# Novel spectrograph/radiometer for cloud top height measurement using three complementary techniques

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## ABSTRACT

A proof-of-concept (POC) instrument system to measure cloud top height from space using three complementary techniques is presented. These techniques use measurements of 1) thermal infrared (IR), 2) molecular oxygen "A" band absorption, and 3) filling-in of Fraunhofer lines (the Ring effect), respectively. Combining three techniques is achieved with a single grating spectrograph with bandpass and order sorting filters by measuring 11 $\mu$m radiation from the zeroth order of the grating for the IR, 750-780 nm radiation from the first order for the "A" band absorption, and 390-400 nm radiation from the second order for the Ca K and H Fraunhofer line filling-in effect. The POC system and its measurement results with the POC system are described.

**Keywords:** cloud, IR, UV, molecular oxygen, Ring effect, Fraunhofer line filling-in effect, spectrograph, radiometer

## 1. INTRODUCTION

Cloud top height is one of the cloud parameters needed in the study of the earth's climate system. More than half of the earth's surface is covered by clouds, which reflect incoming radiation from the sun to the earth, and block outgoing radiation from the earth to space, thus modulating the energy balance of the earth and its atmosphere[1,2,3]. The study by Ohring and Alder[4] is one of the examples which shows the importance of cloud top height. Their modeling study estimates that an increase in cloud height of 1 km would result in an increase in surface temperature of 1.2 K.

Several methods have been proposed to measure cloud top height from space. These methods use thermal radiation from cloud top[5,6], molecular oxygen "A" band absorption[7,8,9,10,11], Fraunhofer line filling-in effects[12,13], stereo-viewing[14], and ranging with a lidar[15], respectively. The thermal IR technique measures the cloud top temperature either from radiance at the atmospheric window near 11 $\mu$m or from radiances at $CO_2$ absorption bands. The cloud top height is inferred from the measured temperature. The molecular oxygen "A" band technique uses observations of backscattered sunlight in the wavelength range of 750 - 780 nm. The atmospheric absorption column depth above the cloud is used to deduce the cloud top height. The third technique uses the Fraunhofer line filling-in effect (also called the Ring effect) at the Ca H and K lines near 390 - 400 nm. The Fraunhofer line is filled-in by atmospheric Rayleigh scattering because rotational Raman scattering, a small fraction of the Rayleigh scattering, smears the Fraunhofer lines in the solar spectrum. The scattering column above the cloud is estimated from the amount of filling-in of the Fraunhofer lines in the earth radiance. The filling-in amount is obtained by comparing the earth radiance spectrum with the extraterrestrial solar spectrum. In the stereo-viewing technique, a cloud is observed from two platforms and the cloud top height is determined from the altitudes of the two platforms and their viewing geometry. In the lidar technique, a direct ranging is used to obtain the cloud height or vertical distribution.

The proposed technique in this paper is to combine the first three techniques described above in one instrument since none of the above techniques is perfect alone. The thermal IR technique has been used operationally in weather satellites, but may not be used for an isothermal atmosphere or for convective clouds, which are not in thermal equilibrium with the atmosphere. Satellite sensors employing the molecular oxygen "A" band just began to fly[16,17]. This technique requires an accurate correction for non-oxygen absorption at the cloud boundary[18], which may hinder the accuracy of the retrieval. The Fraunhofer line filling-in effect technique does not suffer from problems of the thermal IR and the molecular oxygen "A" band techniques, but requires an instrument of high spectral resolution to provide sufficient sensitivity. The stereo-viewing technique may not be practical since it would require two geostationary satellites, with their coverage limited to within 60° of latitude. The lidar technique provides the most accurate and direct measurements of cloud top height. However, it has not been flown on satellites since the requirements of power and the size of the light collecting telescope are prohibitive.

This work studies the feasibility of combining three techniques by building a proof-of-concept (POC) instrument system. This paper describes the POC system and presents preliminary test and measurement results with the system.

## 2. BASELINE INSTRUMENT CONCEPT

Figure 1 shows a schematic of the instrument concept in which three different spectral ranges for three different techniques can be measured simultaneously. This is achieved with a grating spectrograph/radiometer. Zeroth order radiation from the grating is imaged onto an IR detector with an IR filter and lens assembly. The second order of the 390 – 400 nm radiation happens to be close to the "A" band wavelength range. Long and short bandpass filters are used to sort the spectral orders. The lenses shown in Figure 1 are symbolic to represent the objective, collimating, and imaging optics.

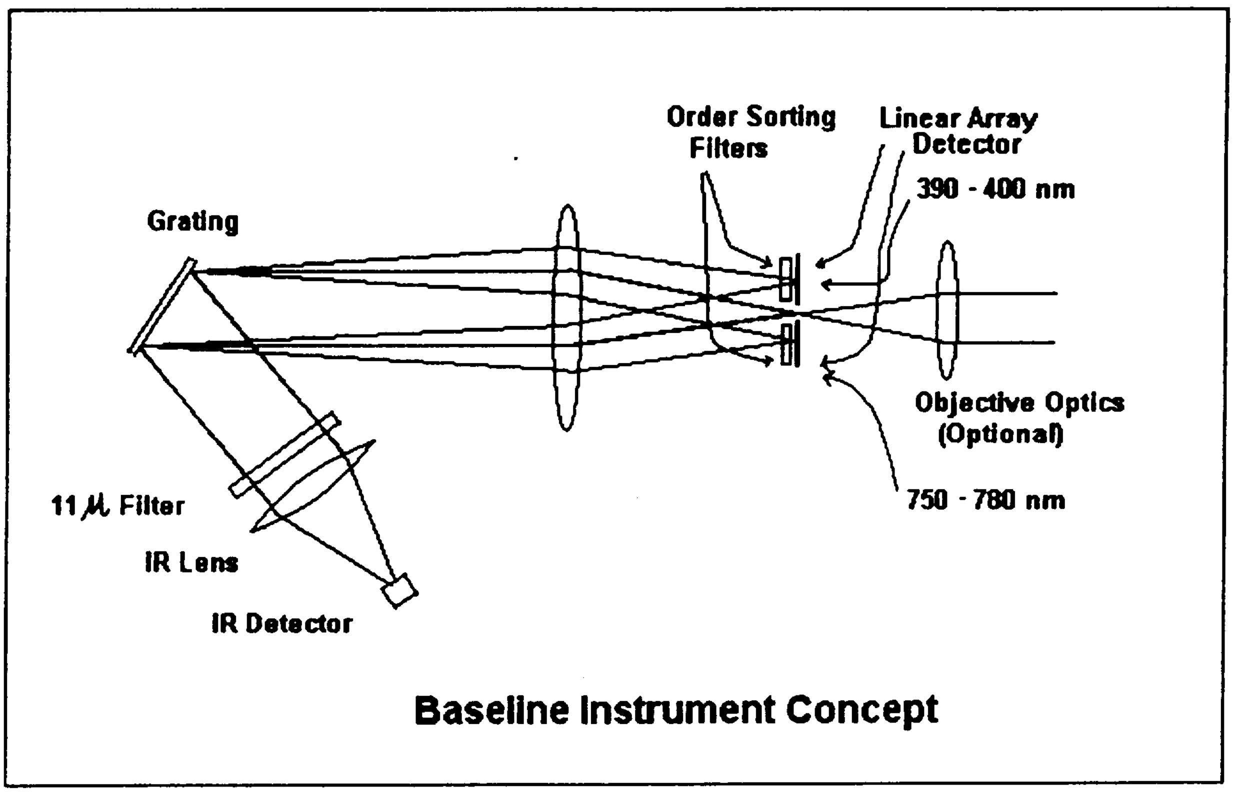


Figure 1. A schematic of baseline instrument concept. Lenses are symbolically used to represent objective, collimating, and imaging optics.

The objective optics are optional and used to limit the field-of-view of the instrument as needed. The spectrograph is shown in the Littrow mounting which will provide compactness in packaging.

## 3. PROOF-OF-CONCEPT INSTRUMENT SYSTEM

A proof-of-concept instrument has been built with an off-the-shelf commercial spectrograph. The spectrograph is a f/3.7 cross Czerny-Turner type with 120 mm focal length. The grating in the spectrograph is a ruled grating with 1200 lines/mm blazing at 750 nm. Two color glass filters butted together in front of the detector are used to sort the spectral orders. The short pass filter has a cut-off near 500 nm and has a transmission of about 70 % at 400 nm. The rejection at 750 – 800 nm is better than $10^{-3}$. The long pass filter has a cut-off near 550 nm and has a transmission of nearly 100 % at 750 – 780 nm. The rejection below 500 nm is better than $10^{-7}$. A 1024 silicon photodiode array detector is placed at the focal plane. The detector is slightly tilted with respect to the focal plane and the order sorting filters to prevent internal multiple reflections at the expense of spectral resolution. For the 50 $\mu$m slit, the nominal spectral resolution is 0.4 nm in the first order and 0.2 nm in the second order. The photodiode array has a 25 $\mu$m pitch between the detector elements and it has a fill factor of 80 %. Thus there are two data samplings within the spectral resolution. The spectrograph has been modified such that the zeroth order radiation is passed through an 11.4 $\mu$m filter with bandwidth of 3.2 $\mu$m, and collected with a ZnSe lens onto a HgCdTe detector, which is cooled with liquid nitrogen in a dewar. A telescope is optional and used when a smaller field-of-view of the instrument is needed. In either case, the instrument has an identical field-of-view for all three different spectral ranges. Figure 2 shows a picture of the POC instrument system.

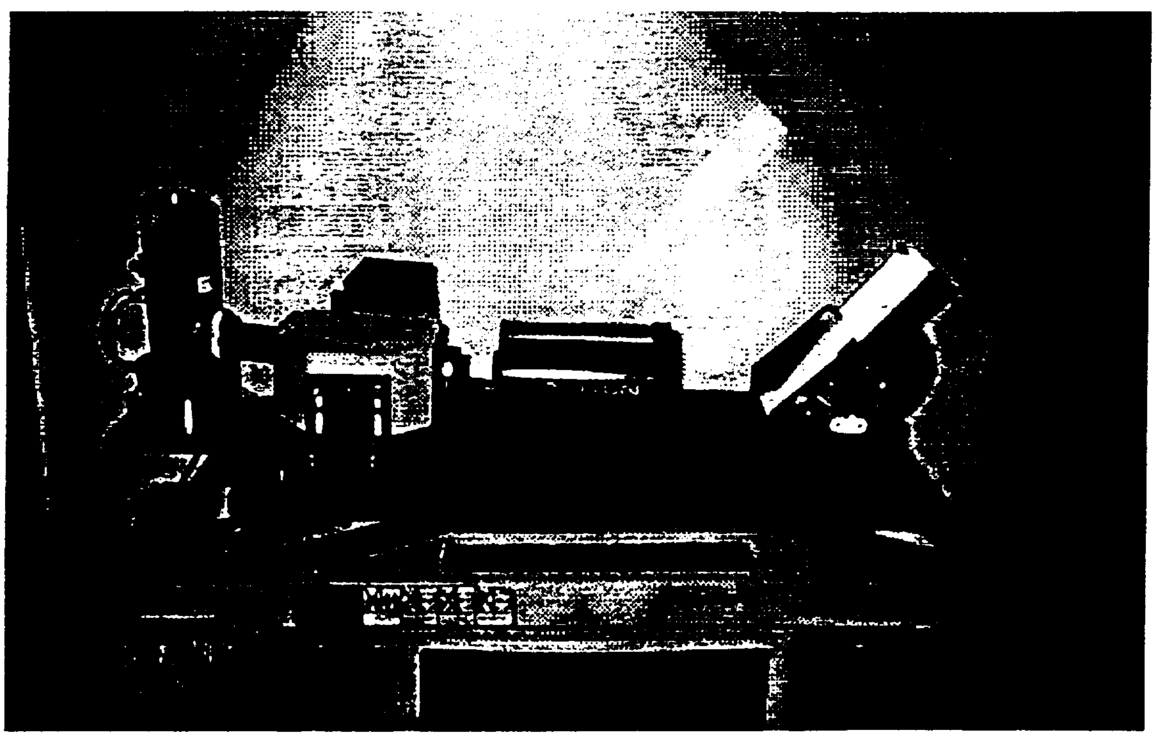

Figure 2. A picture of the proof-of-concept instrument system. A mirror is shown in front of telescope to view the zenith sky. The chopper used in the IR measurement is not shown in this picture.

## 4. TEST AND MEASUREMENTS WITH THE POC SYSTEM

Since the electronics of the POC system has not been fully integrated, the IR radiometer part was tested separately. Figure 3 shows the test setup for the IR radiometer. The targets used for testing the IR were a human hand, a black spray painted honeycomb structure, and an aluminum plate. Liquid nitrogen was poured onto the honeycomb structure to simulate a temporary cold target. The chopper was operated at 940 Hz and the time constant of the lock-in amplifier

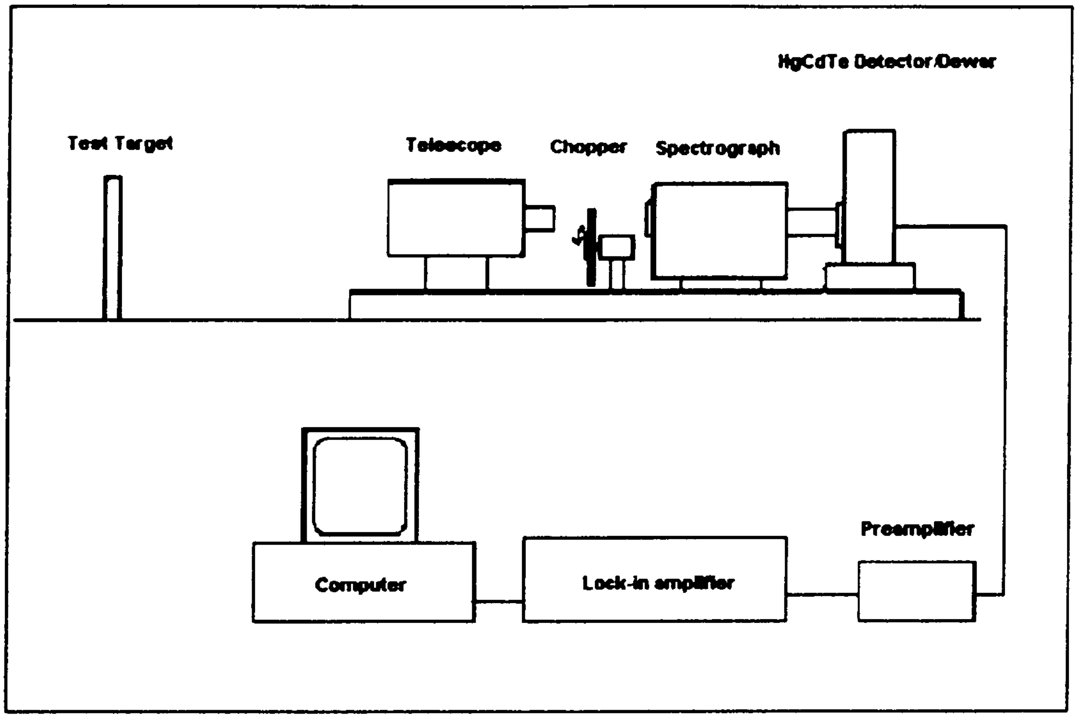


Figure 3. The IR radiometer test setup.

was set to be 1 second. The signal measured with the hand was in the order of 6 mV relative to that with the honeycomb structure cooled with liquid nitrogen while the measured noise was less than 0.01 mV. The signals measured with the room temperature aluminium and the honeycomb target were almost identical and were about 4 mV relative to that with the liquid nitrogen cooled honeycomb structure. This result was in reasonable agreement with the estimated signal-to-noise (S/N) ratio of 1000 for a 330 K blackbody radiance source.

Figure 1 shows the setup for the sky radiance measurement. To measure the solar spectral irradiance reaching the ground, the mirror in the Figure 1 setup is replaced by a $BaSO_4$ diffuser plate. Because the illumination by diffuse sky radiance on the diffuser is significant, the diffuse radiance contribution was measured by blocking the direct illumination, and was subtracted to obtain the irradiance by direct solar illumination, as in Bigger et al.[19]

Figure 4 shows the measured sky spectrum, in arbitrary units. The spectrum for wavelengths longer than 775 nm is second order, so the true wavelength is half the value of the scale. The feature due to absorption by the molecular oxygen "A" band is identified near 760 nm. The Ca K and H Fraunhofer lines are also clearly identified at 393 nm (786 nm in the scale of Figure 4) and at 397 nm (794 nm in Figure 4), respectively. Figure 5 shows the spectrum of the solar spectral irradiance at the ground. The molecular oxygen "A" band and the Ca K and H Fraunhofer lines can be identified in this figure as well.

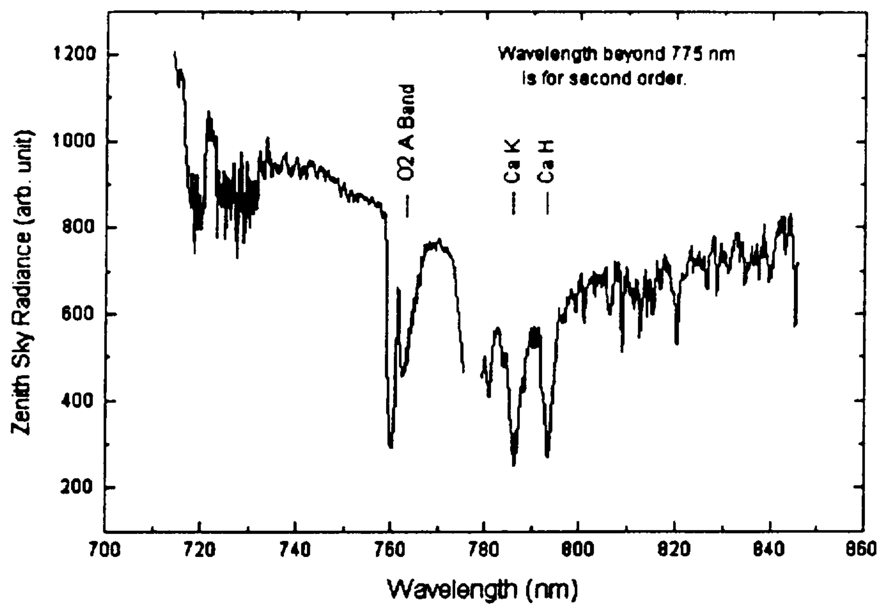


Figure 4. The zenith sky radiance spectrum

Figure 6 shows the ratio of the zenith sky spectrum to the solar spectrum at the ground. The features observed at 393 nm and 397 nm are due to the Ring effect at the Ca K and H Fraunhofer lines. The magnitude of the observed Ring effect is about 5 times larger than the one observed from Nimbus-7 SBUV[12,13,20]. This result is expected since the spectral resolution of the POC system is 5 times better than that of SBUV. Also a feature like a Ring effect is observed at the "A" band. Care must to be taken in interpreting this feature. If there is an optical path difference between observed sky radiance and measured solar irradiance, such an apparent feature can be present. About 80 % of the feature at the "A" band in Figure 6 is due to the optical path difference and 20 % is due to the Ring effect. The Ring effect in the "A" band has been identified from near simultaneous measurements of the sky radiance and the ground solar irradiance. This result will be reported in a separate publication.

## 5. SUMMARY AND CONCLUSIONS

The fabricated proof-of-concept (POC) spectrograph/radiometer system demonstrates that radiation from three spectral ranges corresponding to three different cloud top height measurement techniques can be measured with one compact instrument. The higher spectral resolution at the Ca K and H lines makes the Ring effect technique more sensitive and competitive with other techniques. The POC system provides a complete profile of oxygen "A" band absorption which can be used to check the self consistency of the "A" band technique. The Ring effect at the molecular oxygen "A" band has been positively observed when the source of radiation at the "A" band is molecular scattering. In an analysis of radiation associated with molecular scattering at the "A" band, rotational Raman scattering, which causes the Ring effect, should be considered. The POC needs improvement so that it is not sensitive to polarization in the ultraviolet. A tuning fork chopper with a pseudodepolarizer may fulfill all three measurement requirements when a proper electronic gating is used for the visible and near IR detector integration.

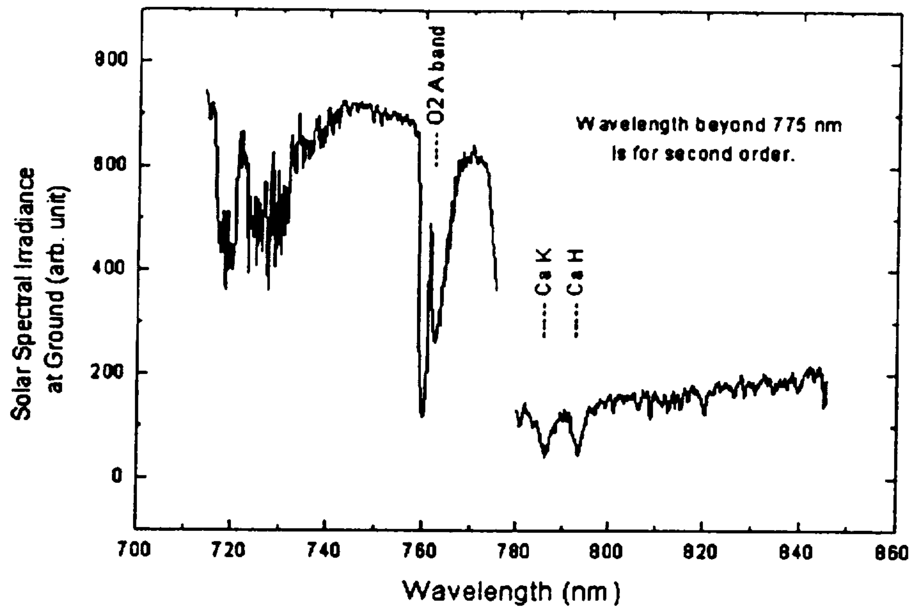


Figure 5. The solar spectrum at the ground

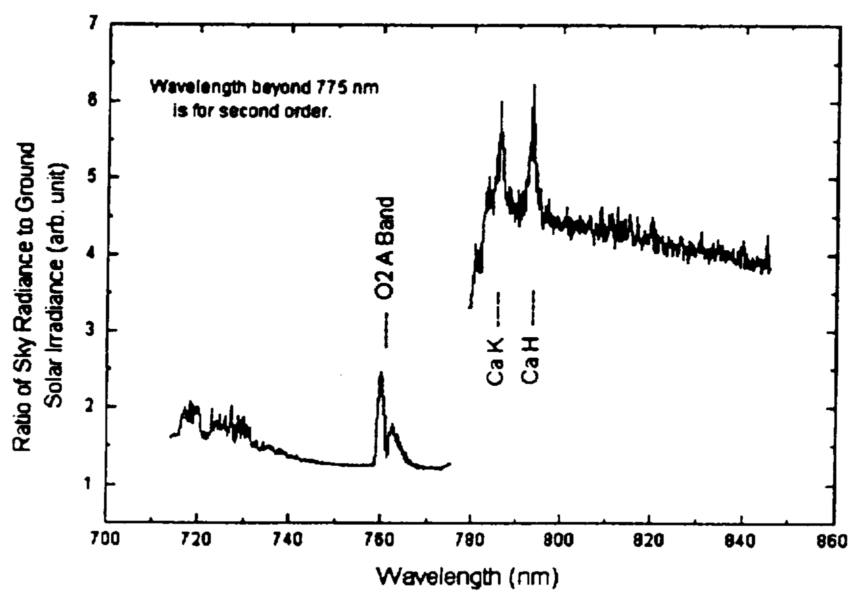


Figure 6. The ratio of the sky radiance spectrum to the solar spectrum at the ground

## ACKNOWLEDGEMENTS

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