically, a ground based sensor provides measurements on much faster timescales than what can be extracted from satellite images available only once every few hours. Figure 3 shows the effect of patches of moist air (clouds?) passing overhead that may or may not be resolved in a 7 μm satellite image. One can easily imagine making thermal infrared observations and experiencing transient spikes of high emissivity on nights for which marginal water vapor conditions are expected based upon satellite images. Having a sensor that quickly detects such spikes of moist air passing overhead would be a useful diagnostic. Beyond rapid transients, a ground based monitor will show slow drifts in PWV on timescales of an hour or two that would be difficult to gauge from satellite images alone. If real-time measurements made by a ground based sensor indicate that water vapor conditions are significantly degrading observations, switching to another (non-thermal) program may be warranted in Gemini's queue of observations.

Future for Satellite Coverage of Gemini N/S Sites

In the near term, water vapor images showing a bit more of the ocean to the east of the Big Island are currently posted in the University of Hawaii's meteorology WEB page (http://lumahai.soest.hawaii.edu). These images are color-coded and were not used in this analysis due to complications with quantifying image brightness, i.e., it was much easier to quantify the image brightness in the simple 8-bit gray-scale images used here. These UH posted images may be helpful for currently running Mauna Kea telescopes since they show patches of dry or moist air *incoming* from the west. It may be possible to arrange for full global GOES-7 images to be located on an ftp disk by the University of Hawaii, which would be ideal for assessing incoming regions of high or low emissivity air. It should be re-emphasized that in practice it is quite helpful to compare these images with near-infrared GOES-7 and GMS-4 images of the Pacific to identify cirrus or frontal systems that are often less well defined in the 7 μm images.

In the long term, current and next-generation satellites in NOAA's GOES series continue to grow in sophistication, offering expanded wavelength coverage and spatial resolution. Though GOES-7 is aging, GOES-8 and GOES-9 (recently launched and in a ramp-up to steady state operation) will continue to support water vapor imaging over both Gemini sites. Currently GOES-8 is located at 90° West longitude, offering excellent water vapor coverage for Cerro Pachon. When GOES-9 is fully commissioned (mid-fall, 1995) it will fill the eastern Pacific slot (GOES-7 will be used only as emergency backup) while GOES-8 remains in the western Atlantic slot (private communication, Dennis Chesters, GOES Project Scientist). There is no reason to expect over the long term that such weather satellites will not be launched and maintained under NOAA's mandate to provide weather information to the United States, well into Gemini's steady state operational phase. European and Japanese sponsored satellites may also be useful in the long term to Gemini as well. Furthermore, the University of Hawaii recently received a grant from NASA to compile weather data for the Pacific basin (private communication, Torben Nielson, Univ. of Hawaii) and the Mauna Kea observatories may be able to tap this resource in coordinating future operations. Finally, ESO is in the midst of an independent analysis of the use of satellite imaging and ground based emissivity measurements over Paranal. This work is being led by Andre Erasmus at the University of Northern Colorado. Initial results indicate good correlation between ground and spaced based measurements of water vapor above Paranal and this ESO sponsored project is now working on prediction algorithms for atmospheric emissivity for Paranal. Maintaining an open dialog with ESO, CTIO, and the various Mauna Kea based observatories on such issues as site monitoring and predicting various atmospheric properties will surely be beneficial to Gemini and our various astronomical neighbors.

Conclusions

A comparison was made between atmospheric water vapor over Mauna Kea, as measured by the CSO τ meter and GOES-7 7 µm images. For unsaturated conditions a correlation exists between measurements made through these completely different techniques. Since 7 µm satellite coverage is likely to remain for many years over both Gemini sites, it should be possible to use such remote sensing to identify and predict optimal conditions to conduct infrared observations. Folding such information into Gemini's observing queue should significantly enhance the overall quality of the infrared observations made with the Gemini-N/S observatories.