Atmospheric Remote Sensing in the Terahertz Region

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Abstract

Remote Sensing of major and minor constituents gases is of very great importance in understanding the atmospheres of earth and planets. Of the minor gases in an atmsophere the most difficult species to observe are often the radicals such as atomic oxygen, hydroxyl, chlorine monoxide and species such as hydrogen chloride, hydrogen fluoride, among others. Observations in the terahertz region of the spectrum have been successful in determining the density of many of these species including the hydroxyl radical. However, the instruments used to date are complex and in general not suitable for spaceflight on small satellites. This study has as its primary goal the presentation of a simple, compact scanning Fabry-Perot interferometer which has the capability to make observations of minor constituents in an atmosphere competative with larger and more complex instrumentation. We illustrate the use of this new instrument by showing how the hydroxyl in the earth's stratosphere can be detected from observations taken at balloon altitude.

1. Introduction:

Development of small and rugged remote sensing instruments to observe the constituents in the planetary atmospheres is of very great interest to the geophysical community. On earth this interest is in part generated from the need to understand the state of the atmosphere in an era where we have just begun to reach an awareness of the impact that man has on the global environment. However, the overriding reason for the interest in the state of the atmosphere is the recognition that our present understanding of this important geophysical system is at best in its infancy. In many cases increased knowledge will come from exploration using new techniques. The most difficult species to observe are often the radicals such as atomic oxygen, hydroxyl, and chlorine monoxide among others.

The hydroxyl radical (OH) is used here to illustrate the capabilities of the instrument that we are developing because it is an important member of the HO_X family and it is very difficult to detect. Hydroxyl is a highly reactive species which enters in many atmospheric chemical reactions including the catalytic cycles of HO_X, NO_X, and ClO_X which lead to the destruction of ozone. In these cycles OH is strongly involved in determining the partition between radicals and reservoir species in the atmosphere.

Observations in the terahertz region of the spectrum have been successful in determining the density of many stratospheric species including the hydroxyl radical [1]. However, the instruments used to date are complex [2] and in general not suitable for spaceflight on small satellites. We show in this paper that a old instrumental concept, the Fabry-Perot interferometer, when applied in a new way, can make a serious contribution to observations of a number of minor gases in the atmosphere.

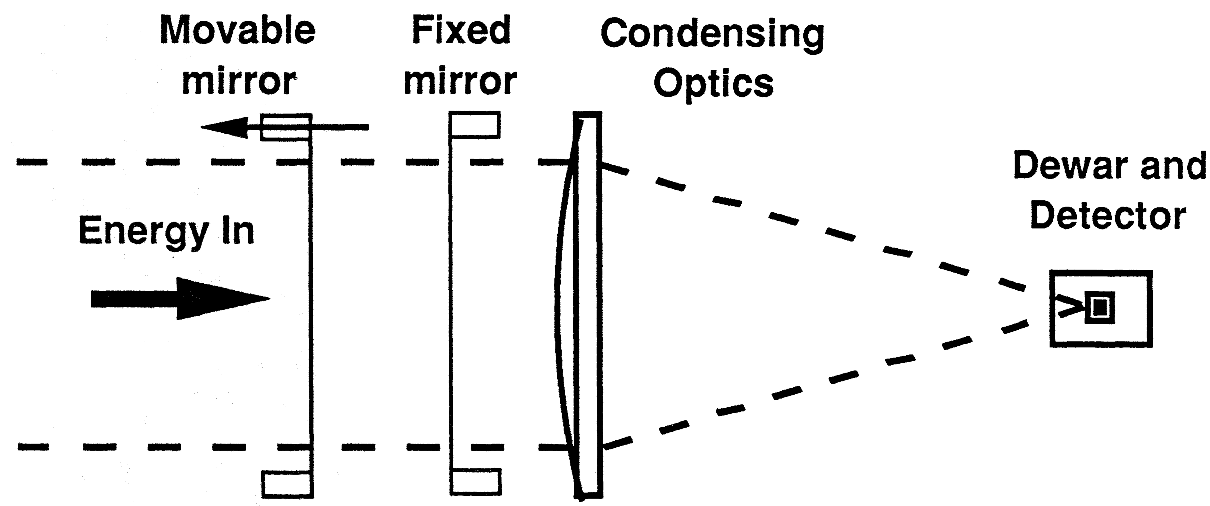
2. Multiplex Fabry-Perot Interferometer

The instrumental study presented in this paper is of a new type of interferometer to examine extended spectral regions in a manner similar to done with a Michaelson interferometer. This new interferometer, called the Multiplex Fabry-Perot Interferometer (MFPI)[3,4,5,6,7] , will produce the same information that is obtained from a high resolution Fourier Transform spectrometer operating at resolutions of the order of $0.003 cm^{-1}$. However, this instrument is much smaller and does not require large mirror stroke of a Michelson Interferometer. In the terahertz where many of the radical species can be observed this new instrument is a metal mesh Fabry-Perot interferometer with a mirror stroke of less than 10 cm. The results shown in this study are preliminary numerical simulations of the instrument function and inversions of simulated spectra obtained with such an instrument. During the next year this numerical model will be used to complete the final design specifications for a balloon flight instrument.

The choice of the Fabry-Perot interferometer for our investigation is based on the experience that exists at the University of Michigan in the design, construction, and operation of this type of instrumentation for ground based observations [8] and for space flight[9].

3. Instrument Concept

Conceptually the MFPI is very elementary, consisting of two very flat partially reflecting surfaces that are moved apart over a distance of about 10 cm. while maintaining their parallelism. This device is illustrated in figure 1 shown below. We note that in addition to the components show there is a metal mesh filter in the dewar to isolate the spectral region of interest.



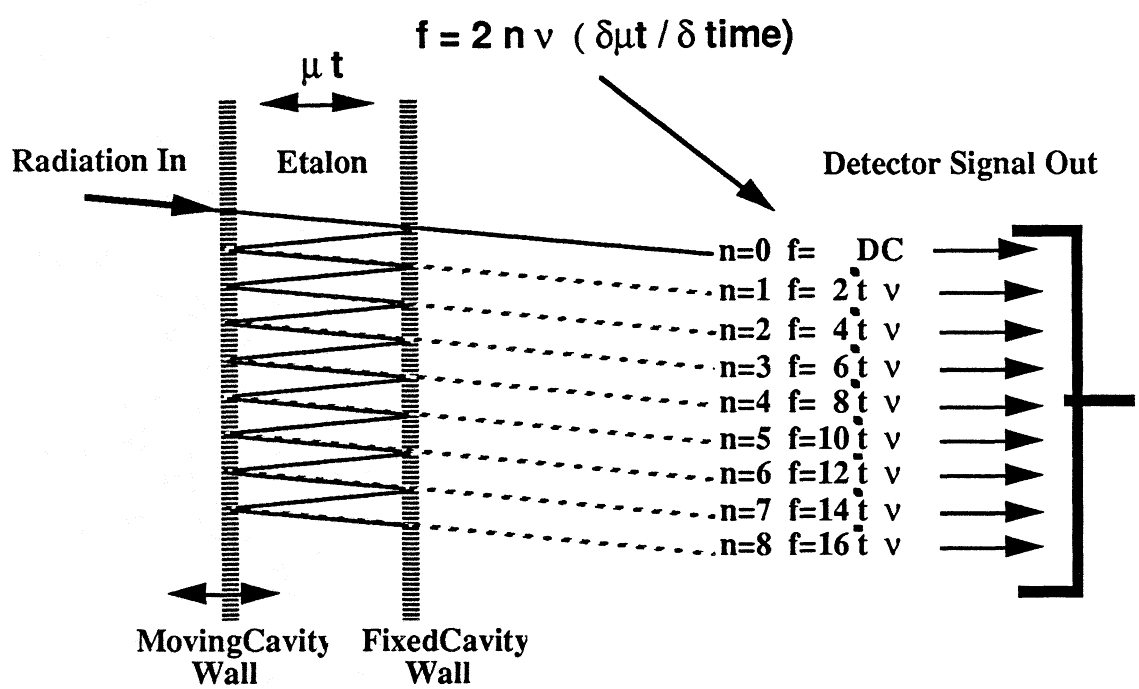
MULTIPLEX FABRY - PEROT INTERFEROMETER

Figure 1

The mirror or etalon will be moved using a simple linear translator and piezoelectric actuators to move the grids during a scan of the instrument. The requirements for parallelism in the terahertz region is relaxed compared to the task in the visible where we have had considerable experience. This cavity, or etalon, acts as a comb filter with a comb separation in the spectrum that is dependent on the separation of the two partially reflecting surfaces. As the surfaces move further and further apart the resolution of the spectrum increases. Consequently, during the beginning of a scan when the etalon surfaces are nearly in contact a low resolution spectrum is determined, and at the end of the motion when the surfaces are far apart the high frequency portion of the spectrum is identified. Throughout the scanning processes the transmitted energy is focused on a cooled detector and a set of fundamental temporal harmonics are extracted from this signal. The interesting characteristic of the multiple pass interferometer is that each reflection of the incoming beam of energy is passed with a unique temporal frequency, thus allowing us to obtain a signal that is equivalent to that of several Fourier Transform spectrometers operating simultaneously as the etalon cavity length is varied.

4. Measurement Technique

The actual measurement is taken by detecting all of the energy that passes through the etalon as one of the etalon plates is moved through a relatively large optical distance.



Multiplex Fabry-Perot Interferometer

Figure 2

The energy transmitted to the detector is modulated by a carrier frequency, f, that depends on the number of times the light has been reflected inside the etalon, or optical cavity. The energy is self-heterodyned within the cavity and the signal can be separated by the number of reflections within the cavity, n, by this frequency of modulation. It is also important to note that the rate of change of path length is directly related to the velocity of the moving cavity wall and also with the number of reflections within the optical cavity.

The energy passing through the etalon with one reflection gives a signal that is equivalent to a Michelson in which the optical path difference between the plates has doubled. The energy passing through the etalon after five reflections is equivalent to that of a Michelson where the path difference has been changed by a factor of ten, and so on. Thus by moving one of the cavity walls over a small distance, e.g., 10 cm, one can measure a signal that is equivalent to moving a Michelson plate over a considerably larger distance. The advantage of using this multiplex technique is thus easy to understand.

The measured signal is the convolution of the atmospheric signal and the instrument function. Numerical simulations have shown that the broadening is considerably narrower for the MFPI than that produced by a Michelson Interferometer.

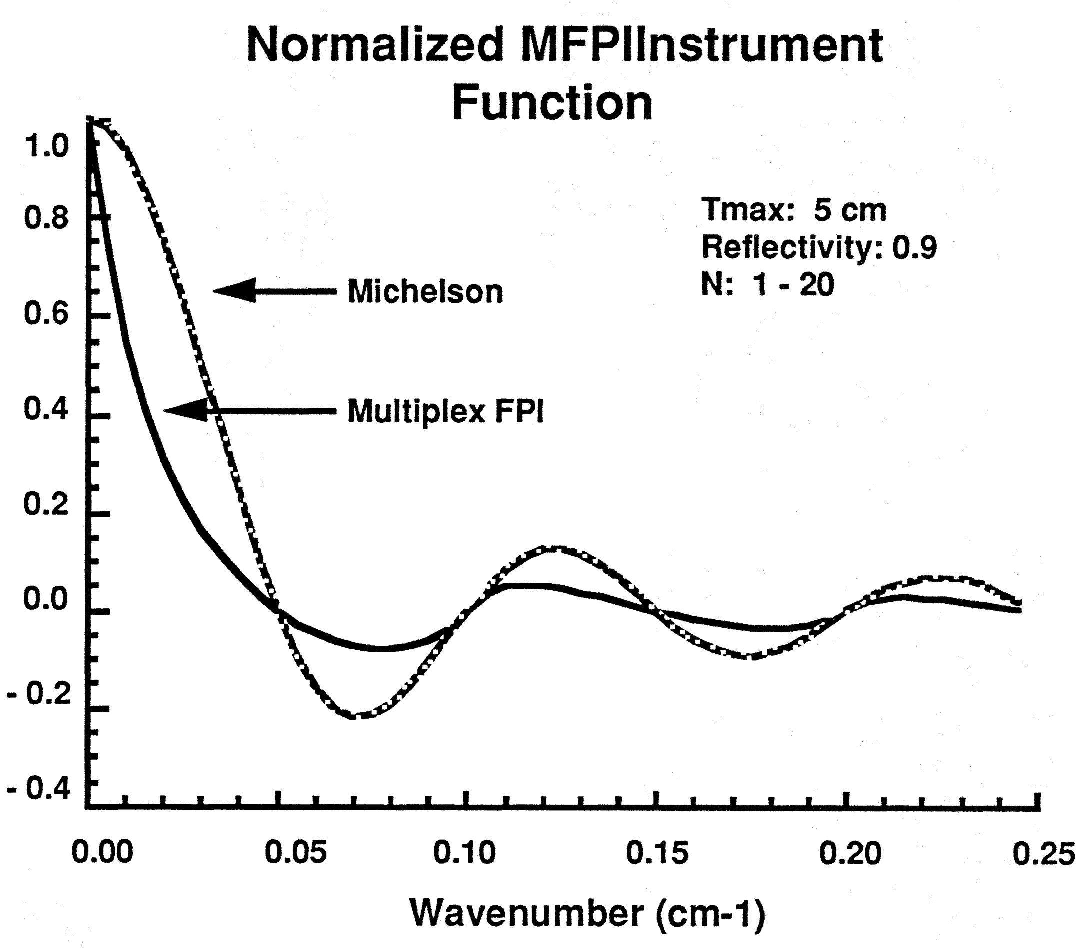


Figure 3

Furthermore, if the signal to noise ratio is sufficiently high the lower harmonics can be ignored. The resulting spectrum has even less broadening than when all of the harmonics are used.

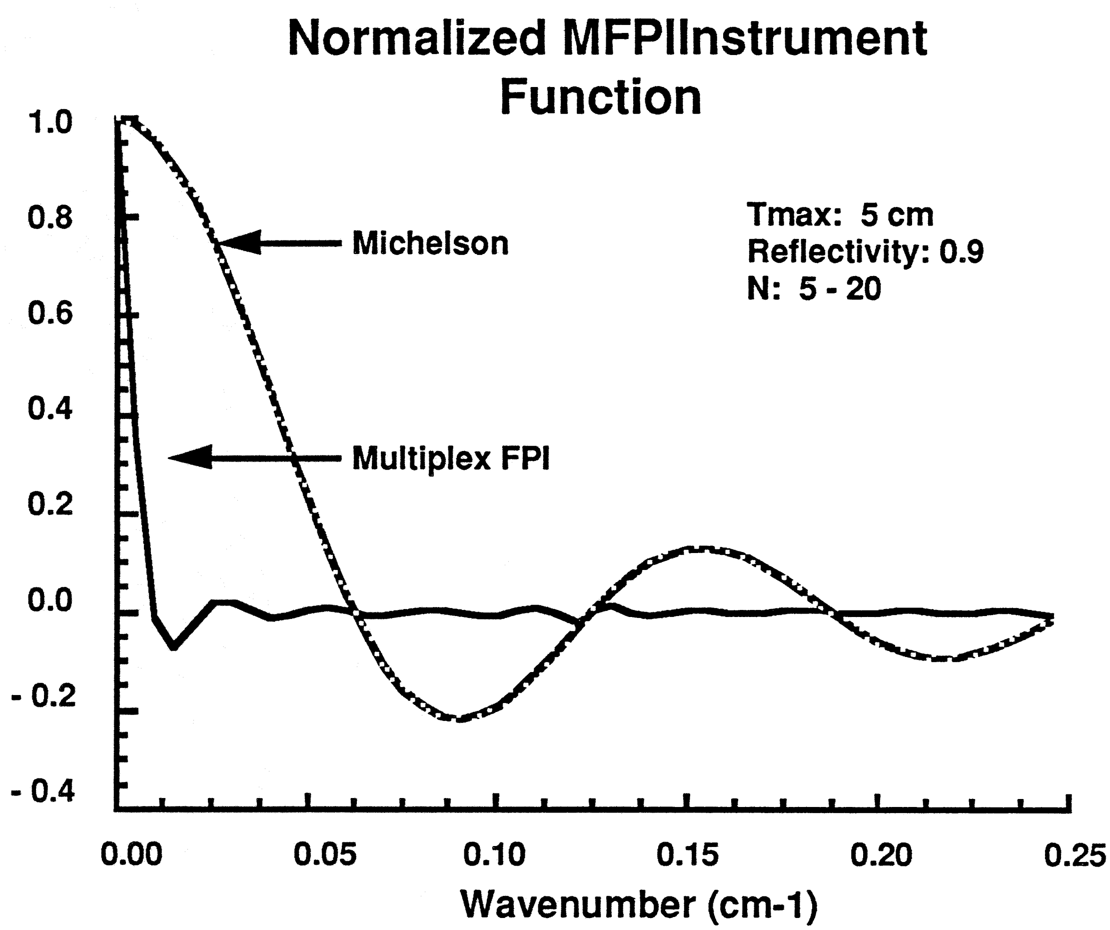


Figure 4

We have developed a radiative transfer code to allow us to examine the spectrum of the earth's atmosphere throughout the terahertz spectral region[10]. This will allow us to identify the important spectral intervals in which to observe the radical species of interest. This code allows us to model the atmospheric spectrum and the solar absorption spectrum when viewed from any point in or above the atmosphere. To test our ability to reconstruct a portion of the spectrum we chose a spectral region around 118 cm^{-1}

because is contains transition lines of O_3, H_2O, and OH.

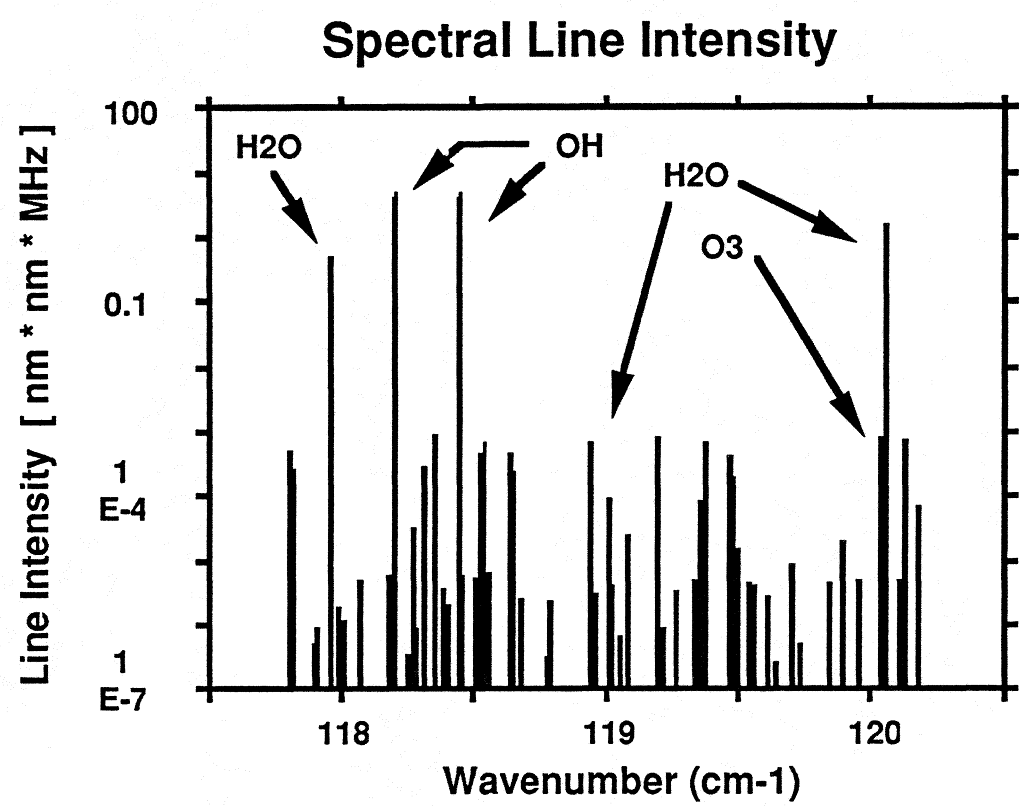


Figure 5

The important spectral lines in this region are shown in figure 5. The OH transitions here are quite intense, however, the brightness of these transitions is small due to the low mixing ratio of OH. In practice this may not be a desirable region in which to measure OH, but for this test case it will allow us to illustrate that it is possible to resolve very weak spectral features. The simulation used the brightness spectrum obtained from our radiative transfer code and determined the instrument response to this spectrum. We then reconstructed the spectrum from the instrumental output using all of the temporal frequencies without weighting. This inversion is elementary and results in the unapadized spectrum shown in figure 6. We note that the comparison is satisfying.

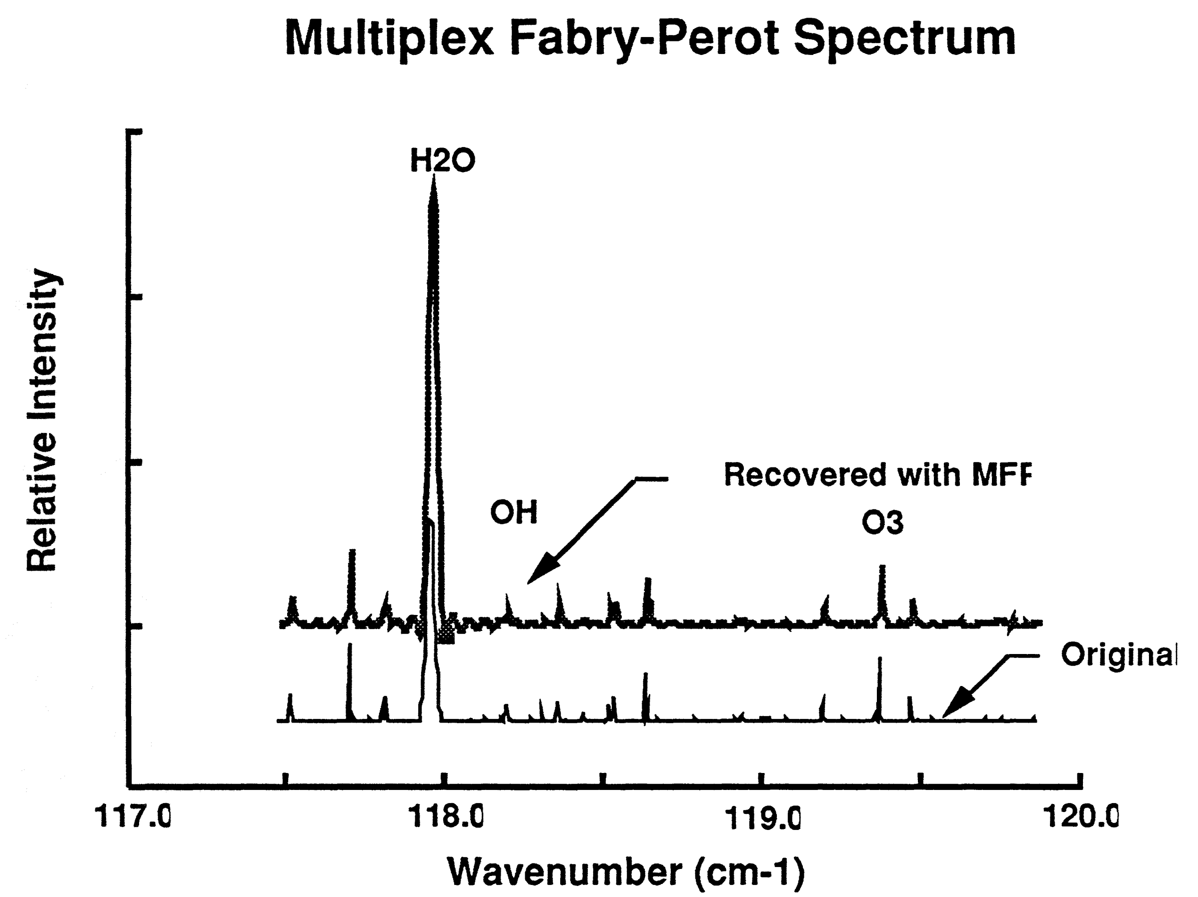


Figure 6

The amplitudes of the retrieved lines are proportional to the area under the spectral feature as illustrated by the water vapor signal. The reconstruction of this spectrum simulated with our radiative transfer model is quite good.

5. Summary

This short paper has illustrated the use of a Fabry-Perot interferometer to observe a modest spectral interval in the terahertz region of the spectrum. We have illustrated that this instrument has the capabilities of a Michaelson interferometer with a much larger mirror motion than is required for the Multiplex Fabry-Perot. We are currently in the preliminary stages of designing an actual instrument for balloon flight and we expect that this new instrumental technique will prove to be very important for both earth and planetary observations.

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