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Calibration lamp design, characterization, and implementation for the Michelson Interferometer for Global High-Resolution Thermospheric Imaging instrument on the Ionospheric Connection satellite

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Abstract

We describe the design and ground-based performance of the two-color calibration lamp for the Michelson Interferometer for Global High-Resolution Thermospheric Imaging (MIGHTI) instrument on the NASA Ionospheric Connection (ICON) satellite. The calibration lamp assembly contains radio frequency excited krypton and neon lamps, which generate emission lines at 557 and 630 nm, respectively, and which are used to monitor thermal drifts in the two MIGHTI Doppler asymmetric spatial heterodyne interferometers. The lamps are coupled to two mixed optical fiber bundles that deliver the calibration signals to the two MIGHTI optical units. The assembly starts reliably, consumes <8 W, and has passed environmental testing for the ICON satellite. The total mass of the lamp assembly is 1.8 kg. Special features of the assembly and its implementation are described along with results of life tests.

Keywords

optics; photonics; light; atomic emission line sources

1 Introduction

The Michelson Interferometer for Global High-Resolution Thermospheric Imaging (MIGHTI) instrument¹ is one of the four scientific instruments on the NASA Ionospheric Connection (ICON) satellite.² ICON is an Explorer class satellite dedicated to studying the Earth's ionosphere/thermosphere region using remote sensing techniques in the visible,

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UV, and IR wavelengths, as well as making *in situ* ion velocity measurements. The ICON mission will explore the connection between lower atmospheric processes and conditions high in the atmosphere.

The MIGHTI instrument will image the Earth's limb to obtain altitude resolved neutral wind profiles in the range of 90 to 300 km. These profiles are obtained by determining the Doppler shift of visible emission lines from thermospheric atomic oxygen. The instrument consists of two sensors that will sequentially observe the same volume of atmosphere in order to obtain two orthogonal line-of-sight measurements of the wind velocity. It employs the Doppler asymmetric spatial heterodyne (DASH) interferometry technique,³ whereby interference fringes within an optical path difference (OPD) interval are measured simultaneously for all tangent altitudes. The resulting fringe patterns (interferograms) from the atmospheric atomic oxygen emissions are recorded on a two-dimensional imaging sensor. One dimension of the sensor images altitudes on the Earth's limb, whereas the other records the fringe pattern, the phase of which carries information about the Doppler shift and thus the atmospheric wind. Figure 1 shows the locations of the MIGHTI sensors on the satellite payload deck, along with the relative placement of the control electronics and the calibration lamp assembly.

The MIGHTI sensors will acquire interferograms of the atmospheric emission every 30 s (day) or 60 s (night), and from the combination of several images from both sensors, determine a wind velocity profile versus altitude. MIGHTI will also determine the temperature profile between 90 and 135 km by measuring the brightness of the molecular oxygen A-band infrared (IR) emission at several wavelengths. The temperature measurement does not require the calibration lamps; further information on it can be found in Stevens et al.⁴

The phases of the fringes produced by the MIGHTI interferometers are sensitive to thermal changes that, if not properly accounted for, can be incorrectly interpreted as atmospheric wind. For this reason, two precautions were taken to compensate for these thermal changes, which are expected to occur both seasonally and within a single orbit. First, the interferometers are housed in an enclosure that is stabilized to a temperature interval of $< \pm 0.1^{\circ}\text{C}$. This minimizes thermal expansion and contraction of the gratings (rule spacing) or changes to the index of refraction of the field widening prisms, both of which would change the observed spatial fringe frequency and phase. Second, an onboard calibration light source is used as a frequency standard. Diffused light from the calibration source is superimposed on the atmospheric signal prior to reaching the interferometers in order to provide a reference fringe pattern, to which the atmospheric fringes can be compared. By choosing a spectral emission line from the calibration lamp that is close in frequency to the atmospheric line, both will experience the same thermally induced phase change, or "thermal drift." The measured phase drift of the on-board calibration line can then be used to correct the atmospheric signal for thermal drift.

Because thermal variations are expected to be periodic orbit to orbit within any given day, standard operation will be to turn on the calibration lamps for only one orbit per day. Atmospheric data taken while the calibration lamps are off will use the thermal drift

measured during the calibration orbit. Seasonal changes are expected to be quite slow, meaning that calibration data are also expected to be applicable to images taken several days later, if necessary. Infrequent use of the calibration lamps is desired for both satellite power consumption concerns and to minimize additional shot noise on the simultaneously measured atmospheric data.

In this paper, we present the design requirements and ground-based performance of the calibration lamp assembly built for MIGHTI by Resonance, Ltd. in Barrie, Ontario, Canada.

2 Design

The MIGHTI instrument monitors the atmospheric wind at all altitudes of interest by measuring both green and red atmospheric oxygen emission lines simultaneously. The rest wavelengths of these atmospheric emission lines are 557.73 nm (green) and 630.03 nm (red). Therefore, the calibration system needs to provide strong, narrow, isolated lines that are spectrally close to these two atmospheric lines of study. Two individual line sources were selected to achieve this requirement. A krypton lamp provides a green line at 557.03 nm and a neon lamp provides a red line at 630.48 nm. Figure 2 shows the emission spectra of the two gases in the relevant wavelength range.

Both lamps consist of radio frequency (RF) excited, electrodeless vacuum sealed Pyrex envelopes, which are filled with a few Torr of the relevant gas. There is a small amount of radioactive material (^{63}Ni , 1.5 μCurie) fused into the wall of the glass tube to keep the gas partially ionized. This helps to initiate reliable plasma formation when the lamps are started by the exciter circuit, as described below. Figure 3 shows two of the lamps under test on the laboratory bench.

The electronics for the calibration lamps are housed in the lamp enclosure above the Pyrex envelopes and consist of the following circuits: a low-voltage power circuit, a high-voltage power circuit, a filter circuit, a timer circuit, and an exciter circuit. The exciter circuit provides the RF signal, which causes the gas to form a plasma and emit the desired spectral line. To ensure reliable plasma formation, the exciter is run with higher power at startup for several seconds before the power is reduced for constant operation. This ignition period is regulated by the timer circuit. The low-voltage circuit operates the electronic lamp controls, whereas the high-voltage and filter circuits supply power to the lamp exciter. This electronics design has space flight heritage from similar calibration lamps flown on the Hubble Space Telescope, WIND, and Gravity Probe B missions^{5–7} and from lamps flown on numerous earlier satellites and rockets. Changes made to the electronics design were necessitated by the need to meet the specific requirements of the MIGHTI instrument and because some electronic components were no longer available. A schematic of the electrical system is shown in Fig. 4, and an exploded view of the calibration lamp assembly showing the internal structure is shown in Fig. 5.

In order to couple as many photons as possible into sixty 200- μm diameter fibers, the plasma-generated light exits each calibration lamp assembly through a 6-mm focal length, $F/1$ lens. The space between the lamp and fiber optics that holds the focusing lens was

designed to optionally hold neutral density (ND) filters. Figure 6 shows a cut-away schematic of one of the exit ports showing the lamp envelope, possible ND filters, and a subminiature version A (SMA) fiber-optic connector. Because the MIGHTI instrument has two identical sensors (MIGHTI-A and MIGHTI-B) and each sensor requires calibration light from both lamps, we designed and fabricated a fiber crossover junction to mix the fibers after they exit the calibration lamp assembly. At this junction, the fibers carrying red light are mixed with those carrying the green light to create two mixed-color bundles, one for each of the two MIGHTI sensors. The fiber size and number of fibers were chosen to optimize signal throughput, signal mixing, and fiber bundling considerations. Figure 7 shows a diagram of this junction.

The aluminum housing of the calibration lamp assembly was constructed to prevent RF leakage from the exciter circuit. It is also vented to allow air to escape during ascent to orbit. The housing is electrically isolated from the payload deck and vibrational isolation is achieved using a viscoelastic mechanical mounting interface.⁸ Because the electrical design relies on routing the 28-V power return through the lamp assembly chassis, the lamp chassis, as well as its electrical harnessing, must be electrically isolated in order to prevent power line currents from flowing through any spacecraft chassis. Furthermore, in an effort to minimize RF leakage from the lamp assembly through the harness, a ceramic capacitor is connected between lamp housing and spacecraft chassis. This provides a low impedance path at higher frequencies while maintaining a high impedance at DC. This custom-built, AC grounding device is attached to the side of the enclosure. The exterior surfaces of the housing are covered in silver-*teflon* tape to facilitate heat radiation toward deep space while on orbit. Figure 8 shows an exterior view of the assembly housing, fiber optics, and crossover junction, as well as the housing on the bench with both lamps turned on. Also seen in the image of the exterior are the air vent, power input connector, and grounding mount location. As seen in Fig. 5, the lamps reside in a lower compartment of the assembly and most of the electronics reside in a separate upper compartment. Conductive, vented enclosures separate the two sections of the box.

The light from the mixed-color fiber bundles enters the MIGHTI sensors through a collimator, filter, diffuser, and beamsplitter. Figure 9 shows a partially transparent drawing of this optical assembly. The light enters via the fiber-optic SMA connector (small light gray square in the right of Fig. 9) on the underside of the holder (transparent green) and immediately encounters a flat folding mirror (small violet cylinder) that reflects the light toward an off-axis parabolic collimating mirror seen in the left of Fig. 9 (violet, on cylindrical mount). The light then passes through a long wave cutoff filter that blocks infrared signal that would otherwise contaminate the atmospheric IR channels of the temperature measurement, followed by a fused silica holographic diffuser⁹ (both in yellow holder). Finally, about 5% of the diffused light incident on the beamsplitter (in brown cubic holder) is superimposed on the atmospheric signal.

3 Output

MIGHTI will observe the atmospheric emission during both day and night. Daytime emission is significantly brighter than that of the night but also includes more stray light. To

increase stray light rejection, the MIGHTI system includes a shutter that can block ~85% of the incident signal. To compensate for this day/night shuttering, which affects the calibration lamp signal as well, the outputs of the calibration lamps are balanced such that the neon signal is roughly six times brighter than that of the krypton lamp. By cross calibrating the two channels preflight, the brighter neon lamp signal can be used to determine thermal drifts in both the atmospheric red and green line observations during the day when the aperture is small. Similarly, the krypton signal is used to determine both red and green thermal drifts at night when the atmospheric emission is dimmer. For night operations during the calibration orbit, the neon lamp is turned off to avoid saturating the detector. Figure 10 shows a MIGHTI fringe pattern for each lamp, krypton on the left and neon on the right, as created by the interferometer and seen by a single row of the imaging detector. Figure 11 shows an entire detector image (binned, or compressed, vertically) of the signal from the calibration lamps with the MIGHTI instrument operating in vacuum with a cooled detector. The krypton signal is on the left and covers the full altitude range of the image window. The neon signal is on the upper right. The lower right area is used for IR molecular oxygen A-band temperature measurements.⁴ Note that grating imperfections cause phase distortion, which can be most easily seen in the left (green) half of the image as both a tilt to the fringes (phase offset between altitudes) and as distortion within a single binned row (mid altitudes, right side of images). This distortion is inherent to the system, reproduced in every image, and is similar between calibration and atmospheric data.¹⁰ Therefore, through proper consideration of ground-based calibration lamp data, we can remove the distortion before atmospheric analysis.

The calibration lamp was designed to work for input voltages between 24 and 34 V, to produce an output of at least 10^6 photons/s at the MIGHTI CCD detector, and to consume <8 W during standard operation (not start-up). Figures 12 and 13 show the output and power of the lamps at all required voltages for the neon and krypton lamps, respectively. The dashed line is the power consumed by the lamp referenced to the left scale, and the solid line provides scaled photon flux referenced to the right scale. The measurement was made with a single 600- μm fiber and then scaled to the expected signal from sixty 200- μm fibers. Adding the results of both lamps together, we measure a maximum operating power of just under 8 W at 34 V.

4 Performance

An engineering unit of the calibration lamp assembly was tested for start-up and long-term performance reliability. Figure 14 shows the combined steady-state current after turn on as a function of time over a period of 10 weeks. The plot shows that the lamp assembly has a conditioning period (discussed below) extending over the first several weeks of operation, after which it approaches a steady-state current of ~253 mA. The tested life time is greater than the mission utilization, assuming a two-year mission with calibration lamps active during one orbit per day. Likewise, during the life test, the krypton lamp was power cycled more than 1000 times, which is more cycling than anticipated to occur during the mission. The neon lamp was restarted 50 times. The lamps have had no starting failures.

The individual brightness outputs of the lamps were measured with a photodiode during the life-time test. Figures 15 and 16 display the relation between signal brightness and current drawn at 28 V for the neon and krypton lamps, respectively. There is a linear correlation seen between the lamp brightnesses and the current drawn by the lamps over the duration of the test.

During the 1600-h life test, there was a slow growth of the current drawn by the combined unit totaling ~6%, with both lamps exhibiting a similar small growth trend. There was also a positive correlation with the brightness of the lamps, so the change is attributed to aging of the electronics in the RF power exciter circuit. One possible explanation is the continued curing of polymer coatings and staking compounds that can affect inductance values in the switching power supply. This growth of both current and light output is small, well characterized, and poses no hazard to the mission, which does not require a constant photon flux from the calibration lamps.

5 Environmental Tests

Here we summarize key environmental survival and operational requirements met by the calibration lamp assembly. The electronic components were chosen to survive launch and operation in a 575-km altitude, 30-deg inclination orbit for a two-year mission, with a total ionizing radiation dose of 5 krad, and an expected flux of 10^9 high-energy (10 MeV) protons per cm^2 over the same period. The source is in compliance with MIL-STD-461C, which provides standards for electromagnetic interference and compatibility. During thermal-vacuum testing of the MIGHTI payload the calibration lamp assembly has been shown to meet its thermal requirements of survival between -45°C and $+65^\circ\text{C}$ and be operational between -25°C and $+55^\circ\text{C}$. A survival heater is provided by the spacecraft, which turns on below -45°C . The calibration source is assembled from precision cleaned parts suitable for a class 10,000 cleanrooms; vacuum baked if feasible. Polymeric materials were selected for low total mass loss and collected volatile condensable material suitable for use in an ultrahigh vacuum environment. In addition, the calibration source is capable of operating at both atmospheric pressure and in the high-vacuum environment of space and vacuum chambers.

Because of its strength and low mass, aluminum alloy 6061-T6 was used to build the lamp enclosure and most of its hardware. The mass of the assembled lamp enclosure was 1.8 kg. The viscoelastic mounting plate and hardware added 0.8 kg, the fiber-optic cables 0.08 kg, and the thermal multilayer blankets 0.04 kg, for a total as flown mass of 2.747 kg.

MIGHTI will launch on a Pegasus XL rocket with SoftRide adapter.¹¹ Vibration loads for the payload instruments were calculated by the spacecraft vendor, and worst case safety factors were applied to generate test conditions. Observatory level vibro-acoustic workmanship testing was the most severe event for the calibration assembly. Vibration test levels were 7g RMS between 30 and 2000 Hz. An adapter plate⁸ with embedded viscoelastic inserts (see Fig. 17) is used to reduce the vibration loads into the lamps and to account for differential thermal expansion between the payload plate and the lamp housing. The inserts also provide the necessary electrical isolation of the calibration lamp enclosure.

6 Summary

A source providing 557- and 630-nm calibration light has been designed, built, and tested for the MIGHTI instrument on the ICON satellite. The source is rugged, lightweight, low power, and meets all performance and environmental requirements. The calibration lamps will provide reference signals during one orbit per day to track and correct periodic thermal changes in the MIGHTI system during an orbit. The ICON spacecraft carrying MIGHTI is expected to launch to a circular 575-km orbit in 2019.

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Biography

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Fig. 1. ICON payload interface plate showing relative placement of the calibration lamp assembly in relation to the two MIGHTI sensors (A and B) and electronics box.

Fig. 2.
Spectra showing krypton in green and neon in red. The emission lines that are utilized by the MIGHTI sensors are at 557.03 nm from krypton and 630.48 nm from neon.

Fig. 3.
Neon (a) and krypton (b) lamps during bench testing.

Fig. 4.
Schematic block diagram of one of the MIGHTI calibration lamp assembly circuit loops.

Fig. 5. Exploded view of the calibration lamp assembly. From the top to bottom are the housing shell, the electronics section, the lamp envelopes and associated exciter coils, and the fiber-optic connectors.

Fig. 6.

Cut away of the calibration lamp exit optics. A short focal length lens or optional ND filters couple the output of the lamp to an optical fiber bundle.

Fig. 7.
Schematic of the fiber crossover piece. 60 individual fibers exit each lamp and are mixed at the junction, supplying both colors to each MIGHTI sensor.

Fig. 8.

(a) Drawing of the outside of the calibration lamp assembly with fiber optics and fiber crossover junction. (b) The calibration lamp assembly with the exit optics removed showing the lit neon and krypton lamps.

Fig. 9. Schematic of the fiber-optic input to the MIGHTI sensor. Light reflects from two mirrors and passes through a filter and diffuser before entering the beam splitter, which superimposes the calibration signal into the DASH light path.

Fig. 10.

Calibration fringe pattern from each lamp, krypton on left and neon on right, as seen by a single row of the MIGHTI detector.

Fig. 11.

Compressed full detector read out of the calibration lamp assembly. The krypton signal is on the left and covers the full image window. The neon signal is on the upper right. The lower right area is used for infrared O₂ A-band temperature measurements. The vertical dimension represents altitudes from 90 to 300 km and the horizontal dimension represents increasing OPD, repeating for each half.

Fig. 12.
Power (dashed, left scale) and relative intensity (solid, right scale) for the neon lamp on the first flight unit (FU #1) assembly.

Fig. 13.
Power (dashed, left scale) and relative intensity (solid, right scale) for the krypton lamp on the FU #1 assembly.

Fig. 14.

Results of the life-time reliability test for the engineering unit of the calibration lamp assembly. Shown is the combined current pulled by the two lamps upon reaching steady state after each start. Data measured at 28-V input.

Fig. 15.

Neon lamp output (in μW) with drawn current during life-time test. Data were taken at 28 V.

Fig. 16. Krypton lamp output (in μW) with drawn current during life-time test. Data were taken at 28 V.

Fig. 17.
Drawing of calibration lamp assembly mounted on adapter plate with embedded viscoelastic isolators (yellow).