Initial results of field testing an infrared water vapour monitor for millimeter astronomy (IRMA III) on Mauna Kea

Robin R. Phillips[a], David A. Naylor[a], James diFrancesco[b] and Brad Gom[a]

[a]University of Lethbridge, Lethbridge, Alberta, Canada;
[b]Hertzberg Institute of Astrophysics, Victoria, British Columbia, Canada

ABSTRACT

The Infrared Radiometer for Millimetre wavelength Astronomy (IRMA) is a compact, light weight, low cost, low maintainance water vapour monitor, with an accuracy that enables it to be used to correct the phase distortions caused by atmospheric water vapour in millimetre wavelength interferometers. The IRMA III prototype is a major improvement on earlier versions of IRMA, with an emphasis on simplicity and reliability. We present results of tests conducted on the Submillimeter Array (SMA) telescope on Mauna Kea in June 2004. The test campaign involved using three IRMA III devices with the SMA to provide phase correction information for improving the quality of the astronomical interferometric data.

Keywords: Millimeter astronomy, water vapour monitor, phase correction

1. INTRODUCTION

Ground based observatories operating at submillimetre wavelengths are seriously hindered by the atmosphere, which absorbs, emits, and scatters electromagnetic radiation. Most of the opacity in this spectral region is due to the presence of several strongly-absorbing water vapour lines. Additional opacity arises from weaker transitions associated with molecular oxygen and ozone. To address this problem, submillimetre observatories are built at dry, high altitude sites such as Mauna Kea, Hawaii (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 semi-transparent spectral 'windows'. Even at these high altitude sites, however, there is still sufficient water vapour to affect observations. Furthermore, the highly polar nature of water molecules results in the non-uniform distribution of the species through the atmosphere. When this is coupled with bulk atmospheric motion above the telescope it results in rapid variations of the line-of-sight precipitable water vapour (pwv) abundance, giving rise to phase distortion of the wavefronts as they propagate through the atmosphere.

One method of correcting for wavefront phase distortion is to measure the amount of water vapour in the telescope beam. Traditionally, this has been derived through periodic skydip measurements, either with a dedicated tipping radiometer or with one of the primary telescope instruments. However, both methods have the disadvantage of yielding only an average measurement of pwv over the whole skydip rather than the desired value along the line-of-sight from the telescope to the source. Moreover, the former method uses an instrument that is offset from the main telescope beam, whereas the latter method requires interrupting observations to perform a skydip.

A more optimal solution is to have a device that looks along the telescope beam and directly determines the line-of-sight pwv column density without requiring skydips. For submillimetre telescopes the traditional method has been to determine the amount water vapour from measurements of the 183 GHz water vapour line using a heterodyne receiver system. This involves measuring the intensity of three narrow bands offset by differing amounts from the line centre (which are hence sensitive to differing amounts of water vapour). This has the disadvantage of requiring a complex and difficult to maintain instrument.

Further author information: (Send correspondence to R.R.P.)
R.R.P.: E-mail: robin.phillips@uleth.ca, Telephone: +1 403 3292741

We have developed an Infrared Radiometer for Millimetre Astronomy (IRMA) which employs a novel technique for measuring atmospheric water vapour content.[1] The IRMA device is a simple infrared radiometer that observes a narrow spectral region around 20 μm (15 THz) which contains only rotational transitions of water vapour. The simplicity, and hence low cost and reliability of such a device, offers many advantages over the 183 GHz system. The ultimate goal for any water vapour monitor operating on a submillimetre telescope is to provide measurements that enable water vapour induced atmospheric effects to be removed from the telescope science data. We have previously demonstrated[2] that the optical depth IRMA measures at 20 μm correlate directly with the optical depth at the operating wavelengths of the telescope (approximately 200 GHz - 1.2 THz or 1300 - 250 μm). The aim of this test campaign was two fold: 1) To demonstrate that the new design for IRMA, in its maintainance free, compact format, could achieve the same noise performance as the laboratory test instrument and 2) to confirm that the emission IRMA is measuring is correlated with the phase distortions seen by an astronomical telescope.

2. THE IRMA III CONCEPT AND DESIGN

There have been two previous versions of the IRMA instrument[1,3] which operated as 'proof of concept' instruments and as such were impractical for use as an observatory facility instrument. They required frequent maintainance and were not designed to be attached to a telescope dish (eg. they could not be tipped in elevation). The IRMA III design takes all the necessary components from the previous designs and places them in a compact, low maintainance package that can be easily attached to an operational telescope.

The IRMA III design has been described in detail elsewhere.[4] In summary, it consists of a 35 x 22 x 19 cm aluminimum box weighing just over 13kg. The box contains a Hymatic Stirling cycle cooler, an attached vacuum vessel containing the 20μm detector and long pass filter, a chopper blade, a 10cm off-axis parabalic mirror, a warm blackbody calibration source and all the required power supplies, electronics and micro-processor needed to operate the instrument. We have also designed and built an alt/az mount and stand that enables the IRMA box to operate independently of a telescope. The IRMA box can either be attached to the mount, which it can then control directly to orientate itself in any desired direction, or it can be mounted directly to a telescope. The IRMA box requires simply mains power and an ethernet connection, both of which enter the box via a single weatherproof connector. The IRMA devices contain small onboard microprocessors[5] (from Rabbit semiconductors) which receive high level commands from a separate, Linux based, control PC. The control PC, which communicates via the ethernet connection can control several IRMA devices. The collected data are periodically transfered back to, and stored on, the control PC.

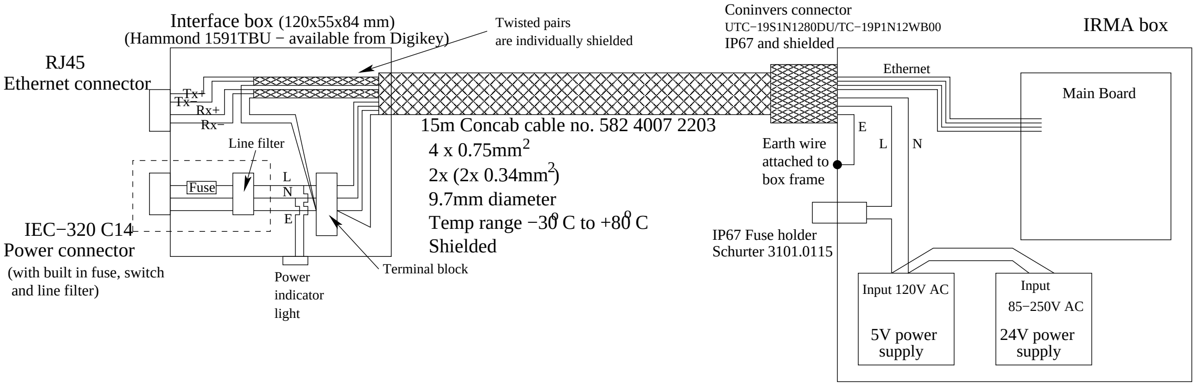

Figure 1. The interface box and cabling used when attached to the SMA.

For this test campaign we were required to interface the IRMA box with the SMA antenna without using the mount section. For this purpose we constructed a small interface box that accepted standard RJ45 and IEC-320C14 ethernet and power connectors. This interface box was connected to the IRMA box using the same connectors that were being used for the IRMA/mount interface cable. This setup then enabled the IRMA boxes to be used either on or off the mounts without any additional modifications. The interface box enabled us to connect to the SMA computer and power network without any modifications to the SMA. Figure 1 shows the configuration whilst attached to the SMA. The choice of exterior cable is important in that it has to be robust enough to withstand the exterior conditions on Mauna Kea but also have sufficent shielding to not introduce radio frequency interference into the SMA cabin (where the astronomical receivers are located).

3. THE HAWAII TEST CAMPAIGN

In order to test the new IRMA design we have mounted a test campaign on Mauna Kea from 24 May to 16 June 2004. For this we shipped three IRMA devices and two mounts to Hawaii. Our original plan was to install the two mounts next to the SAO seeing monitors located between the James Clerk Maxwell Telescope (JCMT) and Caltech Submillimeter Observatory (CSO). Using these mounts we planned to demonstrate initial operation of the IRMA devices and compare their measurements of pwv with the phase variations measured by the SAO seeing monitors. Figure 2 shows the layout that was used whilst we were located outside the JCMT. We also constructed three mounting adaptors to enable the IRMA boxes to be attached to the side of three Submillimeter Array (SMA)[6] antennas, this was planned after initial operation of the IRMA devices had been demonstrated as access to the units is much more difficult once they have been mounted on the SMA.

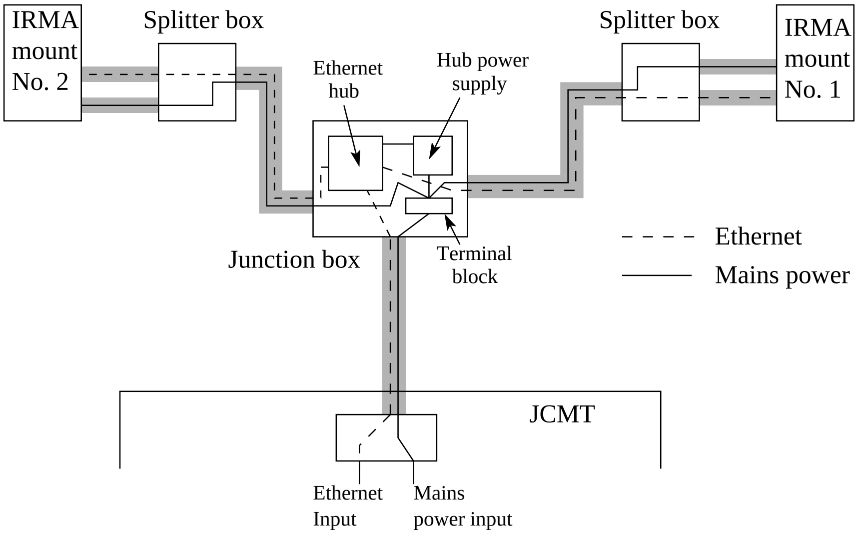

Figure 2. This was the cabling layout whilst we were testing outside the JCMT. The junction and splitter boxes are mounted in weather proof enclosures. This system was very flexible and during initial setup we were able to route one of the cables back inside the JCMT which enabled us to troubleshoot one IRMA inside whilst operating the other one outside.

As with the initial test campaign for almost any new instrument, our plan underwent significant modification as we debugged the instrument. In our case the normal teething problems were compounded by delays in the final construction phases of the project that meant only very limited testing could be performed in Lethbridge. This in particular affected the software for the instrument which needed considerable debugging in the field.

The actual time line in Hawaii was that, after several delays due to the shipping company, when our units finally arrived we rapidly got two IRMAs installed on their mounts outside the JCMT. However we then spent the second week debugging the control software which had numerous problems that effectively prevented us collecting useful data. Once the software problems had been overcome most of the third week was spent fixing various main board and/or pre-amp electronics issues. We were unable to resolve these problems on one unit but in our final week we were able to get both of the other two units working. Given these delays we decided to curtail the SAO phase monitor comparisons and moved straight to the SMA. In our final days we had a trouble free installation on the SMA and were able to start collecting data. As presented in the next section we were able to demonstrate that the two units on different SMA antennas were able to track pwv variations above each telescope. The third unit was returned to the University of Lethbridge and as soon as the electronics are repaired, it will be shipped back to Hawaii for installation on a third SMA antenna. In the week before this paper was submitted we had a data collection run with the aim of measuring phase variations using the SMA's main instrumentation on a bright astronomical source to see if this correlates with the pwv differences between the two IRMA units. Initial results from this run are presented in the next section. More detailed analysis this data set along with data from the ongoing tests as well as data from the third unit will be presented in a future paper.

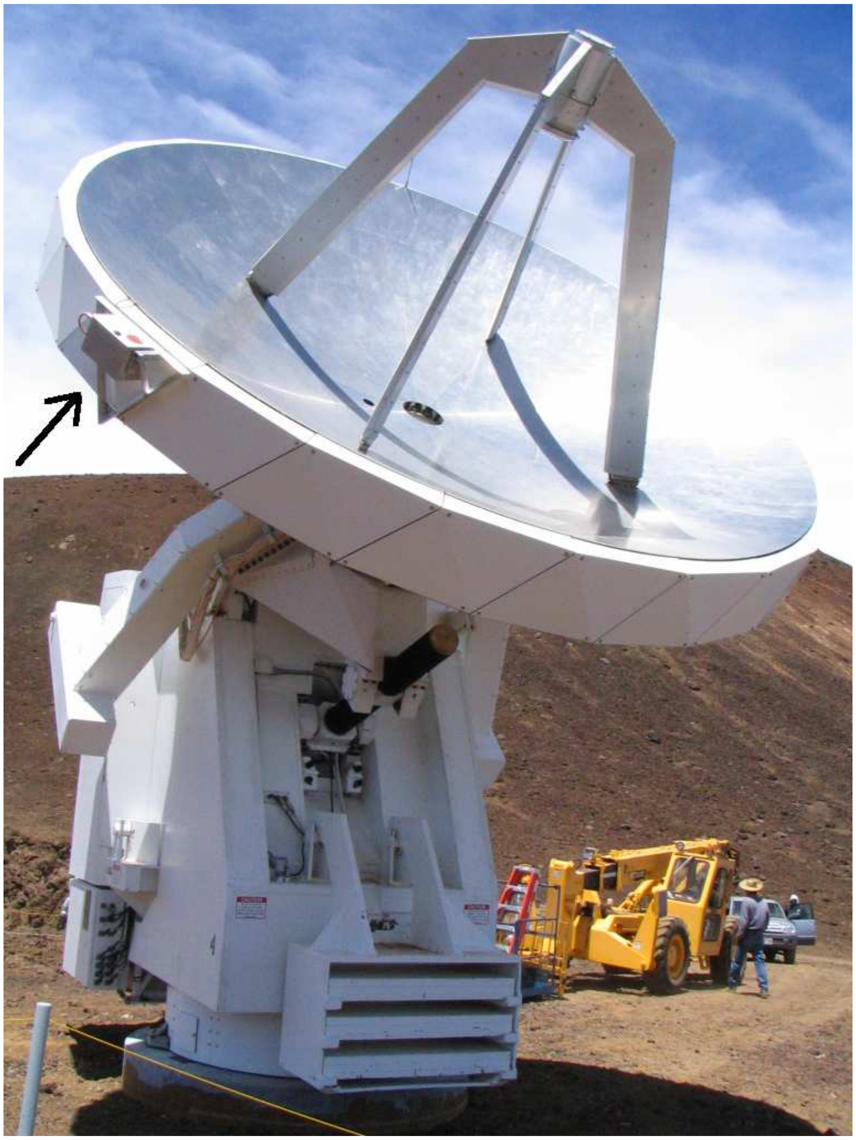

Figure 3. The IRMA box attached to antenna No. 5 of the SMA. IRMA is on the rim of the dish (as indicated by the arrow). The triangular mount attaches onto three existing bolts that hold the protective panels onto the backing structure. Thus no mechanical modifications were required on the SMA in order to attach IRMA.

4. INITIAL RESULTS

Our initial tests, the results of which are presented here, were designed with the aim of demonstrating the basic operation of the two working units, in particular their ability to track pwv variations. Before being attached to the SMA antennae both units were calibrated using a liquid Nitrogen filled bucket (the inside of which was lined with ecosorb) and ecosorb ambient loads. The spectral power observed from two different temperatures can be calculated from Plack's radiation law and hence we can determine the spectral power radiated by the sky in future observations. The spectral radiance when observing a load at a given temperature, T, is obtained from:

$$S_T = \int_{filterwindow} \frac{2hc^2\sigma^3}{e^{\left(\frac{hc\sigma}{kT} - 1\right)}} \times F_\sigma dw \tag{1}$$

where h is Planck's constant, k, is Boltzman's constant, c is the speed of light. F_σ is the filter profile at wavenumber σ. The spectral power is then simply

$$S_p = S_T \times Throughput \tag{2}$$

Where the $Throughput$ is the product of the beam area and solid angle.

The above equation, with appropriate constants for our system is used to determine the scale given on the y-axis of Figures 4 and 5. It should be noted that, due to the very short period available for testing the completed units prior to shipping to Hawaii, we were unable to determine the filter profile using a Fourier Transform Spectrometer. Hence the filter profile used to generate the scales in the two figures is only a crude Gaussian approximation to the true profile. Therefore the the values on the scale should be considered arbitrary. We are in the process of determining a more precise calibration of this scale.

Figure 4 shows the first set of simultaneous data taken with two IRMA units attached to the SMA antennas 4 and 5. These were positioned on pads 14 and 16 which are 141m apart. The CSO 225 GHz Tau readings were fluctuating in the range implying 3-4 mm of pwv were present during these observations. The data collection starts at about 14:00 HST and hence covers the late afternoon period that usually has turbulent, variable atmosphere over the summit of Mauna Kea.

The lower two lines (black and grey) show the spectral power emission from the column of atmosphere above each antenna. The constant offset between the two units is most likely due to the idential filter profiles used in the initial reduction - it is highly unlikely that the profile will be identical for both units. This will be removed in future, more complete, analysis

The top line is the difference in the signal between the two units (shifted by 1×10^{-5} for clarity) and is a measure of the difference in pwv in the column of atmosphere above each antenna. For the first 1500 seconds the two antenna were pointing in the same direction at a source (Jupiter), which was approximated 40° elevation (but climbing rapidly) at the start of the dataset. At 1500 seconds one of the antenna was then slewed to point 50° away from the other. At arround 3000 seconds it was then slewed back to point at Jupiter again and remained that way until evening observing started at arround 12000 seconds, after which there are numerous slews but both antenna are always moved together.

It can clearly be seen that the datastreams from the two IRMA units correspond very closely to one another when the antenna are both pointing in the same direction - even rapid, large variations in pwv are tracked nearly simultaneously. However, when the two units point in different directions, they are no longer measuing the same area of sky and the data does not correlate. It is also noticable how the difference reading later in the evening, after the sky has become less turbulent, is much smoother than during the mid afternoon. This provides good evidence that the differences in the measured value between the two units really is due to atmospheric difference above each antenna.

Figure 5 shows the results of comparing the difference between the two IRMA unit signals with a measure of phase derived from SMA's observations of an astronomical source at 220GHz. The black vertical lines highlight features that are visible in both datasets. Due to a software error in the IRMA controllers there is a

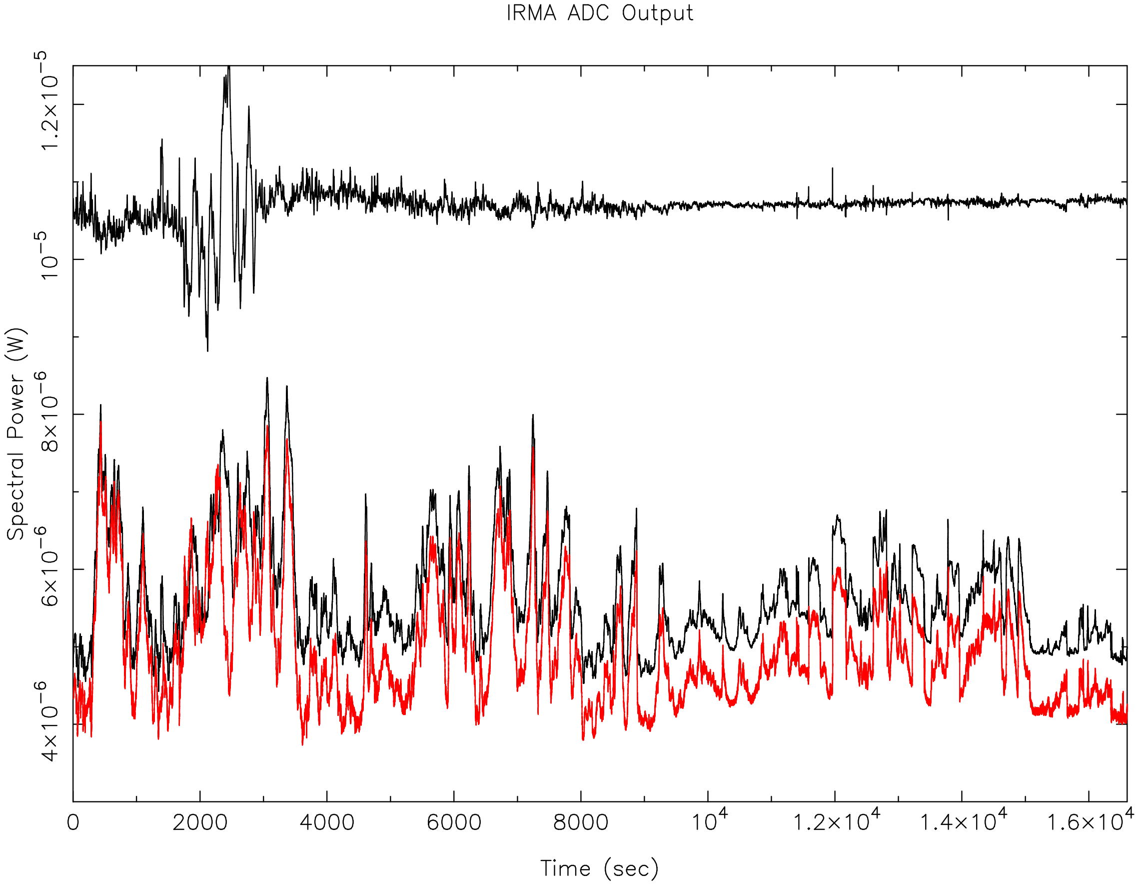

Figure 4. A 4.5 hour data collection run on 15 June 2004 using both IRMA units on two different SMA antennea. The lower two lines are the outputs from the two IRMA units. The upper line is the difference between the two units, shifted vertically. Between approximated 1500 sec and 3000 sec the two antenna were pointing 50° apart, for the rest of the time they were pointing at the sime point in the sky.

slight time drift on the IRMA signals. We have attempted to correct for this but small errors remain, hence minor missalignments between features in the two data streams are not significant. Part way through our test campaign we implemented an improvement in the IRMA electronics for one of the units. The effect of this can been seen in upper of the two IRMA data lines, which has a noise level that is a factor of 3-4 lower than the bottom line. Hence the noise in the difference plot, is almost entirely due to the single noisier IRMA unit. In addition we have since discovered another software error that meant we were only integrating on the sky for 135ms out of every 385ms. Hence a combination of these two effects means that future data runs should show about a factor of 5 improvement in signal to noise performance.

For the first part of the run, the SMA antenna were tracking a source low in the sky, hence there is little noticable phase information in the data as it is too noisy. However after 9000 sec the antennae slew to about 80° and thereafter features can clearly be made out. It is noticable that the IRMA data shows no significant increase in noise at the lower elevations (except in the late afternoon where the atmosphere is very turbulent).

5. CONCLUSION

We have completed the construtction of three 20μm IRMA water vapour monitor devices and have successfully installed two of them on the Smithsonian Millimeter Array on Mauna Kea (with a third to follow shortly). Our initial few data collection runs have shown that the two IRMA devices are tracking the atmospheric preciptable

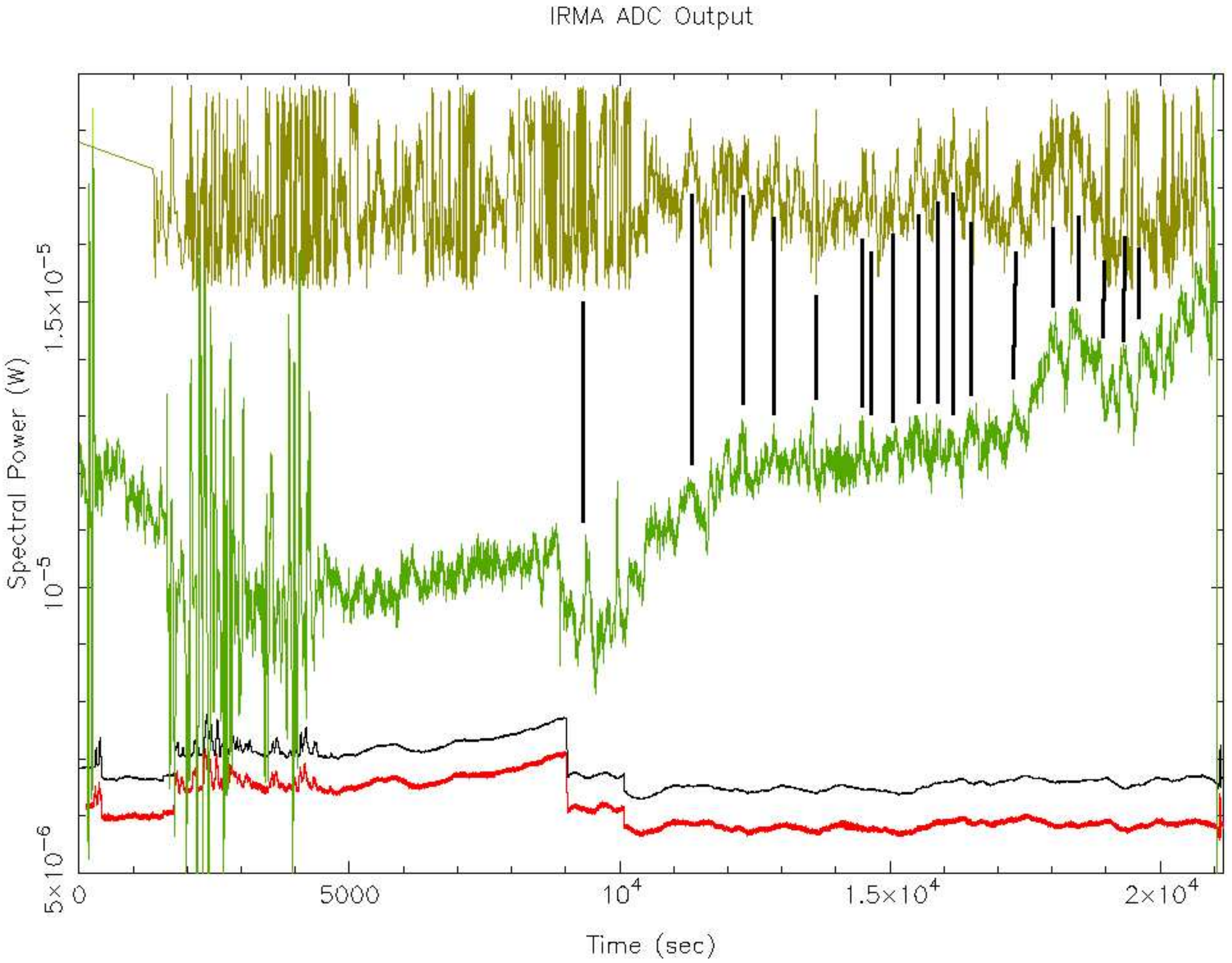

Figure 5. A 6 hour data collection run on 23 June 2004 using both IRMA units and simultaneously measuring phase using the SMA's normal astronomical instrumentation. The lower two lines are the outputs from the two IRMA units. The lower grey line is the difference between the two IRMA units, magnified 25 times and shifted vertically to bring it into view. The upper grey line is phase information as determined by the SMA when observing a bright astronomical source. The black vertical lines highlight features that can be seen in both the SMA phase data and the IRMA difference data. See text for further explanations.

water vapour and independently provide similar absolute measures of sky brightness. Further, comparison of the differences between the sky brightness measured by the two units and phase as measured by the SMAs astronomical instumentation shows good correllation. We interpret this as confirmation that the IRMA units are measuring precipitable water vapour column abundance above each antenna and that they are measuring this with sufficient accuracy to be able to determine the phase variations that the water vapour is causing in the signal from an astronomical source.

Future work will on these data will provide a more precise calibration of the IRMA units and will then attempt to use the IRMA data to apply phase correction information to the SMA data sets.

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