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Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

Water Vapour Radiometry

An Introduction

Reuben Neate, Tinus Stander

DARA Training School, HartRAO, September 2025

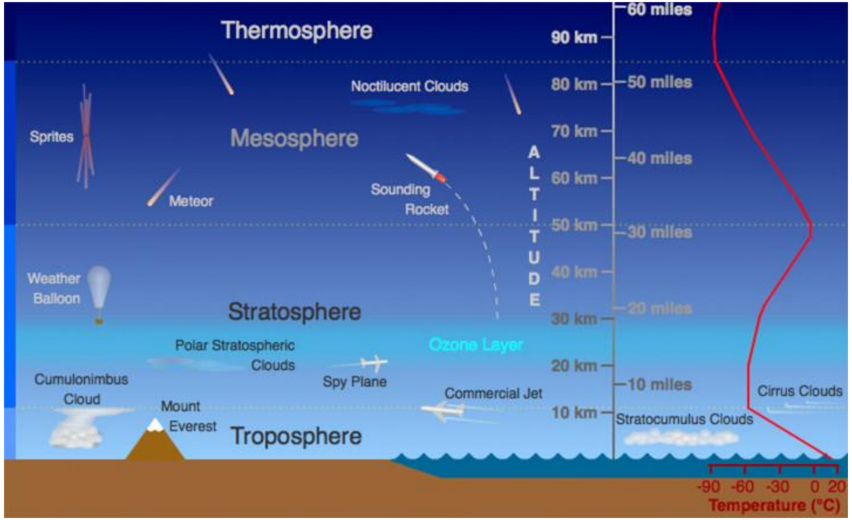
Agenda

- Principles of radiometry
  - The atmosphere
  - Emission and absorption by atmospheric gasses
  - Black bodies, Planck's Law, Rayleigh-Jeans Approximation
- Tropospheric water vapour
  - Specific emission / absorption spectrum
  - Importance to radio astronomy
  - Data products
- Radiometers
  - Principle of operation
  - Performance Metrics
  - Architectures
- Some WVR details and examples
  - Calibration
  - System Integration
- Development Opportunities

Principles of radiometry

The atmosphere

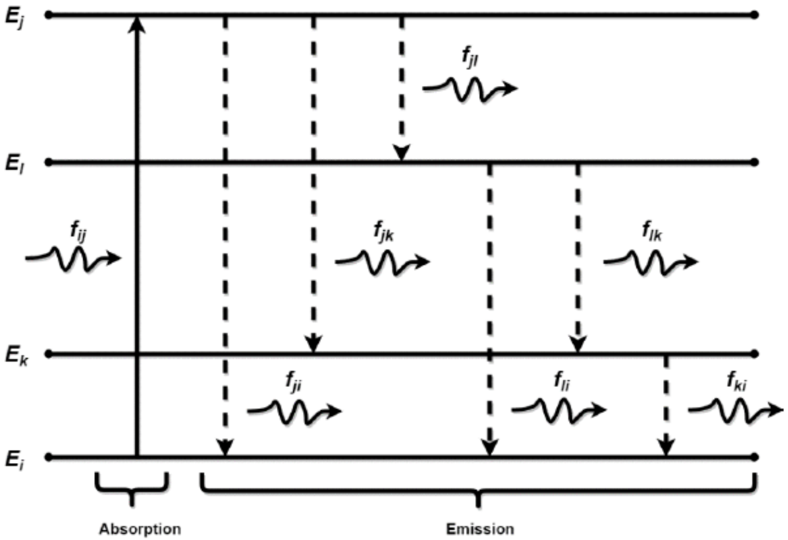
- O_2, N_2, CO_2, H_2O
- Troposphere lowest 10km
  - 75% total mass, 99% H_20
- Most distributions uniform and stable
  - Not H_2O!



scied.ucar.edu

Emission and absorption

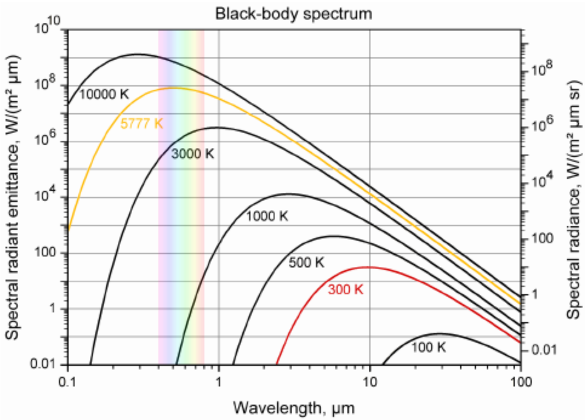
- Gas molecules have finite energy states
- Transition between states
  - Absorption: collect a photon
  - Emission: release a photon
- Photon energy → frequency
  - $E = hf$
- Emission / absorption spikes
  - Known transitions



SM Walker, TUT, 2019.

Black body radiation

- Absorb and emit with 100% efficiency
  - Idealised, but handy
- Emission determined by
  - Temperature
  - Frequency
- Planck's law:
  - Radiance, temperature and wavelength
- Rayleigh-Jeans approximation
  - Linear at microwave frequencies



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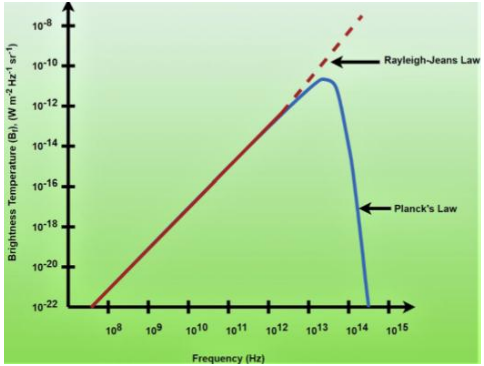

SM Walker, TUT, 2019.

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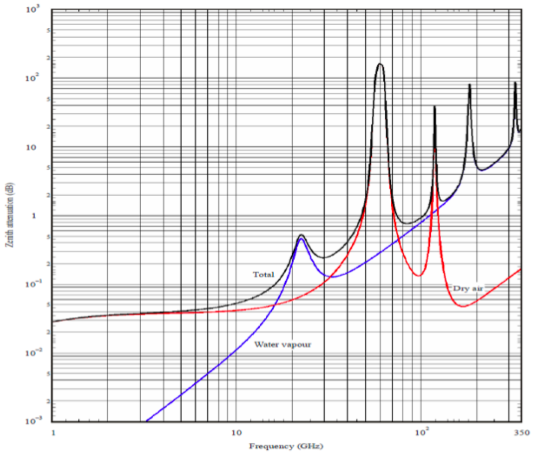
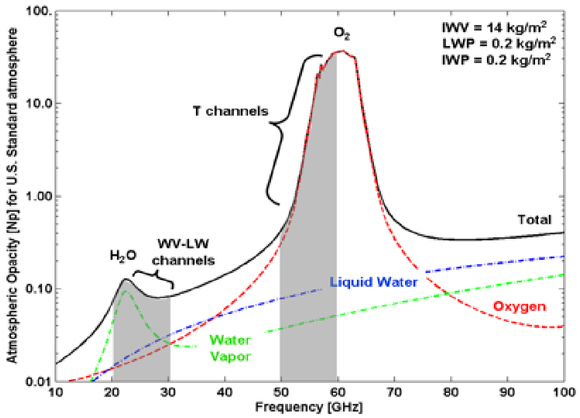
Tropospheric water vapour

Emission spectrum

- Lines at 22.24, 183.31, 325.5 GHz
- Pressure broadening
  - Estimate concentration from total power OR spectrum shape
- Liquid water continuum
  - Offset to water vapour emission

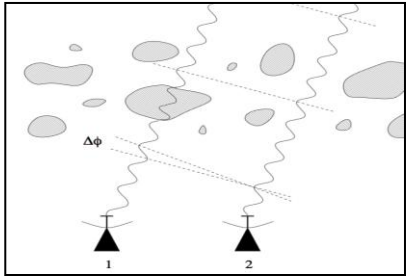


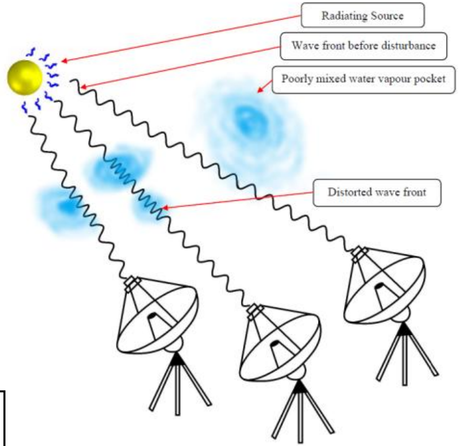


http://propagation.ece.gatech.edu
http://cfa.aquila.infn.it/wiki.eg-climet.org/index.php5/MWR_Fundamentals

The problem with water vapour and VLBI

- Delay and attenuation not uniform at all sites
- Need to measure water vapour
  - Path delay correction
  - Site management
    - Monitoring, scheduling
  - Site surveying

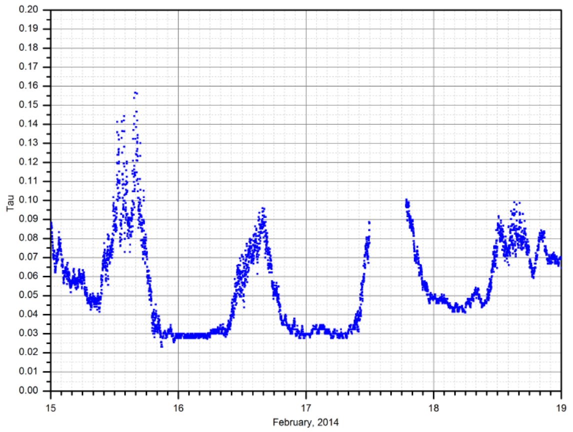




SM Walker, TUT, 2019.

Data products (1)

- Radiometric brightness temperature (T_B)
- Opacity / optical depth τ
    - Function of atmospheric conditions and T_B
        - T_{mr}: f(T, P, RH) with radiosondes
          OR
        - Tipping curve



Ferrusca et al, Proc. SPIE v9147

$$\tau_\nu = \ln\left[\frac{T_{mr} - 2.7K}{T_{mr} - T_B}\right]$$

$$V_{out}(z) = G\left(T_{sys} + \left(1 - e^{-\tau_0 \sec Z}\right)\cdot T_{atm}\right)$$

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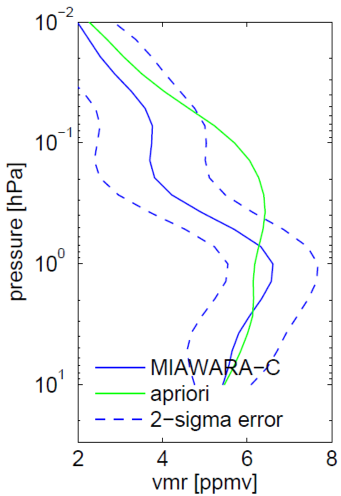
Data products (2)

- Integrated liquid water (ILW), in mm or g/m^2
  - Also: Liquid Water Path (LWP)
  - Liquid water produces continuum radiation, but not significant path delay!
  - Requires multi-band observation
    - Separate into “dry” and “wet” opacity
  - Requires
    - Atmospheric model
    - Solution of radiative transfer equations
    - Data estimates (T, P, RH)
- Integrated Water Vapour (IWV), in mm or g/m^2
  - Also, precipitable water vapour (PWV)
  - Similar process
- Altitude / vertical profiles
  - Needs a spectrum, not singular discrete measurements
  - Forward model fitting based on radiosonde, RADAR or LIDAR data
  - Temperature can be remote sensed @ O_2 lines.



$$\tau = \tau_d + \kappa_V\,(IWV) + \kappa_L\,(LWP)$$

$$LWP = \frac{-\kappa_{V,\nu_2}\tau'_{\nu_1} + \kappa_{V,\nu_1}\tau'_{\nu_2}}{\kappa_{V,\nu_1}\kappa_{L,\nu_2} - \kappa_{V,\nu_2}\kappa_{L,\nu_1}}$$

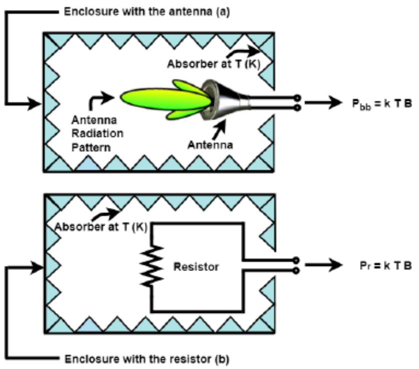
$$IWV = \frac{\kappa_{L,\nu_2}\tau'_{\nu_1} - \kappa_{L,\nu_1}\tau'_{\nu_2}}{\kappa_{V,\nu_1}\kappa_{L,\nu_2} - \kappa_{V,\nu_2}\kappa_{L,\nu_1}}$$

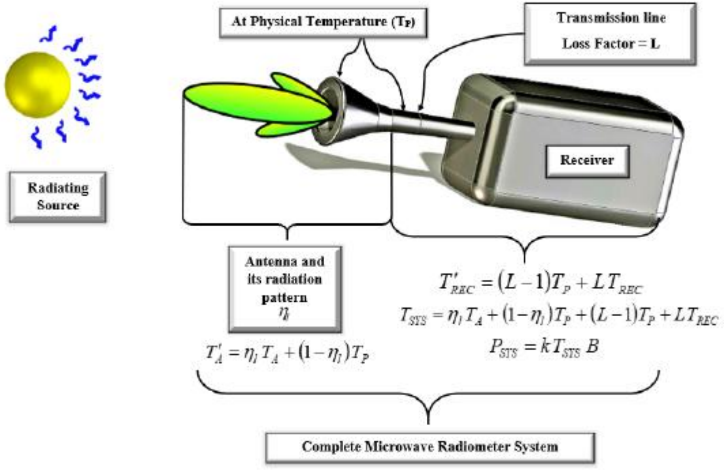
Straub et al, Atmos Meas Tech 3-1-15.

Radiometer Theory

Principles of operation

- P = kTB
  - Power related to brightness temperature
- Relate noise power to voltage
  - Square law detector
- Problem: How distinguish T_{ant} from T_{sys}?





SM Walker, TUT, 2019.

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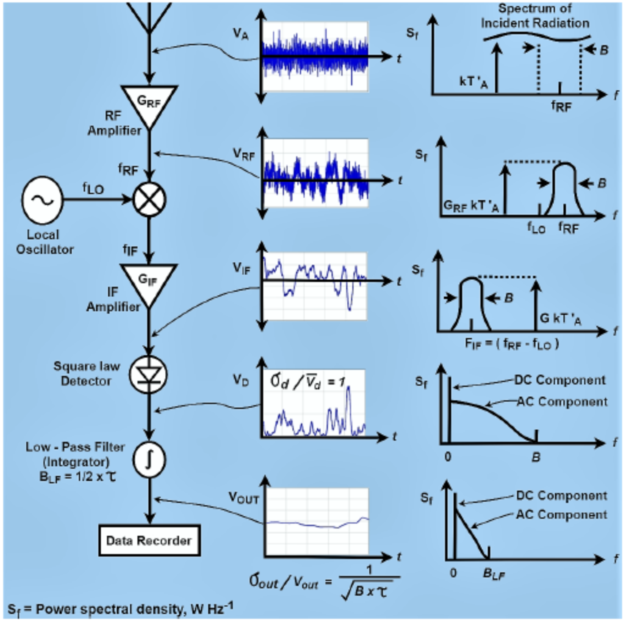
The basic radiometer

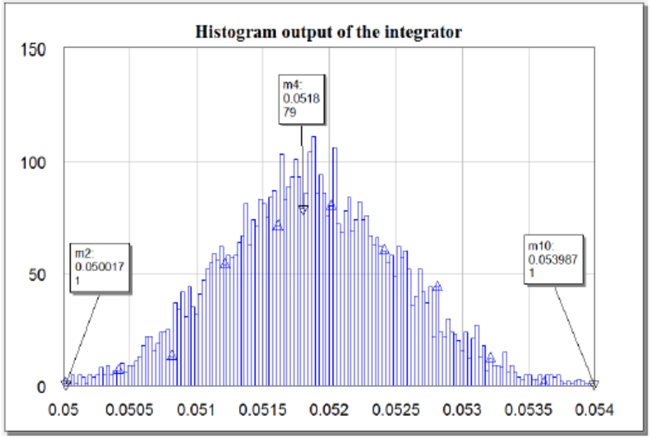
- Antenna
- Gain
- Downconversion
- Detection
- Integration
- Recording

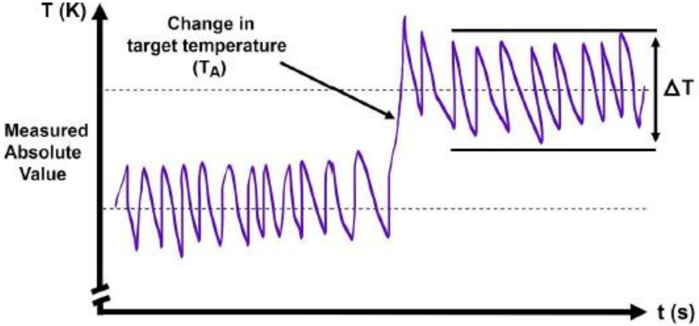


SM Walker, TUT, 2019.

Performance metrics

- Accuracy
  - How reliable is my average voltage?
  - Improved by calibration, low drift
- Resolution
  - How reliable is my instantaneous measurement?
  - Improved by lower Tsys, increased integration time





SM Walker, TUT, 2019.

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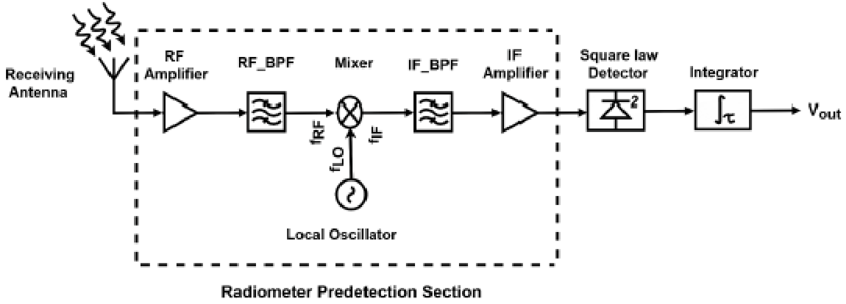
The total power radiometer

- Superheterodyne
- Can be calibrated with front-end switch and noise source
- Sensitive to drift
  - Allen time



$$\Delta T = \frac{T'_A + T_{REC}}{\sqrt{B \cdot \tau}} = \frac{T_{SYS}}{\sqrt{B \cdot \tau}}$$

$$\Delta T_{TPR} = (T_{SYS}) \cdot \sqrt{\frac{1}{B \cdot \tau} + \left(\frac{\Delta G}{G}\right)^2}.$$

SM Walker, TUT, 2019.

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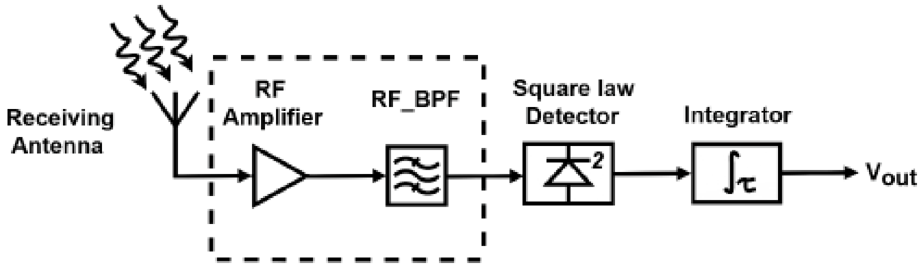
The direct detection radiometer

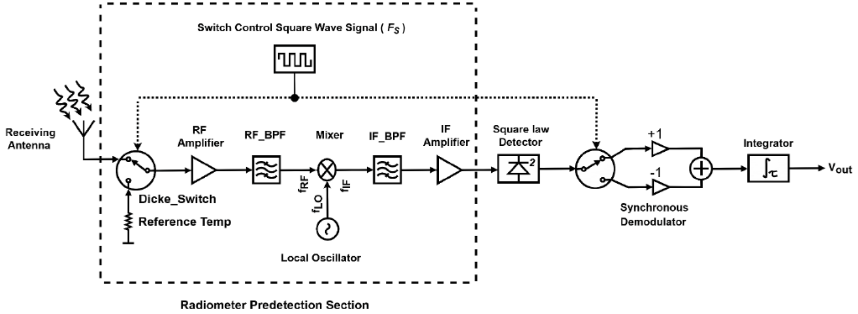
- No downconversion
- High frequency detector
- Still sensitive to drift, 1/f
- No band tuning



SM Walker, TUT, 2019.

Dicke radiometer

- Synchronous demodulation of sky and load
- Compensate for drift
  - Common mode variation
- Requires longer integration times
  - Only looking at sky ½ of time



$$\Delta T_{DR} = \sqrt{\frac{(T'_A + T_{REC})^2}{B \cdot \tau / 2} + \frac{(T_{REF} + T_{REC})^2}{B \cdot \tau / 2} + (T'_A - T_{REF})^2 \cdot \left(\frac{\Delta G}{G}\right)^2}\ .$$

- Seems to work better when load = sky… can we enforce that?

SM Walker, TUT, 2019.

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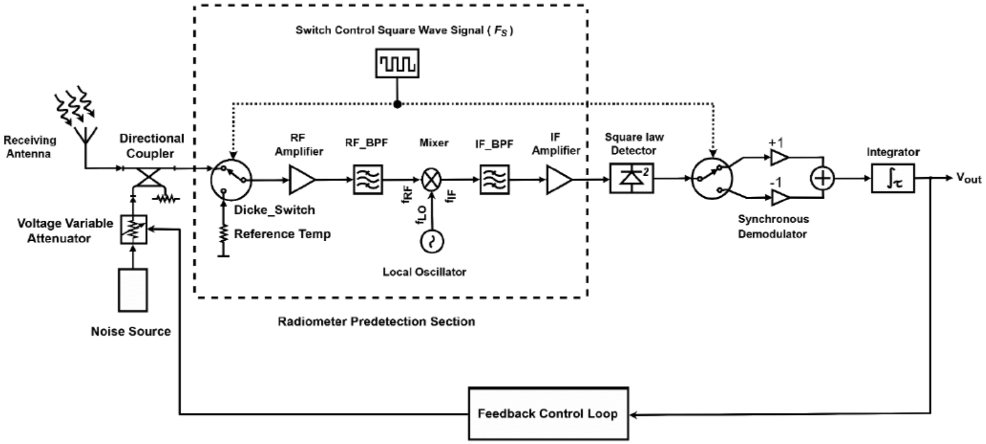
Noise injection radiometer

- Feedback control to equalize sky and load
  - Cancel out drift completely
- Data now the noise injection control, not the noise voltage

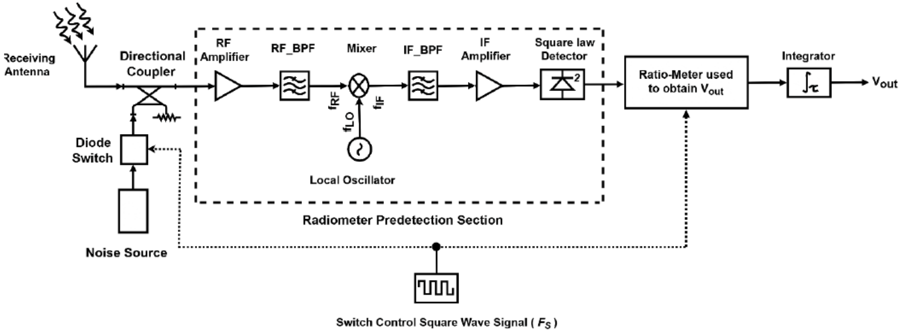


$$\Delta T_{NIR} = \sqrt{\frac{2\,(T'_A + T_{REC})^2 + 2\,(T_{REF} + T_{REC})^2}{\sqrt{B \cdot \tau}}}\ .$$

SM Walker, TUT, 2019.

Noise adding radiometer

- Switches are inconvenient
  - Loss!
- Gradual increasing injection of noise
- Same effect
- Use Y-factor to measure T_{ant}



$$\Delta T_{NAR\ (theoratical)} = \left(\frac{2\ T_{SYS}}{\sqrt{B\cdot\tau}}\right)\cdot\left(1+\frac{T_{SYS}}{T_{inj(on)}}\right)$$

SM Walker, TUT, 2019.

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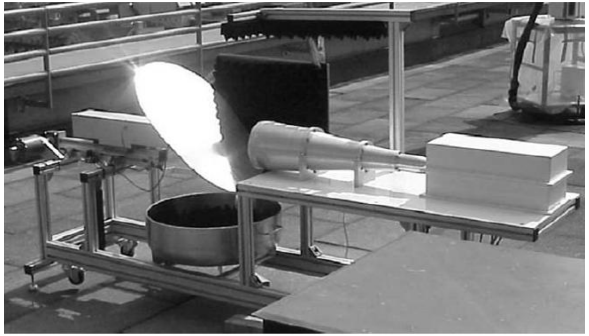
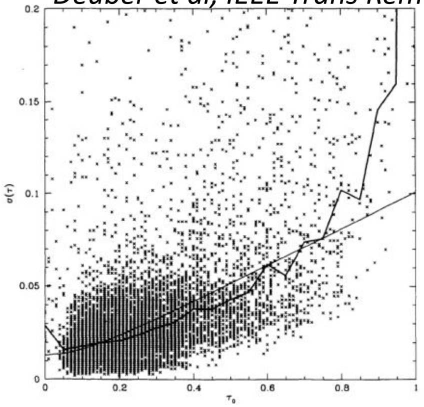
Some practical notes

Calibration

- Built-in noise source
  - Stability
- Liquid nitrogen load calibration
  - Periodic
- Tip curve calibration
  - Solve unknowns T_{sky}, T_{sys}
  - Assume T_{sky} increase by known factor, T_{sys} constant
  - Need regression of many data points
  - Assumes parallel atmosphere
  - Still needs calibrated T reference measurement!



Deuber et al, IEEE Trans Remote Sensing 42(5)



Hiriart et al, Revista Mexicana de Astronomia y Astrofisica 33.

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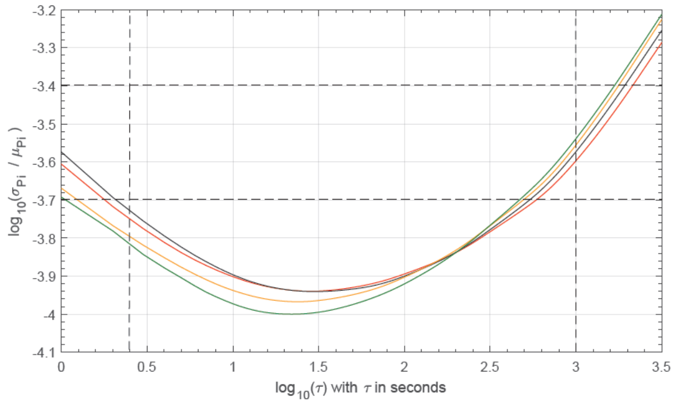
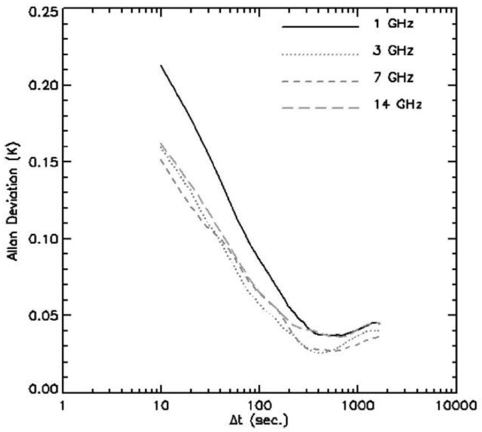
Allan Variance

- Long-term stability measure
- 1/f noise, drift
- Can’t integrate forever!

$$\sigma_y^2(\tau) = \frac{1}{2}\langle(\bar{y}_{n+1} - \bar{y}_n)^2\rangle = \frac{1}{2\tau^2}\langle(x_{n+2} - 2x_{n+1} + x_n)^2\rangle,$$





Gill et al, EVLA memo #203
Pazmany, IEEE Trans. GeoSci Remote Sensing 45(7)

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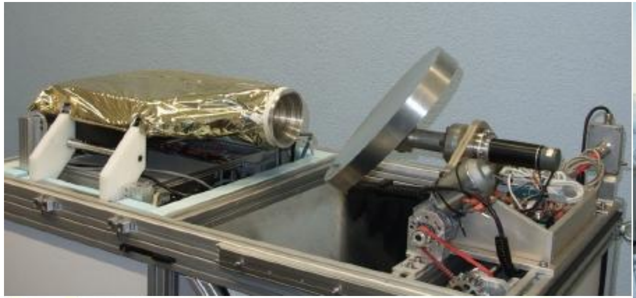
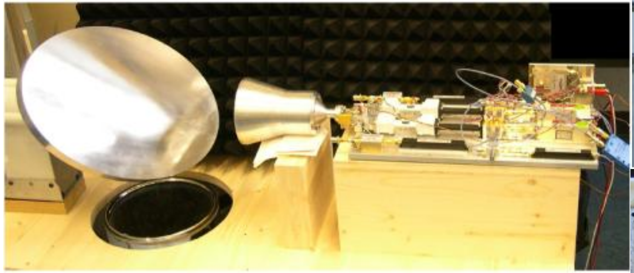
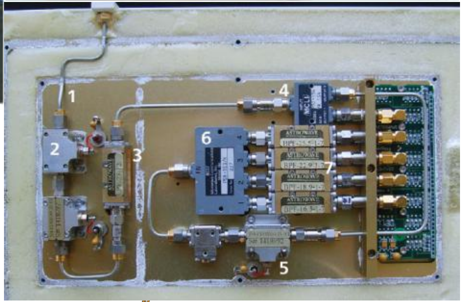
Integration and construction

- Tipping radiometer
  - Rotating mirror
- Internal: waveguide and coax
- Other weather station instruments
  - T, P, RH







Straub et al, Atmos. Meas. Tech., 3, 1–15
Indermuehle et al, PASA, v. 30, e035, 2013

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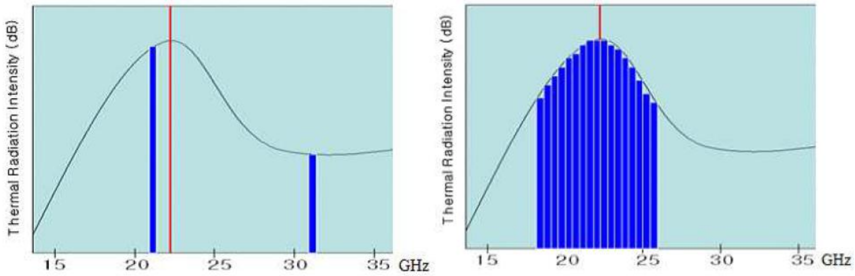
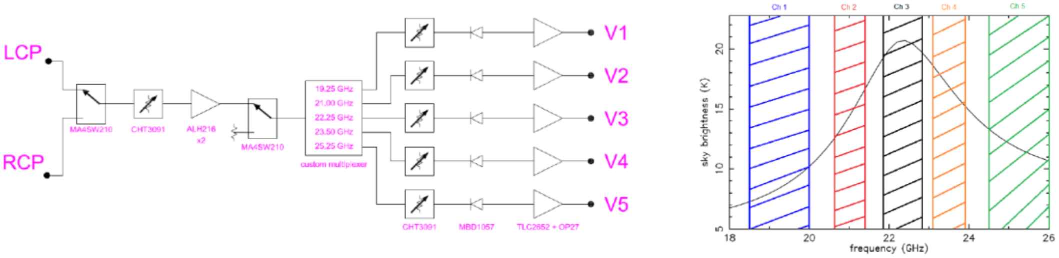
Spectrum & digitization

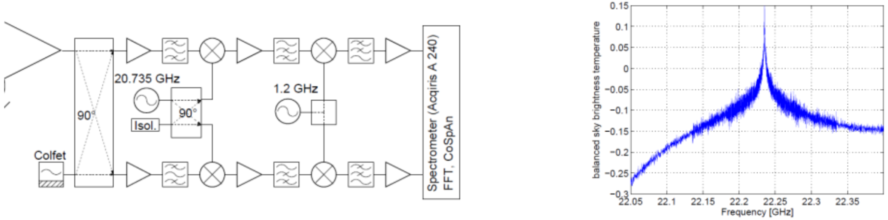
- Single band, integrated
  - Opacity
- Two bands, integrated
  - Distinguish between wet and dry path
- Multiple bands, diodes
  - Spectrum
  - Vertical profiling
  - Lots of duplication
    - Filters!
- Spectrometer
  - Fine resolution
  - Vertical profiling
  - High speed ADC and DSP!



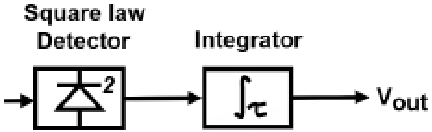
Cho, Bonn University, 2012.



Gill et al, EVLA memo #203



Straub et al, Atmos. Meas. Tech., 3, 1–15



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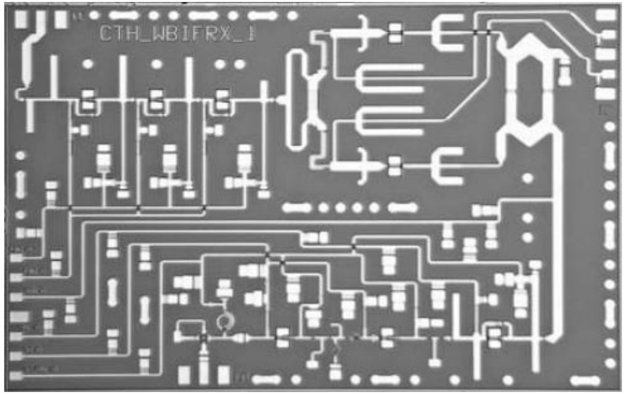
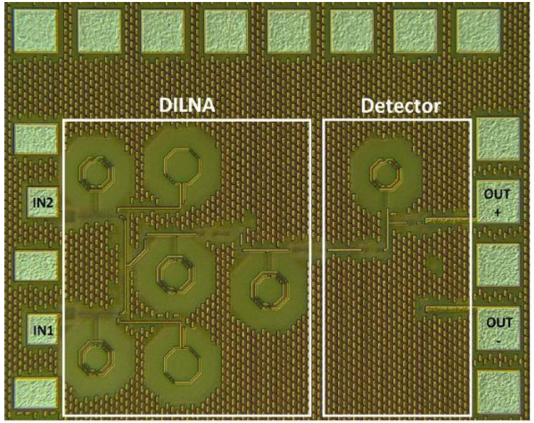
MMIC integration

- Single-chip
  - DDR or TPR
- Typically for space, passive imaging





Gunnarsson et al, RWS2018
Aluigi et al, IEEE Trans CAS 64(12)

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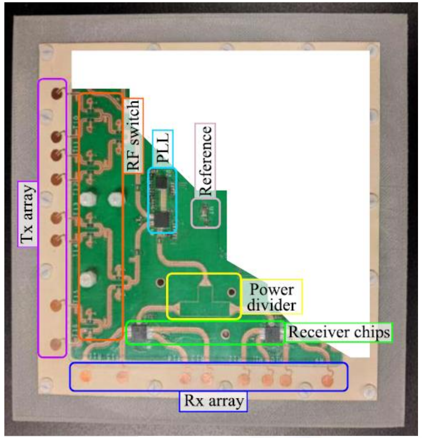
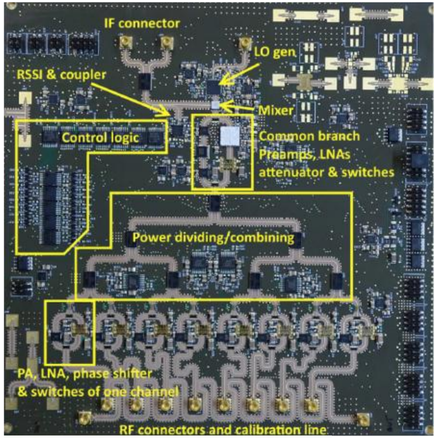
New developments

Development opportunities

- RF PCB integration?
  - Common for SatCom, RADAR
- Get away from isolators?
- Get away from calibrated noise sources?
- Get away from tip curve motors?





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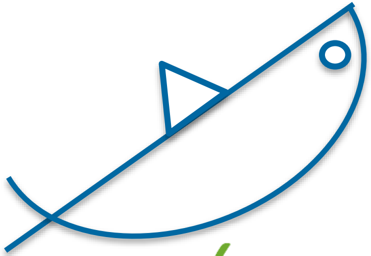
PILCHARD

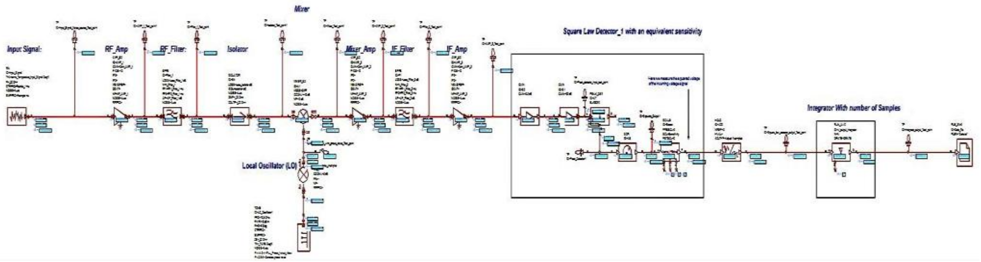
- Planar Integrated Low-Cost H_2O Atmospheric Radiometric Detector
  - In keeping with Hirax, CBASS, MeerKAT…

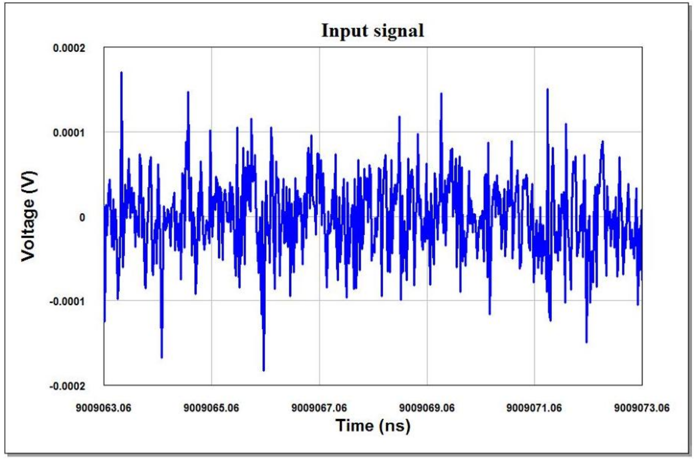


Small	✓	✓
Cheap	✓	✓
Anyone's first choice	✗	✗
Gets the job done	✓	?

Systems modelling (1)

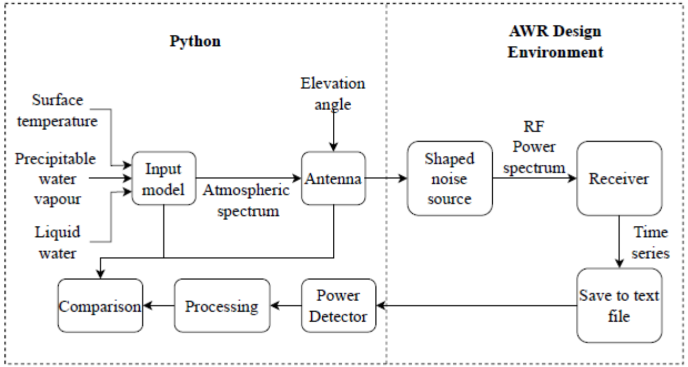
- Use RF system simulator
  - Single UI, environment
  - Easy component checking
  - DR, BW, NF, $\mathscr{L}$
  - Integration time
- Model T_{amb} variation
- Different topologies
  - DDR, TPR, Dicke, noise adding

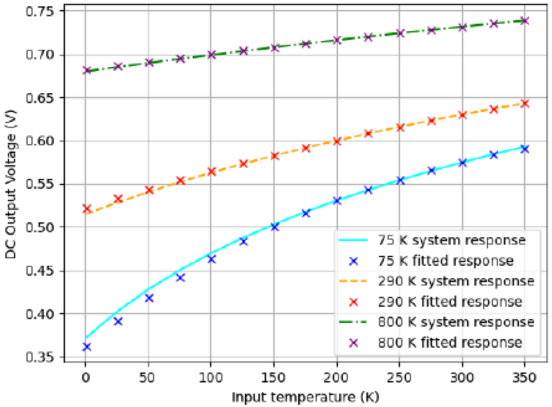




Systems modelling (2)

- Combine RF system with atmosphere / calibration
- Used for trade-off studies
  - Linearity vs. responsivity
  - Error sources in calibration
    - Tsys
    - Elevation pointing error
    - Finite beamwidth





Sources: Neate & Stander, IEEE RADIO 2023

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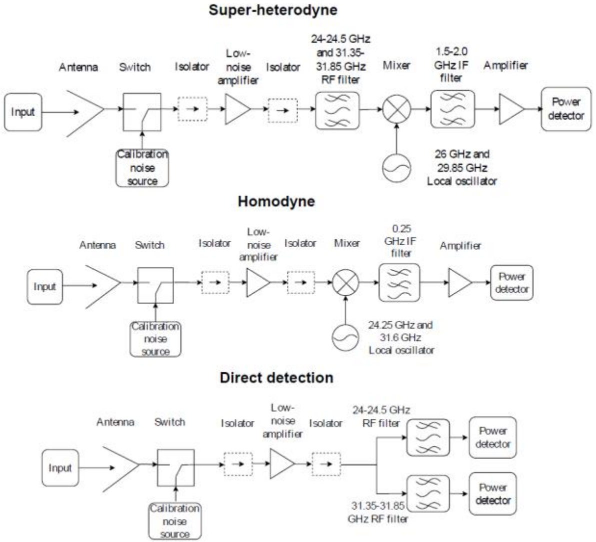
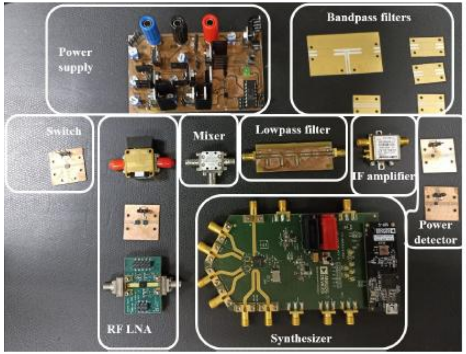
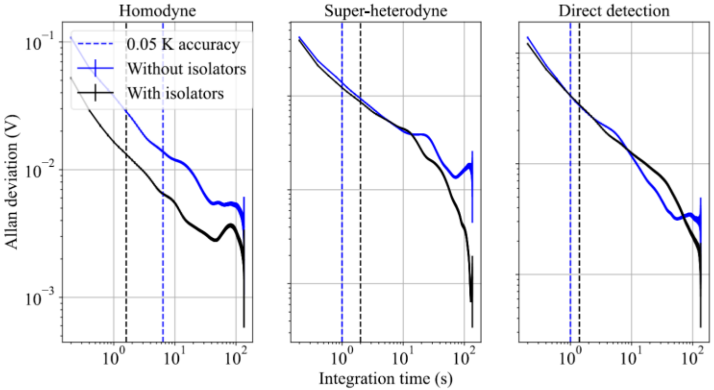
Systems investigation

- Modular building blocks, reconfigured
- Consider DDR, homodyne, heterodyne
- Consider inclusion / omission of isolator
- Findings:
    - Isolator doesn't improve integration time for heterodyne, DDR
    - DDR performs good enough!
        - No mixers, synth



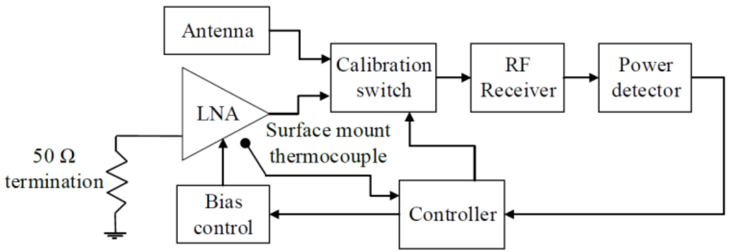


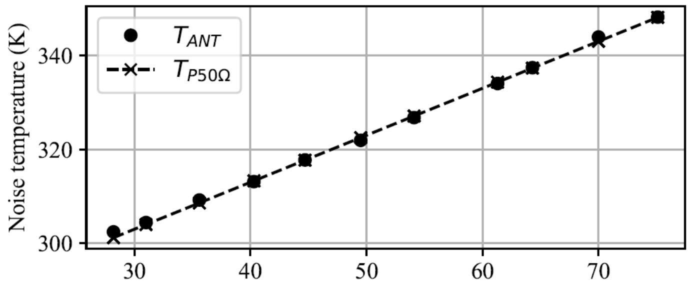


Sources: Neate & Stander, SPIE Astronomical Telescopes + Instrumentation 2024

New calibration paradigms

- Use SMD thermometer as reference
- Noise varied by bias control, LNA amplifies thermal load
- No ENR calibration tables
- No tip curves, moving mirrors
- Use iterative approximation
- Results:
- < 0.43K error maintained over 25 – 80 C





Sources: Neate & Stander, IEEE MWTL 2024

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