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IRMA as a Potential Phase Correction Instrument: Results from the SMA Test Campaign

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Abstract The Infrared Radiometer for Millimetre Astronomy (IRMA) is a real-time water vapour monitor, whose sensitivity and temporal response make it a candidate instrument for the correction of phase distortion caused by atmospheric water vapour in millimetre wavelength interferometers. We present results from a test campaign in which two IRMA devices were mounted on two antennae of the Smithsonian Submillimeter Array (SMA) located atop Mauna Kea, Hawaii. The IRMA measurements are compared to each other, and to phase information derived from astronomical interferometric data to assess their utility as a potential tool in phase correction.

Keywords Millimeter astronomy · Water vapour monitor · Phase correction

1 Introduction

In May 2004, an Infrared Radiometer for Millimetre Astronomy (IRMA) [1], designed to measure atmospheric water vapour, was installed at the Smithsonian Submillimeter Array (SMA) [2] atop Mauna Kea, Hawaii. The goal was to explore the utility of the IRMA instrument as a potential monitor of phase distortion caused by atmospheric water vapour fluctuations along the line-of-sight of a given antenna of the SMA.

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Ground based observatories operating at submillimetre wavelengths are seriously hindered by the Earth's atmosphere. The principal source of opacity in this spectral region is several strongly-absorbing water vapour lines and their wings [3, 4]. Additional contributions to opacity arise from weaker transitions associated with molecular oxygen and ozone. For this reason, submillimetre observatories are typically located at dry, high altitude sites such as Mauna Kea (~4100 m), and Chajnantor, Chile (~5000 m). Locating a submillimetre observatory at a high altitude site places it above much of the atmospheric water vapour, enabling astronomical observations in several partially transparent spectral windows [5]. Even at these sites, however, there is still sufficient water vapour to adversely affect observations. Furthermore, the polar nature of the water molecule results in a non-uniform distribution of the species throughout the atmosphere. When coupled with bulk atmospheric motion above the telescope, rapid variations in the line-of-sight precipitable water vapour (PWV) occur. These variations give rise to phase distortion in the wavefront from an astronomical source as it propagates through the atmosphere.

To correct for wavefront phase distortion one must measure, rapidly and accurately, the amount of water vapour along the telescope line-of-sight. This can be accomplished through periodic sky-dips either with a dedicated tipping radiometer located nearby, or with one of the primary telescope instruments. While tipping radiometers provide measurements of atmospheric water vapour, derived from model fitting to sky-dip data [6], these measures are generally infrequent, ~10 minutes, and at fixed azimuth. Even when sky dipping with the primary telescope instruments, only an average measurement of atmospheric PWV is derived. The efficacy of both methods is limited by the temporal variability of the atmosphere, which, for typical wind speeds and telescope apertures, results in changes in the air column above a telescope on timescales on the order of ~0.1 s.

The ideal solution is a device that monitors line-of-sight PWV without the need to sky-dip, thus providing real-time phase correction information. One such method is to determine the column abundance from measurements of the 183 GHz water vapour emission line using a heterodyne receiver system [7]. In this technique, the measured intensity in three bands displaced from the line centre is used in conjunction with an atmospheric model to retrieve the PWV. While the 183 GHz system views through exactly the same atmosphere as the science instrumentation, since it shares the same antenna, as with all heterodyne instrumentation it contains an active local oscillator (LO). This LO is a source of noise for other sensitive heterodyne instrumentation. Moreover, heterodyne systems tend to be complex and difficult to maintain.

Before presenting the results of the test campaign, it is first necessary to briefly describe the IRMA radiometer.

2 IRMA III

The IRMA radiometer employs a novel technique for determining atmospheric water vapour content and has been described in detail elsewhere [1, 8–10]. IRMA determines PWV amounts from measurements of atmospheric emission in a narrow spectral region around 20 μm (15 THz), which contains only rotational transitions of water vapour [11], and by use of a sophisticated atmospheric model [4]. The

Fig. 1 (Left) An IRMA unit attached to the rim of an SMA antenna dish. The triangular mount attaches onto three existing bolts that hold the protective panels onto the backing structure. (Right) A view from the Subaru Telescope looking south-west, showing IRMA units on the SMA antennae installed on pads 16 (foreground) and 14.

principal advantage of IRMA is that it is a passive device which does not interfere with the sensitive astronomical instrumentation. Unlike the 183 GHz radiometer, IRMA operates near the peak of the Planck curve for atmospheric temperatures, and thus observes a higher incident flux from atmospheric water vapour. However, for the same reason, care must be taken in the design of the radiometer to minimize the detection of stray radiation from sources at ambient temperature. In practice this is accomplished through appropriate baffling. Previous work has shown that IRMA-derived PWV are well correlated with other measures of atmospheric water vapour on Mauna Kea [12, 13].

In the original design [1], IRMA employed a wet cryostat to cool its photoconductive MCT detector. In the current application, one in which IRMA must be attached to the rim of an antenna and oriented in arbitrary directions, liquid cryogens are impractical. In the IRMA III design the cryostat has been replaced with a closed-cycle Stirling cooler [14], which maintains the temperature of the photoconductor at $\sim$77 K. The resulting instrument is about the size of a shoebox, weighs on the order of 20 kg, and can be attached to the antenna rim without compromising the integrity of the telescope structure, as shown in Fig. 1(left).

3 The SMA test campaign

To test the utility of IRMA as a potential monitor of phase distortion induced by atmospheric water vapour, a campaign was conducted at the Smithsonian

Submillimeter Array at Mauna Kea from May 24 to June 16, 2004. Two IRMA instruments were attached to two of the SMA antennae as shown in Fig. 1(right). Data acquired from the two infrared radiometers and the radio astronomical heterodyne receivers, during this period, form the basis for the results presented in this paper.

Upon receipt of the instruments at the observatory, they were assembled and functional tests were performed. The IRMA units were bolted directly to the telescope backing structure, as shown in Fig. 1(left). The IRMA beam was parallel to, and offset by, half the antenna diameter such that the IRMA beam matched the antenna diameter at a distance of 1 km, as per the design criteria [1]. The alignment of the SMA and IRMA beams was verified by alt-az scans of the Moon. Once in operation, the IRMA units were used to derive the PWV from the site, which was compared with that reported by the Caltech Submillimeter Observatory (CSO) 225 GHz tipping radiometer [6] to confirm that IRMA was performing as expected. Since the CSO PWV values are reported only every 10 minutes and at a fixed azimuth, they are of limited value in any quantitative comparison between the two instruments.

In normal operations, the SMA antennae constantly switch between astronomical sources, sometimes as frequently as once every six minutes. Consequently, both the SMA and IRMA data sets are punctuated by a series of discrete steps as the antennae slew from one position to another. While there is limited scientific value in the radio or infrared data during the slews, these discrete steps are useful for synchronising the two data streams. To investigate the correlation between the infrared measurements of atmospheric flux and the radio measurements of atmospheric phase distortion, data were acquired with the telescopes pointing in the same direction, and pointing 50° apart in azimuth.

4 Results

With the IRMA operational on different antennae, the next step was to check that when both antennae were pointed in the same direction they measured the same amount of PWV. The units were attached to SMA antennae #4 and #5, on pad locations 14 and 16. The two antennae are shown in Fig. 1(right) and have a baseline separation of 141 m. The measurements discussed here were taken between 00:00 and 06:00 UT on June 16, 2004. This corresponds to late afternoon, local Hawaiian time, which is typically characterized by poor and variable atmospheric conditions over the summit of Mauna Kea. Further evidence for the atmospheric variability during this time is provided by the CSO 225 GHz tipping radiometer, which indicated PWV ranging from 3 to 4 mm, generally considered to be poor astronomical observing conditions. The simultaneous IRMA measurements during this 6 hour period are shown in Fig. 2. It can be seen that a high degree of correlation exists between the independent measures of water vapour, as expected. The upper trace in Fig. 2 is the signal voltage from the IRMA unit mounted on antenna #4. The lower trace is the corresponding signal from the IRMA unit mounted on antenna #5, after the data have been calibrated with a gain and offset to account for differences in the signal processing chain, and vertically offset for clarity.

While at first glance the agreement shown in Fig. 2 is impressive, the phase information is derived from the difference between these two traces, as shown in Fig. 3. One way to prove that the difference between the two IRMA units is an

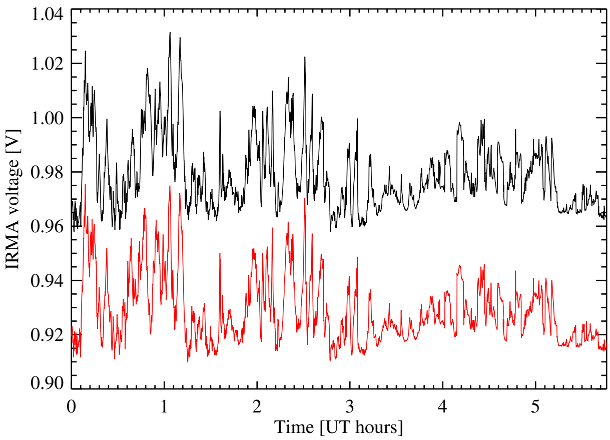

Fig. 2 A 5.5 hour data set from June 16, 2004 from both IRMA units on two different SMA antennae. The upper trace is the signal voltage from one IRMA unit. The lower trace is the signal from the second unit after calibration, offset by −0.05 for clarity.

accurate measure of phase is to compare the difference between the signals when the antennae are viewing the same source, and when they are viewing widely separated sources. This is illustrated in the two time windows highlighted in Fig. 3, which are expanded in Figs. 4 and 5. In the case of the 30 minute time period shown in Fig. 4, the two antennae were pointing 50° apart in azimuth. The upper trace, which shows the difference between the two IRMA measurements, exhibits large fluctuations. The IRMA signals from aligned antennae are shown in Fig. 5 and plotted on same ordinate scale for comparison. The correlation between the two IRMA signals is high – even rapid, large variations in PWV are tracked nearly simultaneously. Also identifiable in the difference shown in Fig. 3 is the relatively turbulent atmosphere during local afternoon times (01:00–03:00 UT) as compared with the calmer nighttime conditions which make Mauna Kea a renowned site for world class observatories. Sunset occurred at 05:13 UT in Fig. 3. The agreement between the signals measured by each IRMA unit when looking at identical sky provides direct evidence that the differences in measured values between the two

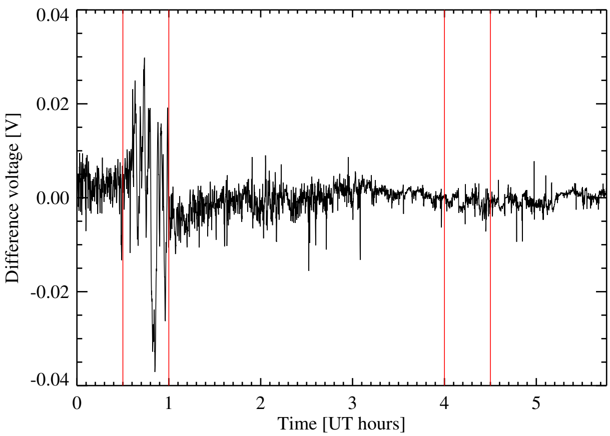

Fig. 3 The difference between the two data sets shown in Fig. 2. The two regions indicated by the vertical lines represent times during which the antennae were widely separated (left), and pointing in the same direction (right).

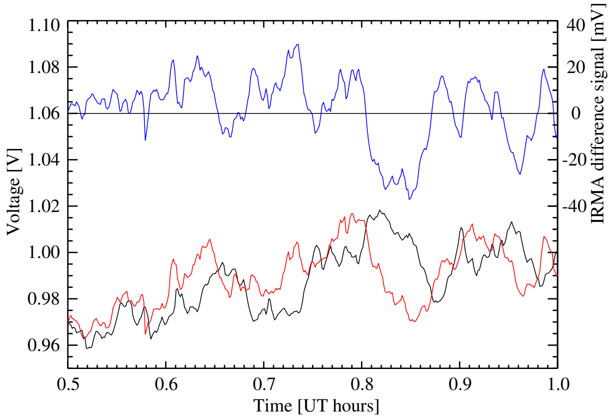

Fig. 4 A zoom of Fig. 3 when the two antennae were pointing 50° apart. The upper trace is the difference between the IRMA measurements (lower traces), offset for clarity. There is seen to be no obvious correlation between the two measurements.

units is primarily due to fluctuations in atmospheric water vapour along the line-of-sight of each antenna.

Theory predicts a relationship between phase delay induced in radio signals and the line-of-sight atmospheric water vapour content, expressed as [15, 16]:

$$\phi = \frac{13\,\pi}{\lambda} \times w \quad , \tag{1}$$

where ϕ is phase [radians], λ is wavelength [m], and w is PWV difference [m]. Although Eq. (1) associates PWV with phase, there is a linear relationship between the IRMA signal voltage and corresponding PWV for small intervals.

The method of calibrating IRMA employed during these tests was a simple, two temperature, linear calibration of flux using an internal blackbody. Unfortunately, during the periods when we had overlapping SMA data, no blackbody calibration data were available. Although this has rendered it impossible to extract calibrated PWV data, to first order PWV is proportional to signal voltage, thus the difference between the two IRMA signal voltages should track the phase from the SMA, according to Eq. (1).

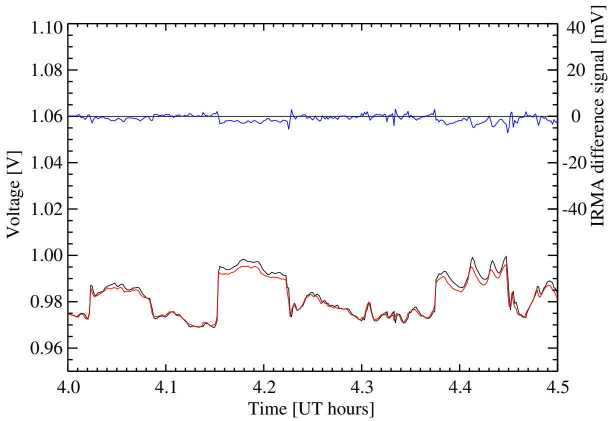

Fig. 5 A zoom of Fig. 3 when the two antennae were pointing in the same direction. The upper trace is the difference between the IRMA measurements (lower traces), offset for clarity. The scale is the same as for Fig. 4, and emphasises the agreement between the two measurements.

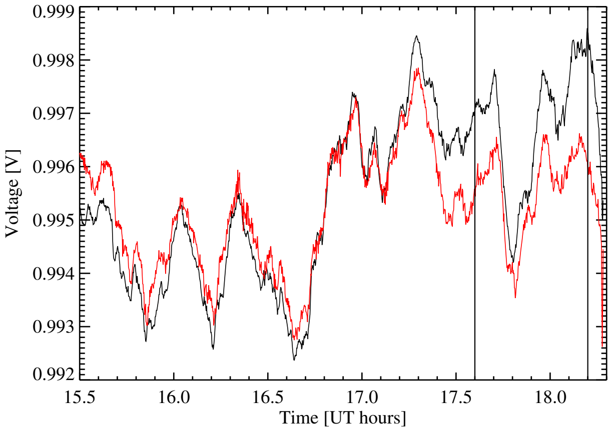

Fig. 6 IRMA signal voltage data collected from both units June 23, 2004 while they were attached to SMA antennae pointing in the same direction. Vertical bars delineate the subset shown in Fig. 7.

Phase information from a radio interferometry measurement is typically obtained by looking at a distant quasar, which can be assumed to be a point source whose wavefronts are plane when they strike the Earth. Equation (2) provides a means to calculate the expected phase, α,

$$\alpha = \frac{2\pi}{\lambda}\left[b\cos(\theta)\cos(\gamma) - d\sin(\theta)\right] , \tag{2}$$

where b is the baseline between the two antennae [m], d is the height difference between the two antennae [m], θ is the elevation angle of the source, γ is the azimuth angle measured with respect to the baseline, and λ is the wavelength of observation [m]. Departures from this equation can be attributed to additional phase delays, ϕ, due to variations in atmospheric water vapour content, w in Eq. (1), and form the subject of the comparison presented below.

Figure 6 shows IRMA measurements taken from a ~3 hour window while the SMA antennae were observing a distant quasar to determine the atmospheric phase variation. Figure 7 shows the phase determined from the radio interferometer (upper trace) after removing the intrinsic geometrical phase, Eq. (2). Also plotted in Fig. 7 is the signal difference from the two IRMA units (lower trace). While

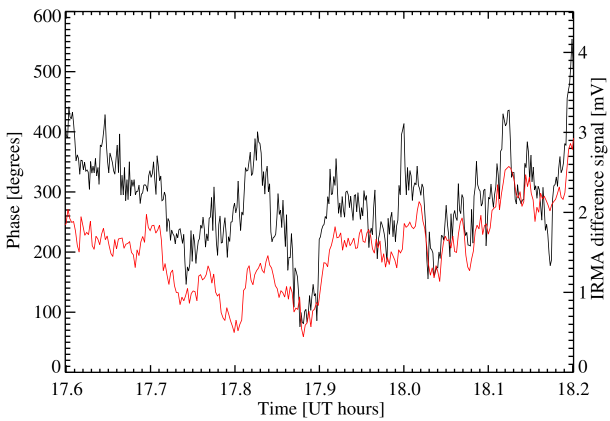

Fig. 7 A subset of Fig. 6 comparing the phase information as determined by the SMA when observing a bright astronomical source (upper trace, black) and the difference voltage between the two IRMA units (lower trace, red).

absence of calibration data precludes validation of Eq. (1), or accurately defining the ordinate scale for the IRMA data, it appears from comparison of features in Fig. 7 that the IRMA difference signal, which is proportional to PWV, is tracking phase variations observed by radio interferometric measurements of a quasar. Although the agreement is not perfect, similar IRMA units, deployed in site testing campaigns, have also demonstrated environmental sensitivity resulting in a slow drift of the instrumental response, as seen in Fig. 7. Calibration has successfully been able to identify and correct for this drift.

5 Conclusion

The goal of this exploratory study was to investigate the utility of the IRMA instrument as a method of providing phase correction information for a radio interferometer, by fast and accurate line-of-sight water vapour measurements. Analysis of data from two IRMA units mounted on the SMA has shown that they are capable of measuring variations of water vapour on rapid timescales. Moreover, the measurements are highly correlated when the units point in the same direction. This correlation breaks down when the antennae are pointing in widely separated directions. Although it was not possible to calibrate the instruments on the antennae, and thus determine PWV values, it has been shown that the IRMA signal voltage differences follow the trend of the phase variations measured by the radio interferometer.

It is important to note that due to the challenges of getting the IRMA and SMA instruments operating simultaneously, a limited amount of overlapping data were available. Furthermore, these data were obtained during poor observing conditions, the CSO recording PWV amounts ranging from 3 to 4 mm. Previous measurements have shown that the sensitivity of IRMA decreases rapidly above 1 mm PWV [1]. To put the current work into perspective, for 1 mm PWV, the typical conditions at Mauna Kea, the sensitivity of IRMA to variations of atmospheric water vapour increases by a factor of 3; and for 0.5 mm PWV, which represent excellent observing conditions, by a factor of 5. From a comparison of the signal-to-noise ratio in the two curves of Fig. 7, IRMA appears to have similar sensitivity to water induced phase delays as that determined from the radio measurements. Taken together, the results presented in this paper, show that the passive, low cost, IRMA concept holds much promise for phase correction of radio astronomical data under typical observing conditions.

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