INFLAME: In-situ Net FLux within the AtMsophere of the Earth

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Abstract. We are developing a set of Michelson interferometers to measure directly the net fluxes of visible and infrared radiation within the Earth's atmosphere. The In-situ Net Flux within the Atmosphere of the Earth (INFLAME) project is focused on developing and demonstrating the technology necessary to provide accurate measurements of the rates of radiative heating and cooling within the atmosphere. This will be accomplished by deploying the INFLAME interferometers on an aircraft and measuring the net fluxes of radiation at several altitudes within the atmosphere. The derivative of the net flux with respect to altitude yields the divergence of the net flux, which is directly proportional to the rate at which radiation is heating or cooling the atmosphere. Accurate direct measurements of the net flux remain one of the outstanding challenges in the field of atmospheric radiation. In our presentation we will review the science that drives the need for net flux measurements as well as the design of the INFLAME instrument, and the current project status. INFLAME is now in year two of a planned three-year development effort and is supported by the Instrument Incubator Program of the Earth-Sun System Technology Office (ESTO).

I. INTRODUCTION

The fundamental equations solved in every atmospheric model include the momentum and continuity equations and the thermodynamic energy equation or equivalently, the first law of thermodynamics. The main terms in the first law which must be determined are the rates of atmospheric heating and cooling due to absorption of solar radiation and emission of infrared radiation. The radiative heating rate *dT/dt* is determined from the expression

$$\frac{dT}{dt} = \frac{-1}{\rho\, c_p}\frac{dF_{net}}{dz} \qquad (1)$$

where ρ is atmospheric density, c_p is the heat capacity at constant pressure, and F_{net} is the net radiative flux at altitude z. The net flux is simply the difference between the energy flowing upward and downward through an aperture of unit area, or $F_{net} = F^{\uparrow} - F^{\downarrow}$. The change in net flux with altitude is the net flux divergence, dF_{net}/dz, and is proportional to the rate dT/dt at which radiation heats or cools the atmosphere. The net fluxes are usually separately determined for the visible (solar) and the infrared (thermal) parts of the spectrum.

Determining the net radiative flux, the flux divergence, and heating rates remains a fundamental goal of many NASA projects. For example, the Clouds and the Earth's Radiant Energy System (CERES) project presently operating on the EOS Terra and Aqua satellites produces net flux and flux divergence data products for several broad atmospheric layers. These are not, however, direct measurements. NASA field experiments have had measurement goals including the determination of net radiative fluxes and heating rates within cirrus clouds.

The measurement of vertical profiles of atmospheric radiative heating was also identified as a Critical Observation in the NASA Suborbital Missions of the Future Workshop held in July, 2004. The workshop report called for the measurement of "vertical profiles of shortwave heating rates in polluted and unpolluted clear and cloudy skies", and that the measurements occur "in regions impacted by major pollution sources such as megacities and industrial regions in different climatological regimes." The workshop reported that net flux measurements would improve the evaluation of climate sensitivity to forcing of aerosols and would also impact weather forecasts and the understanding of the role of heating rates on cloud and precipitation processes. In addition, the workshop reported that measurements of the vertical profile of heating would also impact understanding of the carbon cycle through better understanding of absorbing aerosols and could provide capability for detecting bioaerosol sources and dispersion.

The understanding of the role of aerosols and clouds in climate forcing remains a key issue, as pointed out in the recent IPCC 2007 report. Recent studies have emphasized the importance of flux changes due to tropospheric aerosols which can alter the heating rate (i.e., net flux divergence) profile, particularly near the boundary layer, with possible effects on convection and cloud formation.

To address the outstanding issues of the measurement of net radiative flux we are developing the In-situ Net FLux within the AtMosphere of the Earth (INFLAME) instrument to directly measure the net radiative flux within the atmosphere from an aircraft platform. The project is part of the Instrument Incubator Program of the NASA Earth Sun System Technology Office.

II. COMPARATIVE TECHNOLOGY ASSESSMENT

The past 45 years have seen remarkable progress in the measurement of the visible and infrared radiation fields that control the Earth's energy balance and that are used to remotely sense atmospheric temperature and composition. Sensors in orbit now accurately measure the spectrally integrated top of atmosphere radiance in broad visible and infrared bands for climate observation and in spectrally resolved bands in the visible and infrared for atmospheric temperature, chemical composition, and aerosol determination. Networks of ground based sensors also observe the atmosphere with similar instruments and techniques. The measurement of atmospheric radiation from the vantage of space- and ground-based sensors has dramatically improved in terms of radiometric accuracy and in terms of spatial, temporal, and spectral resolution over time. However, a fundamental measurement of atmospheric radiation, the measurement of radiation fields within the atmosphere, and particularly the direct measurement of the net radiative flux within the atmosphere, has not seen a similar progression. The divergence of the net radiative flux is a fundamental parameter in every model of the atmosphere from weather forecast models to climate forecasts to general circulation models as it determines the rate at which radiation heats or cools the atmosphere.

At present, to our knowledge, there are no extant operational instruments capable of *directly* measuring the net radiative flux within the atmosphere in either the visible or infrared portions of the spectrum. The typical approach to determining the net flux is to have an instrument (or instruments) measure the upwelling and downwelling fluxes separately. In subsequent data processing, the net flux is computed by differencing the measured up and down fluxes. This conventional approach requires that the instrument(s) be absolutely calibrated to a high degree of accuracy, to typically better than 1% absolute over the entire visible and infrared spectral ranges. Otherwise, when the large values of the measured fluxes are differenced, the uncertainty in the calculated net flux may be on the order of the net flux itself. This is a well-known challenge in determining net fluxes, flux divergences, and heating rates with extant sensors and approaches.

INFLAME provides a *direct* measurement of the net flux, and requires high stability with much less stringent requirements on absolute accuracy, thereby removing the major impediment of existing measurements. The INFLAME instruments, deployed on small aircraft, will provide a direct measurement of the net flux radiative, flux divergences, and heating rates in clear sky, in the presence of aerosols, and in the presence of cloud particles.

Despite their fundamental importance, net fluxes and flux divergences within the atmosphere have infrequently been determined, as such measurements are difficult to obtain. Besides requiring a sensor capable of endoatmospheric operation, direct determination of the net flux by measurement is often problematic due to the calibration challenges described above. In addition, most instruments measure the radiance (energy per unit time per unit area per unit solid angle), and the fluxes (energy per unit time per unit area) must be derived using a radiance-to-flux conversion, an inexact process except in the most simple of cases. As detailed below, the proposed INFLAME instrument will directly measure the net flux, thereby significantly reducing the major obstacles to accurate net flux measurements.

The approach to determining the flux divergence in atmospheric modeling is to compute it based on the temperature and composition of the atmosphere via solution of the equation of radiative transfer. These computations depend on accurate knowledge of the atmospheric thermal structure, the chemical composition of the atmosphere, the optical properties of clouds and aerosols, and the spectroscopic properties of the radiatively active gases in the atmosphere. The calculations must also be done at sufficiently fine vertical and horizontal resolution in order to capture accurately variations in these many parameters that affect the value of the net fluxes, flux divergences, and corresponding heating rates. Such calculations have rarely been validated by direct measurement despite their fundamental importance. It is the purpose of the INFLAME project to provide measurements to validate these calculations.

III. The INFLAME Concept

Our goal is to measure the shortwave and longwave net flux with sufficient stability to derive tropospheric heating rates in 1 km layers that are accurate to within 10%. We estimate that this requires measuring the net flux with a stability of 0.2% per km and 0.8% per km in the shortwave and longwave spectral regions, respectively, based on radiative transfer calculations. It is important to note that while measuring the net flux divergence requires that the instrument response be very stable, it does not require a similar level of absolute accuracy in measuring the net flux. If the calibration errors are stable and independent of altitude then the relative uncertainty in the net flux divergence will be no greater than the relative uncertainty in the net flux measurement.

The INFLAME instrument measures the net flux by using a low-resolution Fourier transform spectrometer (FTS) to observe the upward and downward flux simultaneously using the two inputs of the same instrument. The two complementary outputs of the FTS can be transformed to produce spectra proportional to the difference between the two inputs. Shown below in Figure 1 is the notional instrument concept.

To illustrate both the nature of the measurement and some of the systematic errors that must be considered, consider an experiment that attempts to measure the net flux by measuring the temperature difference between two horizontal plates separated by insulation (e.g., the original flat plate "poor man's" radiometers developed by V. Suomi at the University of Wisconsin). The top surface of the top plate and the bottom surface of the bottom plate have high-emissivity coatings to make them good absorbers, so that in principal the temperature difference between the top and bottom plates provides a measurement of the net flux. The first problem that arises when trying to derive the net flux from the temperature difference is that the emissivity of most coatings depends on the angle of incidence, so that more radiation from the zenith (or nadir) is absorbed while more radiation from near the horizon is reflected. The second problem is that the temperature change for both surfaces needs to be corrected for the effect of convective heat loss, and the correction depends on the orientation of the surface and differs for the top and bottom surfaces. Convective heat loss can be reduced by using a window, but then corrections need to be derived for reflection and absorption in the window. In either case the errors in the corrections do not cancel when calculating the temperature difference

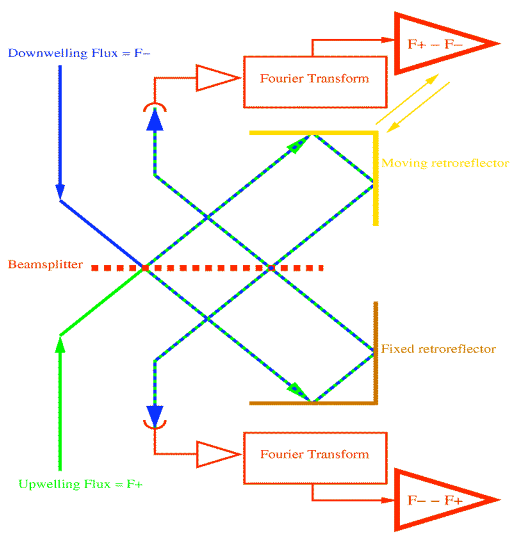

Figure 1. INFLAME measurement concept. Upwelling and downwelling fluxes are directed into the two FTS inputs. The Fourier transform of the two outputs yields the net flux.

We will address the first problem (variable emissivity with angle) by using Winston cone concentrators to partially collimate the flux passing through upward and downward facing entrance apertures, thus minimizing errors caused by the instrument response depending on the angle from the zenith (or nadir.) We address the second problem (temperature variability and convective heating) by using a pair of low-resolution FTS (one for the shortwave and one for the longwave flux) to measure the net flux directly. This has the advantage of converting most of the instrument background into a common-mode signal that is cancelled in the instrument, as well as moving all the optics with the exception of the entrance apertures into the body of the instrument where they can be controlled thermally.

To achieve high stability we start with the following design assumptions: make the primary measurement a differential rather than absolute measurement; make most instrument offsets into common-mode signals that cancel in the FTS; reduce or eliminate thermal gradients in the instrument; and maintain high resonant frequencies for the mechanical structure.

IV. THE INFLAME DESIGN

As discussed above, measuring net flux divergence is exceedingly difficult due to the need to measure small changes in large signals over a wide range of wavelengths covering a hemispherical field-of-view. The individual upwelling and downwelling radiation fluxes are typically two orders of magnitude larger than the net flux divergence, and significant solar and thermal radiation is present within the atmosphere at wavelengths from 100 µm to less than 0.3 µm. In addition, the net flux can vary rapidly in time and space due to clouds, varying surface albedo, and other factors that cannot be controlled during the measurement. A classic approach to a measurement of this type would be to use a radiometer that chops rapidly between uplooking and downlooking views, so that the amplitude of the modulated output is proportional to the difference between downwelling and upwelling radiation, providing a direct measurement of the net flux. We have refined this concept, using a modest resolution Fourier transform spectrometer (FTS) as an optical chopper instead of mechanically alternating the field of view. Independent spectrometers separately cover the solar and thermal fluxes, and by using a Winston cone as the input optic we are able to collect radiation over a full hemisphere and avoid having to convert radiance to flux. The interferometer scan distance is small enough, between 75 and 300 µm, that we can use a commercial piezoelectric drive with capacitive position sensor so that no metrology laser is required.

The INFLAME optical design (Figure 2) is all reflective to provide nearly diffraction-limited performance over the widest possible wavelength range. The only transmissive elements are the vacuum windows and FTS beamsplitters. The windows and beamsplitter substrates are made from the same material, and the detectors and beamsplitter materials are selected to optimize individually the performance of the solar (shortwave, or SW) and thermal (longwave, or LW) instruments. We use a single Offner relay system to image both the uplooking and downlooking Winston cone exit apertures at the FTS retroreflectors, and then two identical

Offner relays are used to form a second image of the input cones at identical Winston cones used to concentrate the radiation onto the detectors. The main Offner secondary mirror also forms a field stop, and because the same field stop is common to both FTS inputs the radiation from the field stop cancels in the instrument.

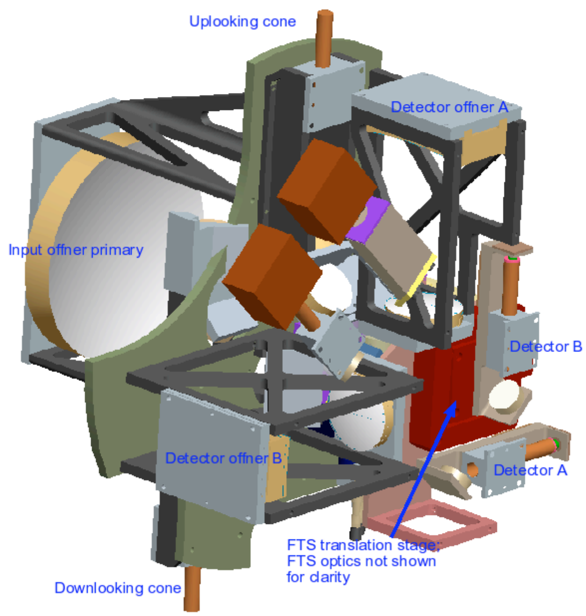

Figure 2. The INFLAME optical design.

Each instrument includes two identical calibration sources that can be swapped for either or both of the input cones. The sources consist of Winston cones identical to the input cones that are coupled either to a thermally-controlled cavity for the LW instrument or to a tungsten lamp and ellipsoidal reflector for the SW instrument. The instruments can be run in any one of three modes: by viewing both calibration sources the instrument gain and offset can be measured; by viewing one calibration source and one input the upwelling or downwelling flux can be measured; and by viewing both inputs the net flux can be measured.

The SW and LW instruments are mounted in individual vacuum housings to improve mechanical and thermal stability. Optical bench temperature is controlled using a two-zone system, with heaters directly on the optical bench to bring the instrument quickly up to operating temperature and subsequently disabled, and a second set of heaters on a thermal shroud used to maintain the operating temperature. Individual thermoelectric coolers are used to control detector temperatures for maximum instrument stability. Vacuum housings and optical paths are sized to fit in luggage compartments in Learjet wing-tip fuel tanks that provide nearly unobstructed uplooking and downlooking fields of view.

We have adopted a PC-104 form factor for the data acquisition and control electronics. A commercial CPU board will be used, and we have designed and fabricated custom boards for the science and engineering data acquisition, thermal, and power control systems.

V. Deployment Of INFLAME

In order to make the net flux measurements the INFLAME instruments must be deployed on a platform within the atmosphere. As indicated in Equation 1, determination of the heating rate requires measurements of net fluxes at different altitudes. The derivative of the vertical profile of net flux yields the rate at which the atmosphere is being heated or cooled by radiation.

We are designing INFLAME to be deployed in the wing-tip luggage compartments of a Lear Jet model 35 aircraft. The two INFLAME instruments (one longwave FTS, one shortwave FTS) will be situated separately, one in each wing tip compartment. This facilitates the design and minimizes issues related to aircraft stability that we encountered when considering placing both instruments in one wing tip pod.

The advantage of a Lear Jet platform for the INFLAME measurements are many: the aircraft type is readily available, meaning INFLAME can be flown almost anywhere at any time; the luggage compartments in which the instruments will be installed are already FAA certified; the cost per flight hour is relatively low; and the aircraft has a ceiling of approximately 45,000 feet (14 km) which is the entire depth of the troposphere over most of the Earth excepting the Tropics. Thus we expect that INFLAME will be able to participate in numerous field campaigns in the future.

VI. Summary

The INFLAME instrument is now under development at NASA Langley as part of the Instrument Incubator Program. INFLAME will measure the net flux as a function of altitude while deployed on a conventional aircraft. The derivative with respect to altitude of this profile of net flux will yield the rate of heating or cooling due to radiation in the atmosphere. The design of INFLAME to produce a differential measurement will alleviate many challenges posed to a direct measurement of the net flux. The INFLAME project is a 3 year program and the flight demonstration on a Lear Jet 35 will occur in the summer of 2008.

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