Far-infrared spectroscopy of the troposphere (FIRST): sensor calibration performance

G. Bingham[a,*], H. Latvakoski[a], S. Wellard[a], D. Garlick[a], M. Mlynczak[b], D. Johnson[b], W. Traub[c], K. Jucks[c]

[a]Space Dynamics Laboratory, Utah State University, Logan, UT 84341-1947
[b]NASA, Langley Research Center, Hampton, VA 23681
[c]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

Abstract – The radiative balance of the troposphere, and hence global climate, is dominated by the infrared absorption and emission of water vapor, particularly at far-infrared (far-IR) wavelengths from 15-50 μm. Current and planned satellites observe the infrared region to about 15.4 μm, leaving spectral measurement of the far-IR region unsupported. The far-infrared spectroscopy of the troposphere (FIRST) project will provide a balloon-based demonstration of the key technologies required for a space-based far-IR spectral sensor. We discuss the FIRST Fourier transform spectrometer system (0.6 cm^{-1} unapodized resolution), along with its radiometric calibration in the spectral range from 10 to 100 μm.

Keywords: interferometer, far-infrared, calibration, water vapor, global energy balance

1. INTRODUCTION

The Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument is a Fourier Transform Spectrometer presently under development by NASA through the Instrument Incubator Program (IIP). FIRST is designed to measure the infrared spectrum in the nadir view between 10 and 100 micrometers (1000 to 100 wavenumbers) at 0.6 wavenumber unapodized spectral resolution from a high altitude (35 km) balloon platform. The instrument has completed thermal vacuum testing and radiometric calibration and is waiting its inaugural flight. The FIRST instrument has been prepared for flight on a high altitude balloon from Fort Sumner, New Mexico, to complete its technology demonstration and validation. The thermal vacuum test data are being analyzed to develop an understanding of this new instrument. FIRST is designed to demonstrate two high priority climate measurements, calibrated radiances and the calculation of profiles of upper tropospheric and lower stratospheric water vapor using the far-IR.

1.1. Significance

The scientific case for directly measuring the far-infrared emission is reviewed by Mlynczak et al. (2002) and references therein. We define the far-IR to encompass wavelengths between 15 and 100 μm because this portion of the Earth's emission spectrum is not directly observed from space despite its fundamental importance. Approximately one-half of the energy leaving the Earth is contained in this spectral region. One-half to three-quarters of the energy leaving the atmosphere is in the far-infrared. Figure 1 is a computation (Collins and Mlynczak, 2001) of the ratio of the far-infrared flux at the top of the atmosphere to the total infrared flux at the top of the atmosphere using the NCAR Community Atmosphere Model (CAM). The CAM clearly illustrates that over half of the energy leaving the planet is in the far-IR.

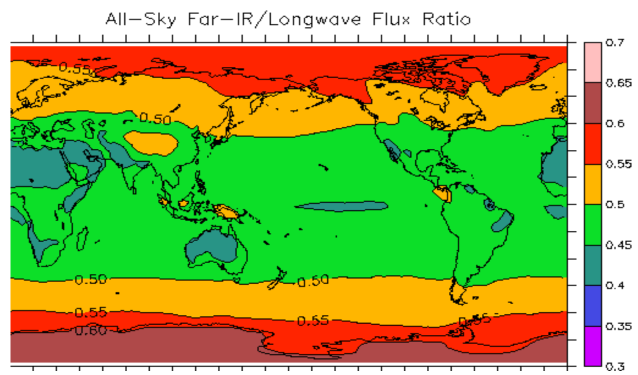

Figure 1. Ratio of the top-of-atmosphere far-infrared flux to the total infrared flux as computed by the NCAR Community Atmosphere Model.

The far-IR is important for more reasons than total energy loss from the planet. Earth's climate is influenced strongly by radiative cooling associated with the emission of infrared radiation by water vapor at far-IR wavelengths extending out beyond 60 μm. The free troposphere cools radiatively almost exclusively in the far-IR. Water vapor is also the principal greenhouse gas, absorbing a significant fraction of the upwelling radiation from the Earth's surface and providing much of the downwelling longwave flux that warms the Earth's surface (i.e., the greenhouse effect). The distribution of water vapor and associated far-IR radiative forcings and feedbacks are well recognized as major uncertainties in predicting future climate.

We note that the outgoing far-infrared radiation is modulated by cirrus clouds. The distribution of cirrus cloud systems, especially in the tropical upper atmosphere, implies that cirrus clouds play an important role in climate (Liou, 1986). Effects of cirrus in attenuating the far-IR to 25 μm have been shown by the Russian *Meteor* spacecraft (Spankuch and Dohler, 1985). Spectral measurements of the far-IR may also offer the potential for increased accuracy in water vapor profiles retrieved from emission measurements (Mertens, 2002). Far-infrared measurements also offer the potential for determining the optical properties of cirrus particles (Yang et al., 2003). Measurements of the far-IR will provide basic information on the Earth's atmosphere and climate system and contribute significantly

[*] Tel: (435) 797-4600; Fax: (435) 797-4366; email: gail.bingham@sdl.usu.edu

to understanding how the Earth is responding to various natural and anthropogenic forcings.

2. THE FIRST INSTRUMENT: DESCRIPTION AND TECHNOLOGY

The FIRST sensor system mechanical model and optical path are shown in Figure 2. FIRST is an Imaging Fourier Transform Spectrometer (IFTS) design, but the focal plane array is under-populated at present. FIRST is designed to demonstrate the capability of the IFTS to support the 10 x 10 array of 10 km IFOVs that would be required to provide daily global coverage from a cross track scanning LEO satellite. In its IIP configuration, only ten of the potential 100 detector elements are populated, with dual detector elements located at each FPA corner and at the FPA center. The detector FPA assembly is LHe cooled to 4 K. Radiometric calibration of the ten simultaneously collected, 0.6 cm-1 unapodized resolution, earth view spectra over the full 10 to 100 μm spectral range is provided by sequentially scanning a warm (~ 300 K) deep cavity black body and deep space. This calibration system uses the same approach as the HIS, AERI, MAERI, S-HIS, NAST and CrIS instruments. FIRST meets the NEΔT performance goal of 0.2 K from 10 to 60 μm and 0.5 K from 60 – 100 μm (Revercomb et al., 2004; Revercomb et al., 2003).

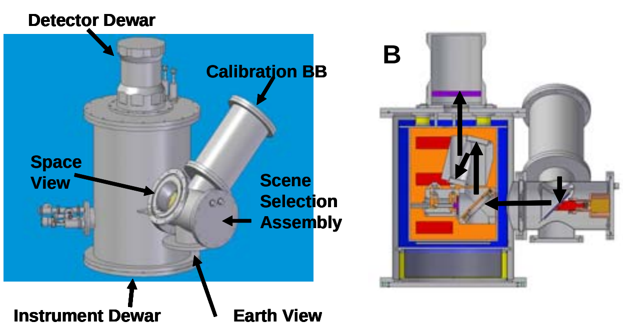

Figure 2. (A) The FIRST sensor model showing the major components and the selectable measurement and calibration views. (B) The optical path through the sensor, with the scene selection mirror looking into the warm, deep cavity, far IR blackbody.

3. FIRST CALIBRATION

A critical component of the FIRST effort was to demonstrate accurate, verifiable atmospheric measurements from our validation balloon flight. Calibration characteristics were designed into the FIRST system from the beginning, and the detailed calibration efforts developed for GIFTS and CrIS have been considered in developing the calibration plan. Calibrating FIRST requires addressing basic issues of absolute radiometric response, frequency scale, instrument line shape, phase alignment and self-apodization. Techniques for quantifying and modeling these effects are being applied to FIRST (Bingham et al., 1997; Zhou et al., 1998; Best et al., 2004; Elwell et al., 2003; Knuteson, 2004). For earth scene calibration, FIRST utilizes the same calibration scheme adopted by the NPOESS Cross Track Infrared Sounder (CrIS) sensor. During measurement operations, the scene selection mirror is rotated to view space (cold BB) and a warm blackbody at regular intervals. Spectra from each source are averaged and applied to the Earth spectra during the absolute calibration process. Using this technique, UW has recently shown calibration agreement between the aircraft mounted S-HIS and the AQUA AIRS sounder of about 0.1 K (Revercomb et al., 2004, Revercomb et al., 2003).

3.1. Calibration Approach

The FIRST calibration measured system dark currents, trends and SNR, transient behavior tests, absolute responsivity, linearity correction, and point response measurements for wavelength scale verification and instrument line shape. The FTS system used in FIRST has a well-understood instrument line shape (ILS), depending mainly on the wavelength of the laser used for sampling and the geometry of the focal plane relative to the interferometer axis. System linearity correction is critical for sounder spectral measurements. This was measured using a small signal response vs. signal level data set collected with SDL's Multifunction Infrared Calibrator version 2 (MIC 2) (Tansock et al., 1994; Blakely, 1996).

A focal plane array (detector position) map was also developed using an external source and the collimator. This Point Response Measurement was established by moving the point source in a grid pattern around the array at one cone diameter spacing. We paused and collected spectra at each point, which gives pixel pointing and location data and a rough PRF. A more accurate PRF was then collected, covering 2 cone diameters of each pixel with a grid at ¼ cone spacing. The system PRF is used to derive the MTF of the detector, the effective solid angle, and the scatter associated with each populated detector location.

3.2. Calibration Sources

The equipment used for the FIRST calibration included a cold source (for backgrounds), a variable temperature blackbody, a gas cell, a collimated source, and equipment to measure non-linearity and instrument line shape. SDL has invested significantly in the FIRST calibration equipment to expand its capability to the Far-IR. As the 25-100 μm region is not normally observed by operational, experimental or defense systems, certified spectral calibration sources for this region are not available. SDL developed a set of new, full aperture blackbody sources to provide accurate calibration across this entire band (Bingham et al., 2004). These include a LHe cooled low background source to provide system noise and scattering measurements, a warm (300 K) blackbody to establish the upper range calibration in both flight and ground calibration, and a variable temperature source (80 – 300 K) to provide a full range, absolutely known calibration standard. All three sources are deep cavity, multiple bounce designs (using Z302 paint) that differ most significantly in their thermal control properties. The sources have estimated maximum temperature uncertainties of 70 mK.

The SDL MIC 2 chamber was also used in the FIRST calibration effort. MIC 2 provides a 200 in focal length collimated source, a Jones source, a scatter source, and an extended blackbody source (< 25μm). MIC 2 was cooled with LN_2 cooled for low backgrounds, and is a well characterized system having been used extensively for NASA and DOD space sensor calibrations. It includes an apertured input window that allows high temperature sources (300-1200 K) to be used during the calibration.

3.3. System Performance

Because FIRST is a new instrument, there are many of the fine details of the system performance that are still under investigation, and the data shown here should be considered preliminary. The FIRST instrument, with its flight and absolute calibration sources attached to the scene section assembly, is shown in Figure 3 The instrument is shown in the absolute calibration mode, using the three source arrangement. An example FIRST interferogram of a warm blackbody from detector 1 is shown in Figure 4. The scan is sampled every laser fringe so the full interferogram is 24960 points, but the signal is low outside this range. The high and low gain channels have been combined (though near the center the interferogram is always the low gain channel times ~100), and the signal has been linearized. The rms noise on the high gain channel is 24 mV due to detector Johnson noise, while the noise on the low gain channel is 6.5 mV and is due to electronic pick-up. Interferograms in reverse directions and from all detectors are similar.

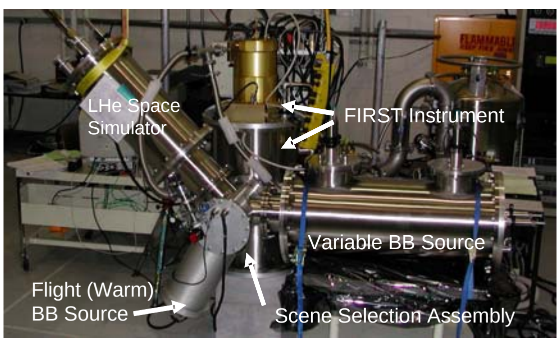

Figure 3. A photograph of the FIRST instrument configured for absolute calibration, with the Warm (flight), space simulation (LHe) and variable temperature (80-300K) blackbody sources attached.

Figure 4. The central portion of an interferogram of a warm blackbody source with both the high and low gain channels combined.

Figure 5 shows the calculated responsivities for detector one from 9 spectra collected over a two-day period. The responsivities are found from background subtracted warm blackbody (WBB) spectra, phase corrected, which have been divided by a Planck function at the temperature of the WBB. The plots show the real and imaginary components on the same scale, and the imaginary component is clearly insignificant. The responses are not identical as the structure amplitude and position change slightly over time, as well as fine shifts in the overall shape of the curve. The structure in the responsivity function is due to transmission features in the beamsplitter. System response up to 2000 cm^{-1} is available, but the responsivity is dominated by large absorption features in the beamsplitter and therefore has not been shown.

Figure 6 (A) shows spectra from detector 1 in the forward direction of the warm blackbody taken about an hour and a half apart. These spectra are a combination of ~20 individual scans. The plots show magnitude and phase. The wavenumber resolution is 0.643 wavenumbers. The phases are different because of slow shifts in the relative spacing of the laser and IR interferometers. As this type of change in phase is linear with wavenumber, it is easy to align the phases. The magnitudes vary by up to 0.004 of the units shown here over a day, and more from day to day, while the shape of the phase curves do not change significantly over time. Backgrounds (SVS scans) show a similar variation in magnitude, and more variation in the shape of the phase curves. The spectra extend to 7901 wavenumbers, but there are no useful data above the range shown here. The wiggles in the spectra with a period of ~100 wavenumbers are due to the polypropylene windows.

Figure 6 (B) shows spectra of the warm blackbody and the space view simulator. As in (A), these are combinations of 20 scans from detector 1 in the forward direction. The phases do not match because out of phase light is present (which may be due to beamsplitter emission). Because of the above-mentioned variation on interferometer optical paths, these phases must be aligned to the correct relative position before spectra can be background subtracted. Since these curves will never overlap, the proper match is not obvious. For the WBB spectra, the phase alignment is found (to within ~0.5°) by comparing spectra of the WBB and Space View Source (SVS) taken immediately after each other. (The data shown here have been aligned.) The phases for scans of the variable temperature Long Wave IR Calibration Source (LWIRCS) at various temperatures are aligned by making these cross where the phases of the WBB and SVS scans cross.

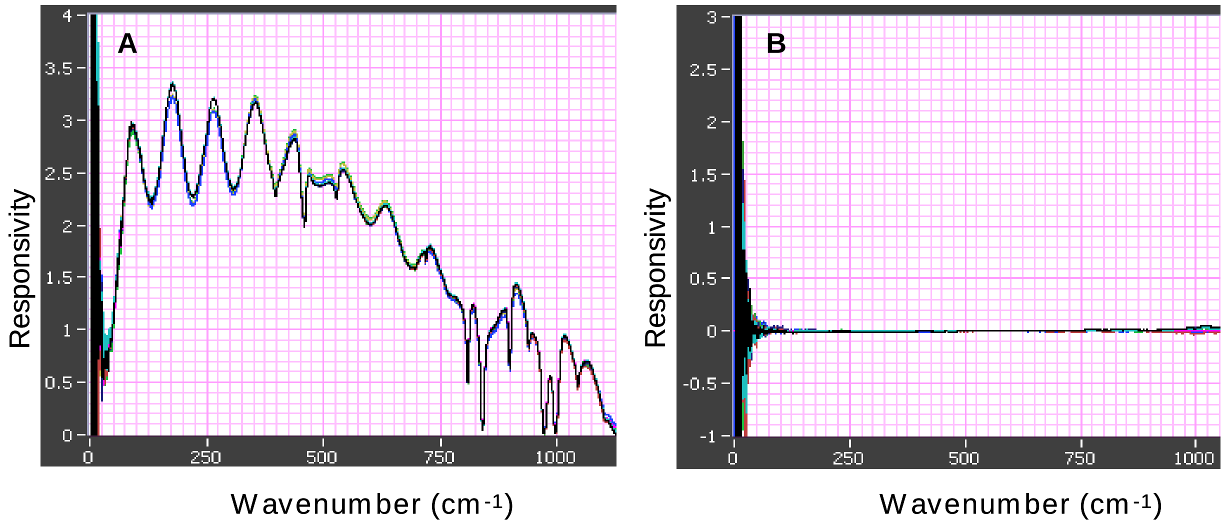

Figure 5 (A). System stability, shown by the real responsivity of detector 1 looking at a warm blackbody calculated for 9 spectra collected over a 2-day period. (B) The imaginary responsivity of the same spectra.

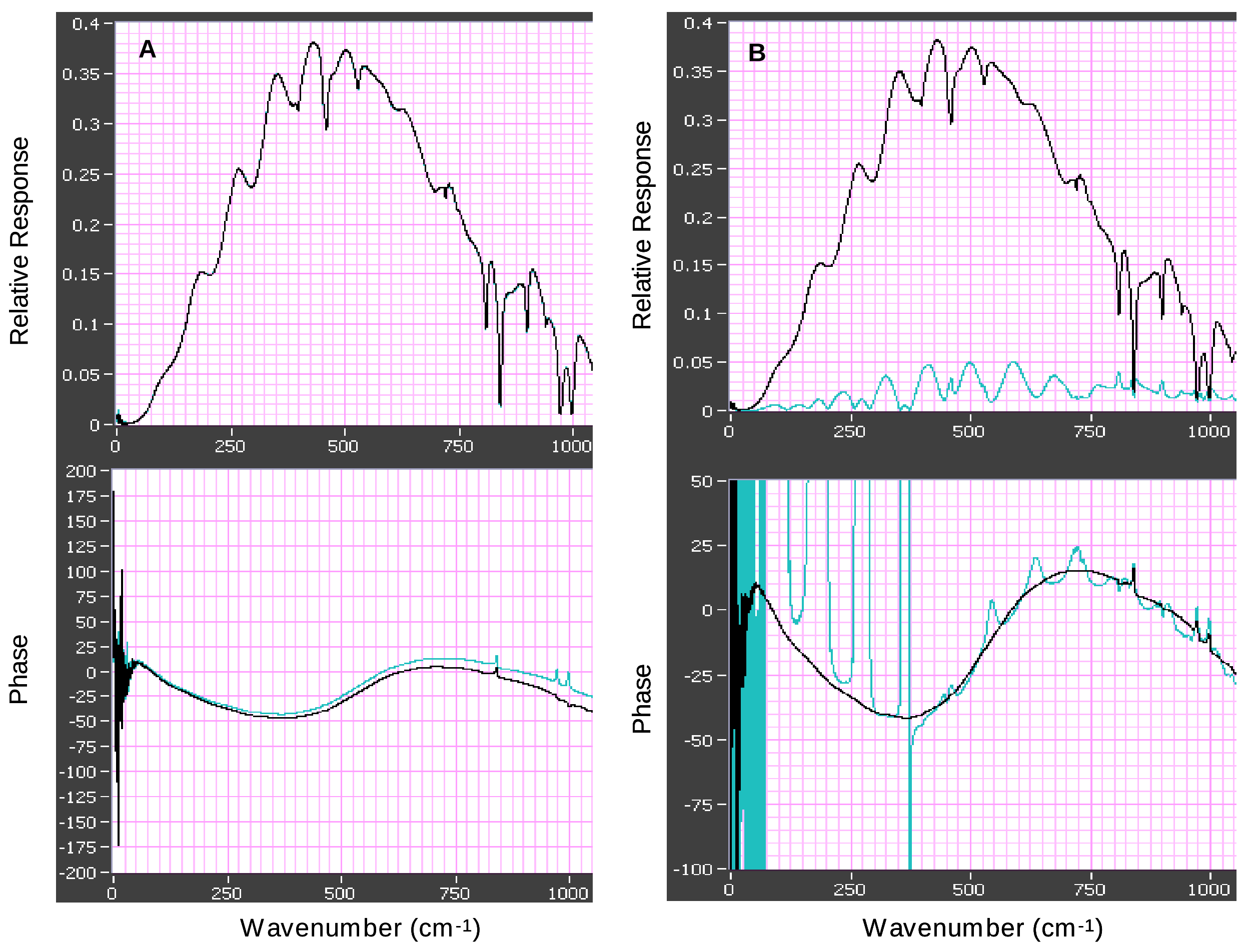

Figure 6. (A) Relative response and phase of 20 scans of two spectra of the warm BB collected 1.5 hours apart. (B) The relative response and phase from the warm and space simulation BBs showing the phase differences.

Figure 7 (A) shows the radiance from LWIRCS at a variety of temperatures as measured by FIRST. These spectra are background subtracted, phase corrected and divided by the responsivity curve. The data used here are from detector 1 collected in the forward direction. The structure in the curves (noise spikes) result from errors in the responsivity curves due to small values where the beamsplitter transmission is low. Figure 7 (B) shows the resulting Brightness temperatures of LWIRCS as measured by FIRST. They are calculated by using the inverse Planck function on the radiance curves.

Figure 7 shows that FIRST is meeting its significant performance specifications. The temperature error is dominated by broad systematic variations. The high frequency variations (the barely visible fuzz) are at a level of 0.1 K peak to peak between 250 and 950 wavenumbers. This corresponds to an rms error of 0.1 K in an individual scan, thus meeting the sensitivity requirements. Because the broad systematic variations are the same in both forward and reverse data, they are not due to any random source such as vibrations or the excess noise in the low gain channel. All detectors measure a slightly too low brightness temperatures, and these data show structure similar to those in the responsivity. This suggests changes in the window temperature and/or shape and transmission may be the dominant error. The variation base of window transmission has not been corrected at this stage of the analysis.

4. CONCLUSION

FIRST, a Fourier Transform Spectrometer presently under development by NASA and SDL under the NASA Instrument Incubator Program, is a demonstration instrument for a future, far IR space based sensor. FIRST is designed to measure the infrared spectrum in the nadir view between 10 and 100 micrometers (1000 to 100 wavenumbers) at 0.6 wavenumber unapodized spectral resolution from a high altitude (35 km) balloon platform. The instrument has been subjected to an intensive thermal vacuum and calibration exercise and is presently waiting its turn to be flown on a high altitude balloon from Fort Sumner, New Mexico. This will complete its technology demonstration and validation under the IIP program. Initial analysis of calibration data, taken with the new, SDL developed Far-IR calibration sources, indicates that FIRST will achieve its 0.2 K sensitivity goal, but bias in the calibration, possibly due to window temperature changes, is still being investigated.

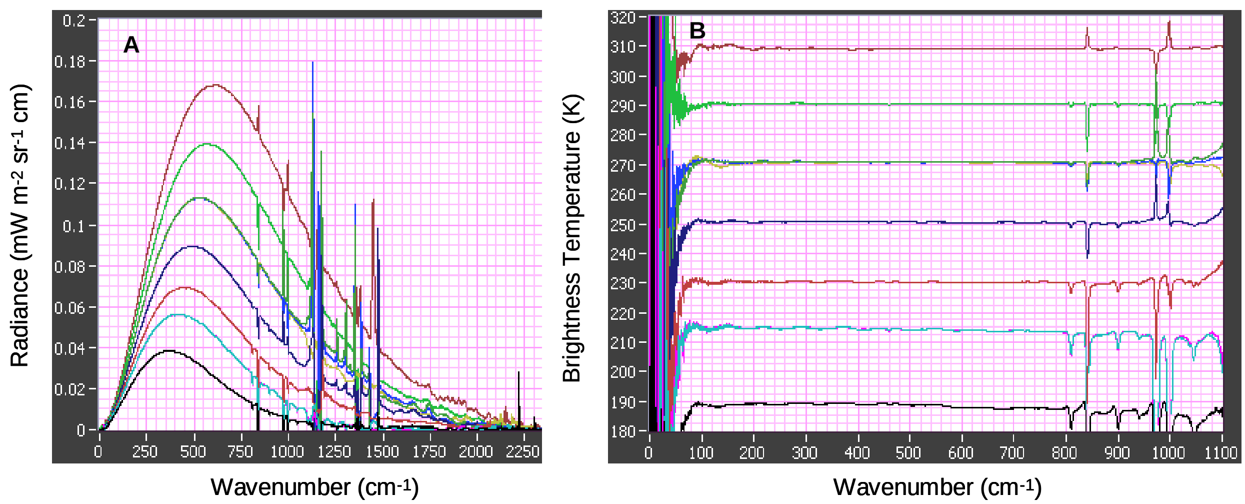

Figure 7. (A) Calibrated Radiance response with the LWIRCS at various temperatures. Structure is the results from error due to small values in the responsivity curves where the beamsplitter transmission is low. (B) The spectral temperature response curves resulting from dividing te curves in (A) by their inverse Plank functions.

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