Precipitable water vapour above La Silla Paranal Observatory

F. Kerber et al.
European Southern Observatory

at Astronomy Site Testing Data Conference, Valparaiso
Collaboration

- University of Lethbridge, Canada
  - R. Querel, D. Naylor, G. Tompkins

- U. Valparaiso
  - A. Chacón, O. Cuevas, M. Cure, L. Cortes, M. Caneo, L. Illanes

- GMT, Las Campanas
  - J. Thomas-Osip, G. Prieto

- TMT
  - A. Otárola, M. Schöck, T. Travouillon

- ESO
Outline

• PWV - why & how
• E-ELT site testing
• Goals
• Archival data - reconstructing the past
• PWV campaigns - what we have learned
• Results & Future work
Atmospheric Water Vapour

- Precipitable water vapour (PWV)
  - column of atmospheric water [mm]
  - crucial for atmospheric opacity in IR
  - Long-term: site quality
  - Short-term: operational issue
E-ELT site testing

- PWV is one factor for site selection
- Better understand atmospheric PWV
  - Variability
  - Calibrate measurements
- La Silla & Paranal well-established sites
- Report to Site Selection Advisory Committee
Goals:

• Reconstruct Record of Precipitable Water Vapour (PWV) over Paranal & La Silla
• Correlate with satellite data to establish Paranal & La Silla as reference sites for E-ELT site evaluation
• Evaluate merit of methods for operational use at observatory
Reconstructing the PWV History

- La Silla Paranal
  - UVES & FEROS
- Standard Star Observations
  - White dwarfs - featureless spectrum
  - Taken every UVES night; ~1200 observations useable
  - Time coverage: 2000-2009
  - Wide slit: 5/10 arcsec
  - UVES reprocessing with master calibration files
Atmosphere Model: PWV

- Atmospheric model BTRAM (Univ. Lethbridge)
  - HITRAN (2008)
  - Multi-layer atmospheric radiative transfer model
  - Mid-latitude profile modified with site-specific archival radiosonde data from Antofagasta
  - 580-980 nm, >1000 lines
  - Validated at LCO with MIKE observations
  - Comparison with IRMA (Querel et al. 2008)
Atmospheric Model: PWV

$H_2O$ only,
$PWV = 1 \text{ mm}$

All other constituents:
$CO_2, O_2$

F. Kerber et al.
Valparaiso, Dec 1st-3rd, 2010
UVES data (White dwarf)

Wavelength (Å)

Plot from ESO Quality Control Report, R. Hanuschik

F. Kerber et al.  Valparaiso, Dec 1st-3rd, 2010 10
Paranal: wet & dry

PWV = 1.02 mm

PWV = 3.68 mm

Transmission

UVES data
BTRAM fit

Wavelength [nm]

716 718 720 722 724

F. Kerber et al. Valparaiso, Dec 1st-3rd, 2010
Satellite Data

- **GOES**
  - Time resolution 1 every 3 h, 24 h a day
  - Spatial resolution 12 by 12 km (3 pixel binning)
  - Brightness at 6.5 & 10.7 μm - clear nights only

- **ENVISAT**
  - Time resolution 1 every 2-3 days, daytime
  - MERIS: Spatial resolution 1 by 1 km
  - Spectrum: 890-900 nm
Paranal
UVES archival Data
Paranal archival PWV
Paranal archival PWV


PWV [mm]

Time [MJD]

54280  54300  54320  54340  54360  54380  54400

GOES  MERIS  UVES
Paranal archival PWV

April 2004

May 2004

June 2004

PWV [mm]

GOES
MERIS
UVES

Time [MJD]

53080
53100
53120
53140
53160
53180

F. Kerber et al. Valparaiso, Dec 1st-3rd, 2010 16
Paranal archival PWV

May 6, 2004
May 16, 2004
May 26, 2004

GOES
MERIS
UVES

PWV [mm]

Time [MJD]

F. Kerber et al. Valparaiso, Dec 1st-3rd, 2010 17
## PWV site statistics

<table>
<thead>
<tr>
<th>Paranal</th>
<th>Median PWV [mm]</th>
<th>&lt; 1 mm [%]</th>
<th>&lt; 1.5 mm [%]</th>
<th>&lt; 2 mm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVES</td>
<td>2.1 ± 0.3 (2.2)</td>
<td>13.5</td>
<td>32</td>
<td>47.3</td>
</tr>
<tr>
<td>GOES</td>
<td>2.4 ± 0.5 (1.8)</td>
<td>4.8</td>
<td>18.9</td>
<td>38</td>
</tr>
<tr>
<td>MERIS</td>
<td>2.7 ± 0.3 (2.0)</td>
<td>1.5</td>
<td>7.9</td>
<td>29</td>
</tr>
</tbody>
</table>
## PWV site statistics

<table>
<thead>
<tr>
<th>La Silla</th>
<th>Median PWV [mm]</th>
<th>&lt; 1 mm [%]</th>
<th>&lt; 1.5 mm [%]</th>
<th>&lt; 2 mm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEROS</td>
<td>3.4 ± 0.4 (2.4)</td>
<td>3.3</td>
<td>9.2</td>
<td>18.4</td>
</tr>
<tr>
<td>GOES</td>
<td>5.9 ± 0.6 (2.5)</td>
<td>0.02</td>
<td>0.4</td>
<td>1.8</td>
</tr>
<tr>
<td>MERIS</td>
<td>3.6 ± 0.5 (2.3)</td>
<td>0.8</td>
<td>11.2</td>
<td>20</td>
</tr>
</tbody>
</table>
PWV Campaigns
Jul/Aug & Nov 2009
Llullaillaco volcano (6,720 m)
190 km east on Argentinean border
Atmospheric transmission

BTRAM: Mauna Kea, PWV = 1 mm
Radiosondes

A. Chacón et al. (U. Valparaiso)

F. Kerber et al. Valparaiso, Dec 1st-3rd, 2010-23
Radiosonde Profiles

Temperature

Dew Point
La Silla / Las Campanas (May 2009)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Period</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>La Silla</strong> (Lat: -29°15’ 15.0”, Long: -70°44’ 22.0”, Alt: 2400 m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiosondes</td>
<td>May 5–15</td>
<td>17/20 launches; ~1.5 h each, up to 20–25 km</td>
</tr>
<tr>
<td>BACHES</td>
<td>May 4–15</td>
<td>9.5/12 nights; 375 spectra, cadence ~15 min</td>
</tr>
<tr>
<td>FEROS</td>
<td>May 6, 7</td>
<td>0.9/2 nights; 319 spectra, cadence minutes</td>
</tr>
<tr>
<td>HARPS</td>
<td>May 8, 9</td>
<td>2/2 nights; 978 spectra, cadence minutes</td>
</tr>
<tr>
<td>IRMA 11</td>
<td>May 3–15</td>
<td>Nightly coverage; ~168 hours, cadence seconds</td>
</tr>
<tr>
<td>IRMA 12</td>
<td>May 3–15</td>
<td>Nightly coverage; ~179 hours, cadence seconds</td>
</tr>
<tr>
<td>Lunar Spectrophotometer</td>
<td>May 5–15</td>
<td>~1500 scans, cadence seconds</td>
</tr>
</tbody>
</table>

**Las Campanas** (Lat: -29°0’ 54.0”, Long: -70°41’ 32.0”, Alt: 2380 m)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Period</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRMA 1</td>
<td>Continuous</td>
<td>Nightly coverage; ~124 hours, cadence seconds</td>
</tr>
<tr>
<td>MIKE</td>
<td>May 9, 10, 14</td>
<td>2.5/3 nights; 1449 spectra, cadence &lt;30 sec.</td>
</tr>
</tbody>
</table>
La Silla / Las Campanas (May 2009)

Measured PWV: 2 to 12 mm

F. Kerber et al.  Valparaiso, Dec 1st-3rd, 2010 26
Paranal/Armazones, July/Nov 2009

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Period</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACHES</td>
<td>Aug. 1–10</td>
<td>142 spectra, cadence 15–30 min</td>
</tr>
<tr>
<td>UVES</td>
<td>July 31-Aug. 8</td>
<td>10.5 h, 474 spectra cadence up to 30s</td>
</tr>
<tr>
<td>VISIR</td>
<td>July 31–Aug. 16</td>
<td>46 spectra</td>
</tr>
<tr>
<td>CRIRES</td>
<td>July 29–Aug. 15</td>
<td>53 spectra</td>
</tr>
<tr>
<td>IRMA 11</td>
<td>July 29-Aug. 10</td>
<td>~150 h; cadence seconds</td>
</tr>
<tr>
<td>IRMA 12</td>
<td>Aug. 3–8</td>
<td>~50 h each on Paranal &amp; Armazones, cadence sec</td>
</tr>
<tr>
<td>Radiosondes</td>
<td>July 29–Aug. 10</td>
<td>23/23 launches; ~1.5 h each, up to 20–25 km</td>
</tr>
<tr>
<td>Lunar Spectrophotometer</td>
<td>Aug. 1–7</td>
<td>55 scans, cadence seconds</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Period</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVES</td>
<td>Nov. 11–17</td>
<td>11 h, 450 spectra cadence up to 30s</td>
</tr>
<tr>
<td>VISIR</td>
<td>Nov. 10–21</td>
<td>25 spectra</td>
</tr>
<tr>
<td>CRIRES</td>
<td>Nov. 9–21</td>
<td>60 spectra</td>
</tr>
<tr>
<td>IRMA 11</td>
<td>Nov. 8–19</td>
<td>~120 h Paranal, ~85 h on Armazones; cadence seconds</td>
</tr>
<tr>
<td>IRMA 12</td>
<td>Nov. 9–20,</td>
<td>~200 h Paranal, cadence seconds; left operating</td>
</tr>
<tr>
<td>Radiosondes</td>
<td>Nov. 9–19</td>
<td>29/29 launches; ~1.5 h each, up to 20–25 km</td>
</tr>
</tbody>
</table>
Paranal (July/August 2009)

Measured PWV: 0.3 to 4 mm

F. Kerber et al.  Valparaiso, Dec 1st-3rd, 2010 28
Paranal (November 2009)

Measured PWV: 1 to 4 mm

F. Kerber et al. Valparaiso, Dec 1st-3rd, 2010
IRMAs on Paranal and Armazones

Delta PWV from RS (ANF): ~0.3 mm

F. Kerber et al.        Valparaiso, Dec 1st-3rd, 2010 30
Comparison to radiosondes

<table>
<thead>
<tr>
<th>Instrument</th>
<th>λ</th>
<th>#</th>
<th>PWV [mm]</th>
<th>Slope</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACHES</td>
<td>710–850 nm</td>
<td>26</td>
<td>0.3 – 10.0</td>
<td>0.82</td>
<td>0.94</td>
</tr>
<tr>
<td>UVES</td>
<td>710–850 nm</td>
<td>29</td>
<td>0.4 - 3.3</td>
<td>0.84</td>
<td>0.79</td>
</tr>
<tr>
<td>CRIRES</td>
<td>5038–5063 nm</td>
<td>40</td>
<td>0.8 - 2.9</td>
<td>0.91</td>
<td>0.72</td>
</tr>
<tr>
<td>VISIR</td>
<td>19.3–19.7 μm</td>
<td>20</td>
<td>1.1 - 3.1</td>
<td>1.10</td>
<td>0.65</td>
</tr>
<tr>
<td>IRMA (all)</td>
<td>20 μm</td>
<td>57</td>
<td>0.4 - 10.0</td>
<td>0.97</td>
<td>0.93</td>
</tr>
<tr>
<td>GOES La Silla</td>
<td>6.7, 10.7 μm</td>
<td>17</td>
<td>3.0 - 10.0</td>
<td>0.97</td>
<td>0.12</td>
</tr>
<tr>
<td>GOES Paranal</td>
<td>6.7, 10.7 μm</td>
<td>52</td>
<td>0.4 - 4.0</td>
<td>0.95</td>
<td>-0.76</td>
</tr>
<tr>
<td>APEX</td>
<td>183 Ghz</td>
<td>11</td>
<td>0.2 - 1.4</td>
<td>0.95</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Radiosonde vs GOES

\[ y = 0.97x \]
\[ R^2 = 0.73 \]

\[ y = 0.96x \]
\[ R^2 = 0.04 \]
Results

- Median PWV over La Silla Paranal - E-ELT site evaluation
  - Paranal 2.4 mm
  - La Silla 3.7 mm
  - Armazones 2.1 mm (Otárola et al. 2010: 2.9 mm)

- Validated various methods with respect to radiosondes
  - 700 nm - 20 µm & 183 Ghz
  - 5-20%; ≥0.05/0.5 mm

- Remote sensing data (satellites) usable for statistical analysis only, ok for site evaluation
Next Steps

• Complete analysis (typical time scale of variability)

• **Monitoring** at Paranal:

• VISIR upgrade includes PWV monitor

• PWV forecasting using WRF model (U. Valparaiso)
PWV Time dependence

- IRMA 10 days
- PWV typical time constant is hours

T. Travouillon

F. Kerber et al. Valparaiso,
PWV Time dependence

ATACAMA: Fractional variability between the 5min and the 30min data series

Minutes elapsed since beginning of observations, 9 days of data
PWV Time dependence

A. Otárola
F. Kerber et al.
VISIR upgrade project

- VISIR: mid-IR imager & spectrograph at VLT
  - 10 µm (N-band) & 20 µm (Q-band)
- VLT: Visitor/service mode: ~50/50 split
- Optimize use of low PWV
- Stand-alone high time resolution monitor
- PWV as user-defined constraint

MIR atmosphere transmission at Paranal

Transmission vs. Wavelength (µm)
VISIR upgrade project

• Science benefit for demanding observations
  – imaging of faint sources in Q,
  – high-precision photometry,
  – spectroscopy of $\text{H}_2$ 0-0 S(1) at 17.02 $\mu$m,
  – imaging and spectroscopy in N-band $< 8 \mu$m,
  – detection of water vapour in circumstellar disks
Next Steps

- PWV as operational tool
- Stand-alone monitor on Paranal - VISIR upgrade
- Constraint for SM observations

**VISIR: 7-12%**
Summary - Goals met

• History of PWV over La Silla & Paranal reconstructed from archival data
• Paranal as reference site for Northern Chile
• Feedback to Site selection process
• Merit for Observatory operations
  – Monitoring with high accuracy feasible
  – PWV crucial tool for scheduling of service mode
Summary - Future

- PWV monitor: Stand-alone, high time resolution, high accuracy
- VISIR: Observing constraint - service mode
- Benefit to other instrument (CRIRES, MIDI, ISAAC, ...)
- Comprehensive atmospheric monitoring essential part of infrastructure for E-ELT