Forest Fire Detection by Low-Cost 13GHz Radiometer

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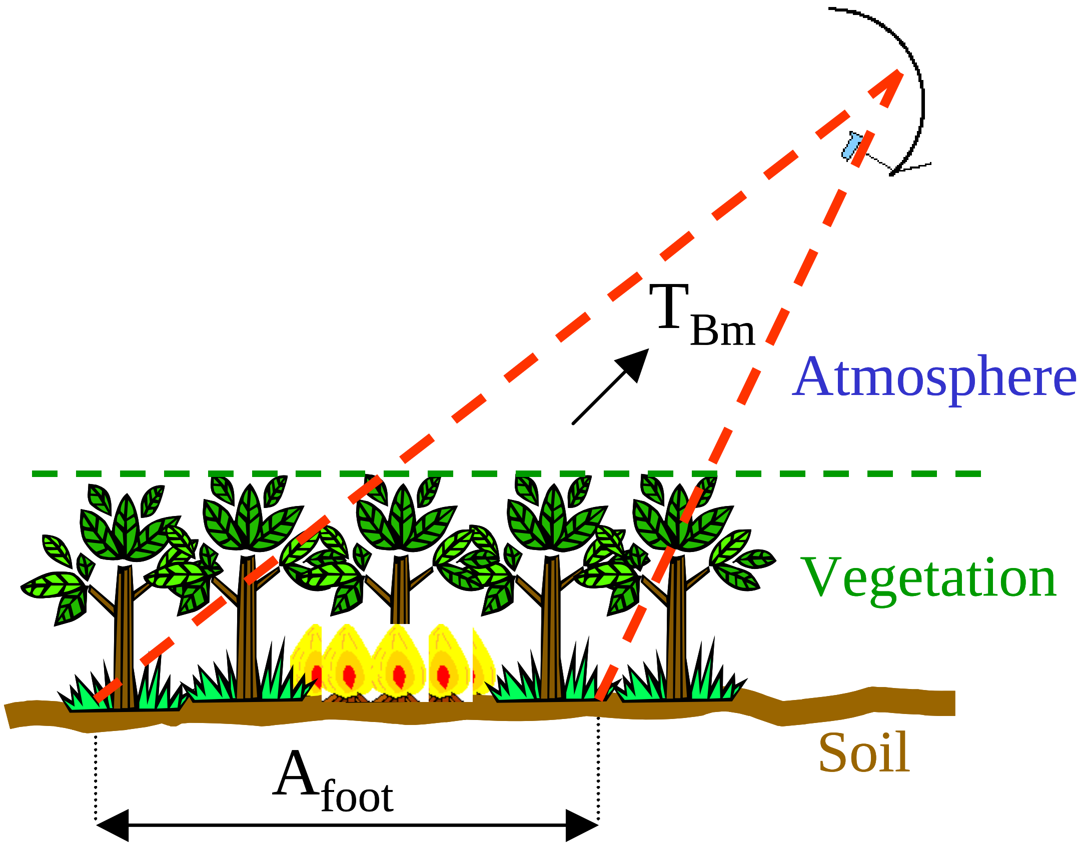
Summary

- Introduction
- Principle of operation
- Sensor architecture
- Radiometer calibration
- Fire experiments
- Conclusions

Introduction

- Microwaves have the inherent capability to penetrate layers of insulating or low-conductivity materials which are non-transparent at optical or infrared frequencies. This property can be exploited to detect fires in forest environment, when they are masked by the vegetation.
- To suit this application, the design of a microwave radiometer must address a number of challenging issues. First, it should be possible to manufacture the sensor at low industrial costs. Secondly such a sensor should feature a good radiometric resolution. Third, the reduction of size, weight and power consumption is very important.
- This talk addresses the detection of forest fires by microwave radiometers. A low-cost sensor has been developed and fire experiments have been successfully carried-out.

Principle of operation (model)



- Scanning antenna mounted over an observation tower.
- Fire up to 1000K.
- Soil and vegetation contributions.
- Filling factor q defined as the ratio between fire area and antenna footprint area.

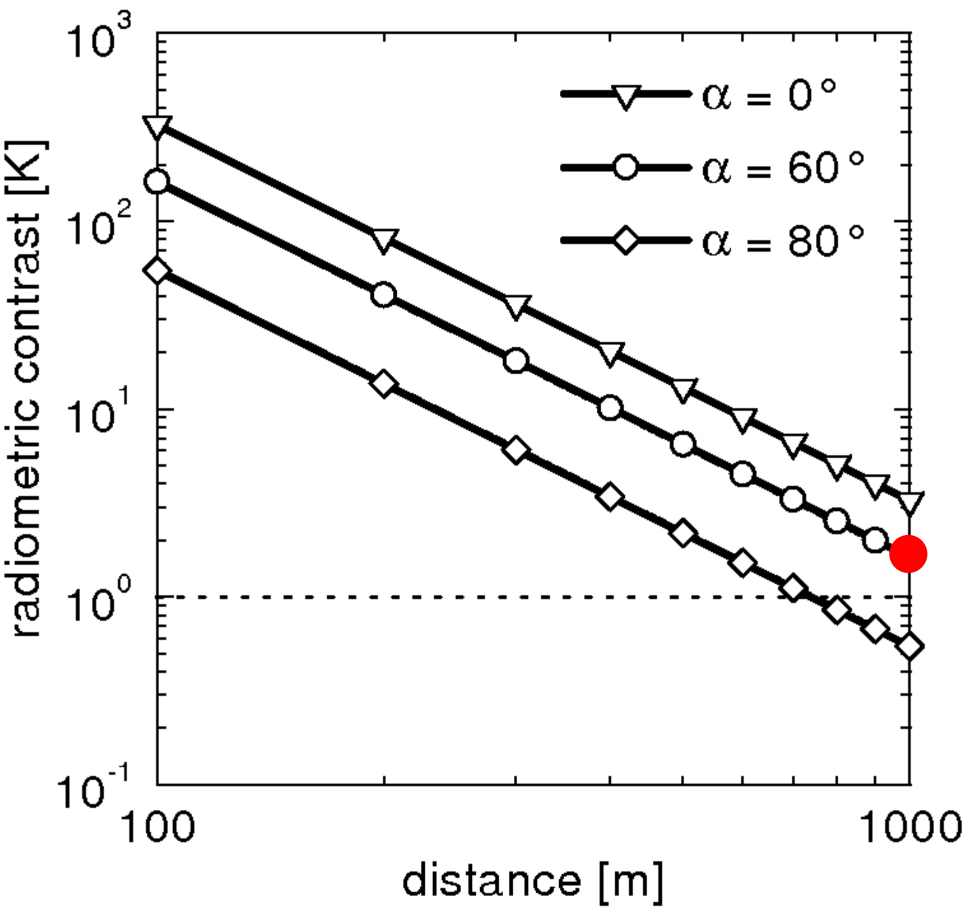
Principle of operation (equations)

- Radiometric contrast (ρ_T) defined as the difference between the brightness temperature in presence of fire with respect to that of the background (soil and vegetation).

$$\rho_T = \left[e_F T_F - e_S T_S - (e_F - e_S) e_V T_V \right] \cdot t_V \cdot t_a \cdot q$$

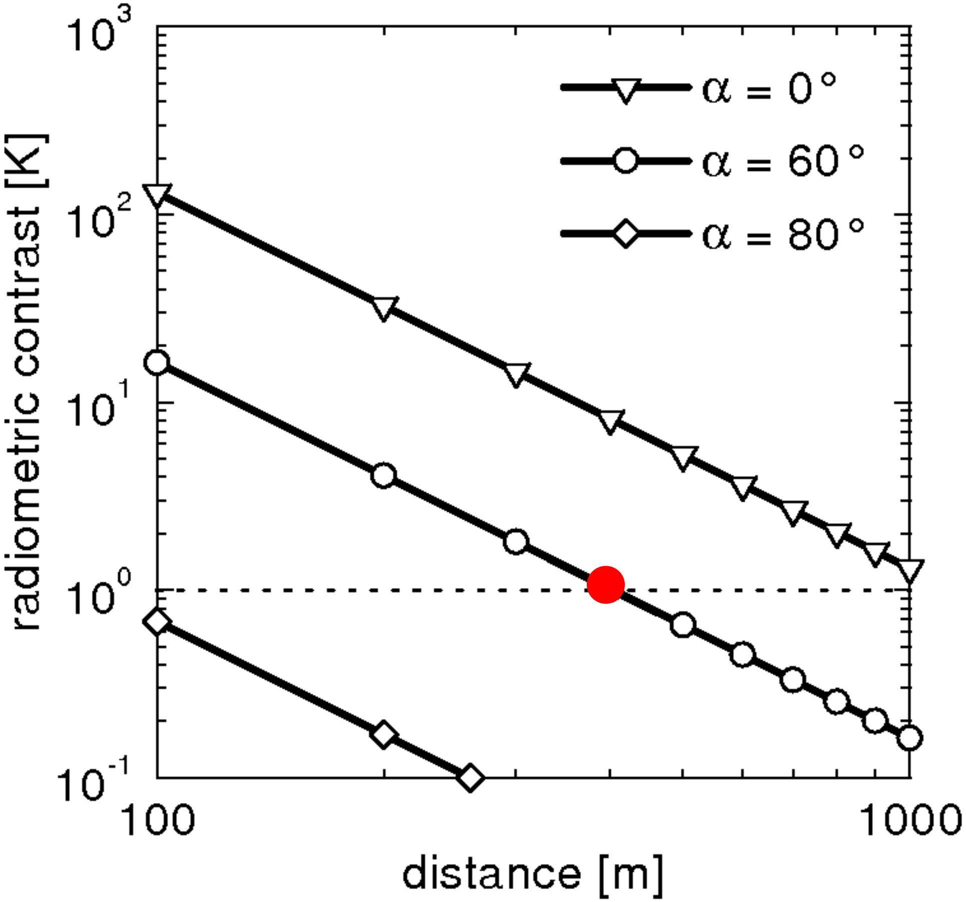
- In the formula the filling factor is $q=A_{fire}/A_{foot}$ while physical temperature, emissivity (e) and transmittance (t) are:
  - ✓ fire (T_F, e_F);
  - ✓ bare soil (T_S , e_S);
  - ✓ vegetation (T_V , e_V , t_V);
  - ✓ atmosphere (t_A).

Principle of operation (maximum range)



- 12.65GHz; 10m^2 fire area; 1000K glowing temperature.
- 37dBi antenna gain: 3° HPBW; 60cm TV-SAT dish with 69% efficiency.
- Threshold equal to the radiometric resolution: about 1K.
- 1km range.

Principle of operation (effect of vegetation)



- Dense Canadian forest: tv=0.4
- 12.65GHz; 10m^2 fire area; 1000K glowing temperature.
- Same antenna and same 1K threshold.
- 0.4km range.

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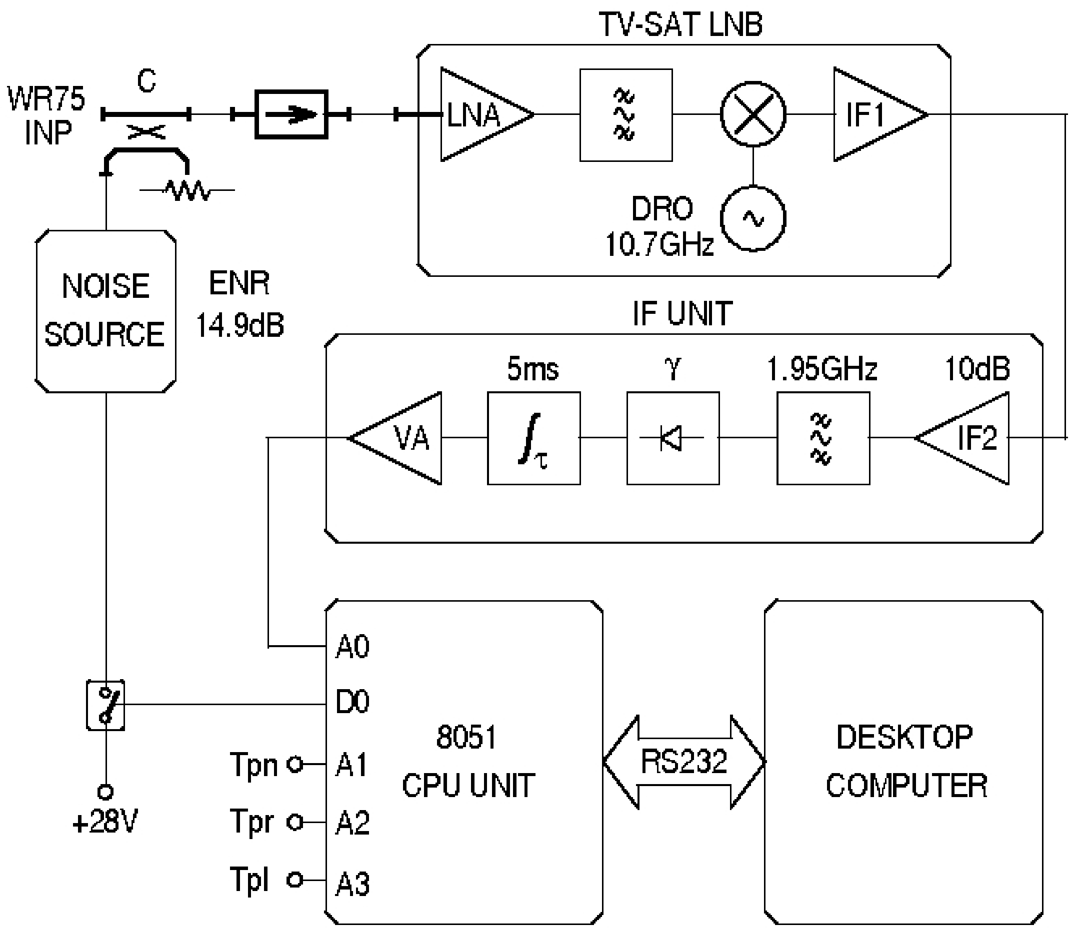
Sensor architecture (schematic)

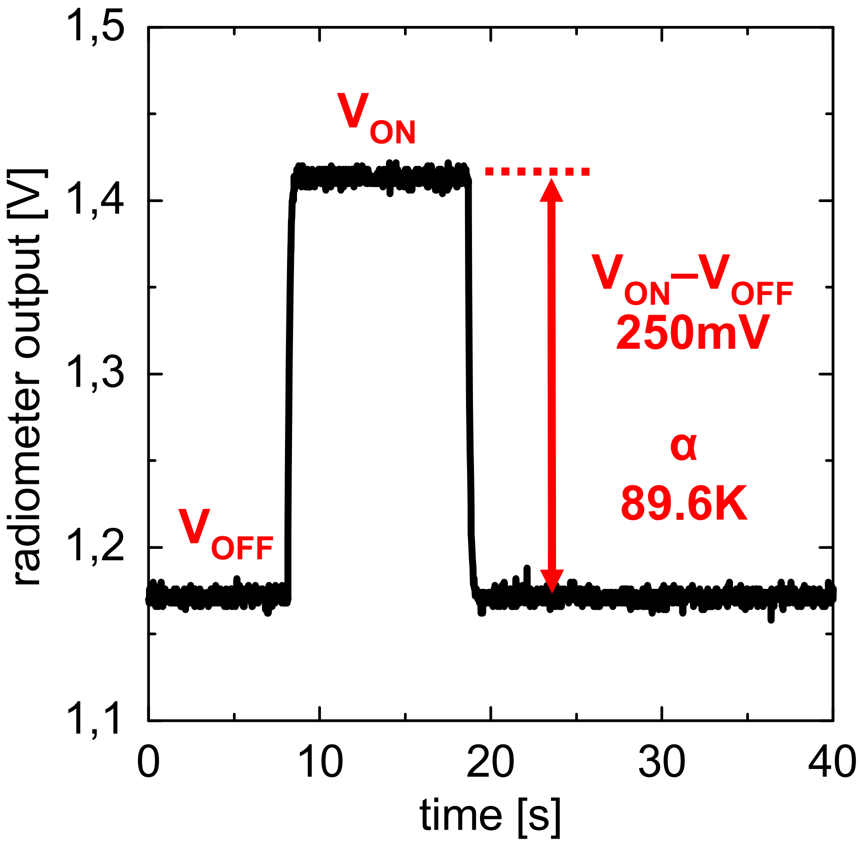


- Continuous gain calibration by noise adding architecture.
- Radiometer offset not corrected (low cost solution).
- Calibration circuit: solid-state noise source and 20dB directional coupler.
- 8051 CPU unit: measurement, calibration, etc.

Sensor architecture (antenna)

- 60cm offset dish antenna for TV-SAT applications.
- 3dB (half-power) beam-width: 3°.
- Antenna gain equal to 37dBi.
- Antenna efficiency equal to 69%.
- Offset angle: 22°.

Sensor architecture (retrieval equations)



scale factor 0.36K/mV

- Antenna temperature T_A retrieved by noise-adding equations:

$$T_A = \alpha \cdot Y - \beta$$

$$Y = \frac{V_{OFF}}{V_{ON} - V_{OFF}}$$

$$\alpha = C \cdot T_0 \cdot ENR$$

$$\beta = T_{REC} + C \cdot T_0$$

- α and β related to system and receiver parameters.

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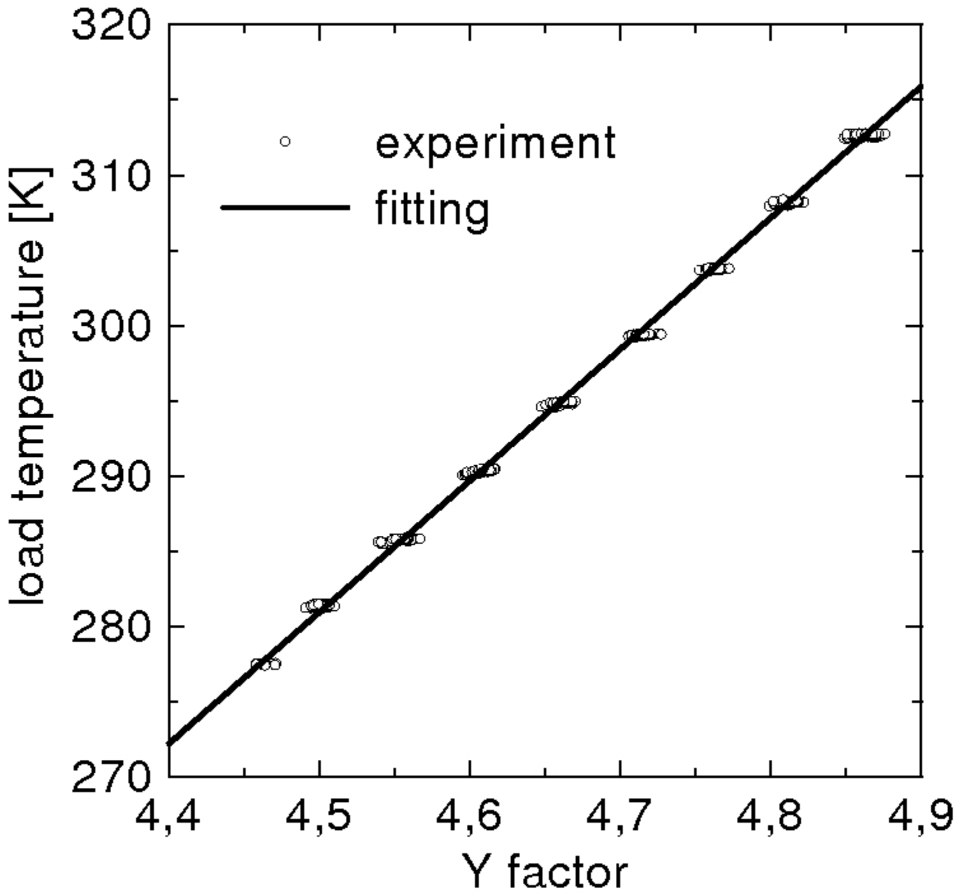
Radiometer calibration (waveguide load)

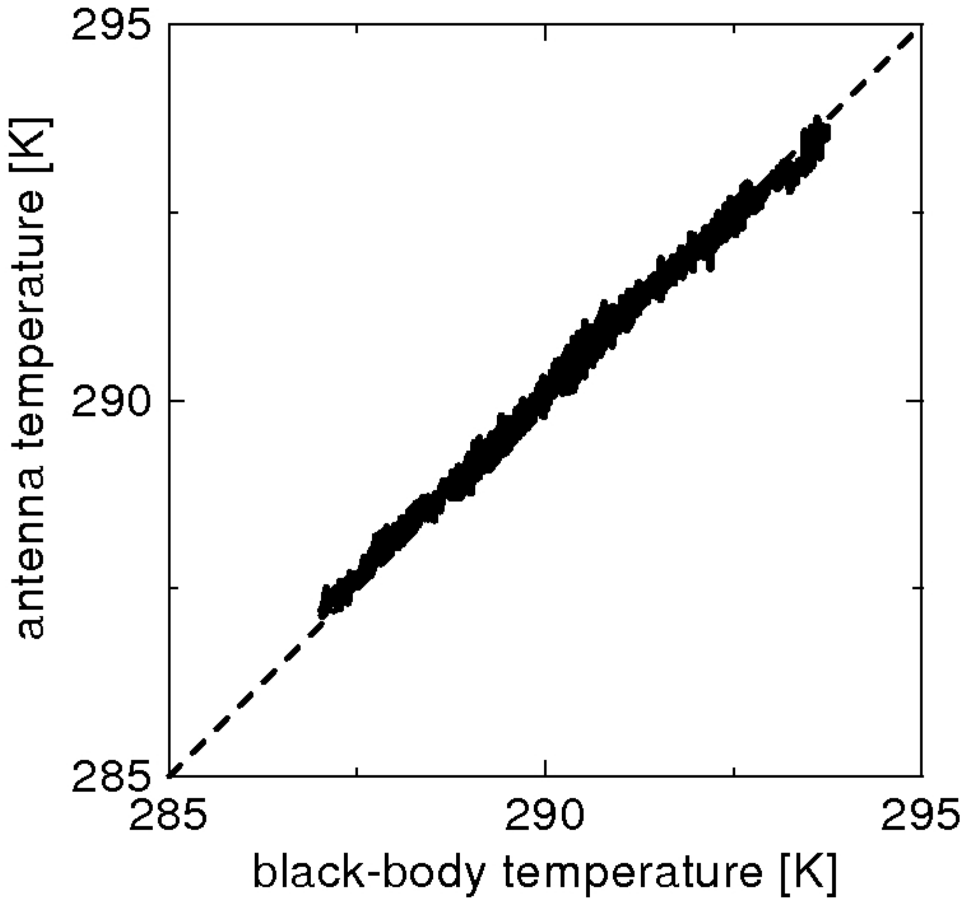


- Receiver terminated with a WR75 load.
- Load inserted into a climatic chamber.
- Temperature swept between 275K and 315K in 5K steps.
- Radiometer constants obtained by fitting.

$$\alpha = 87.4\text{K}$$

$$\beta = 112.4\text{K}$$

Radiometer calibration (black body)

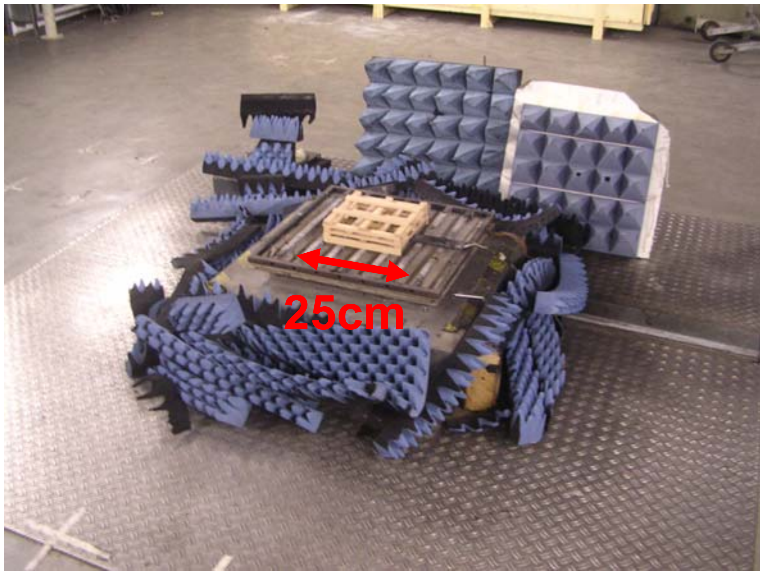


- Receiver connected to a 15dBi standard gain horn antenna.
- Antenna pointed toward a black-body (broadband pyramidal absorber) .
- Radiometer offset increased by 4K due to antenna mismatch.

$$\beta = 116.4\mathrm{K}$$

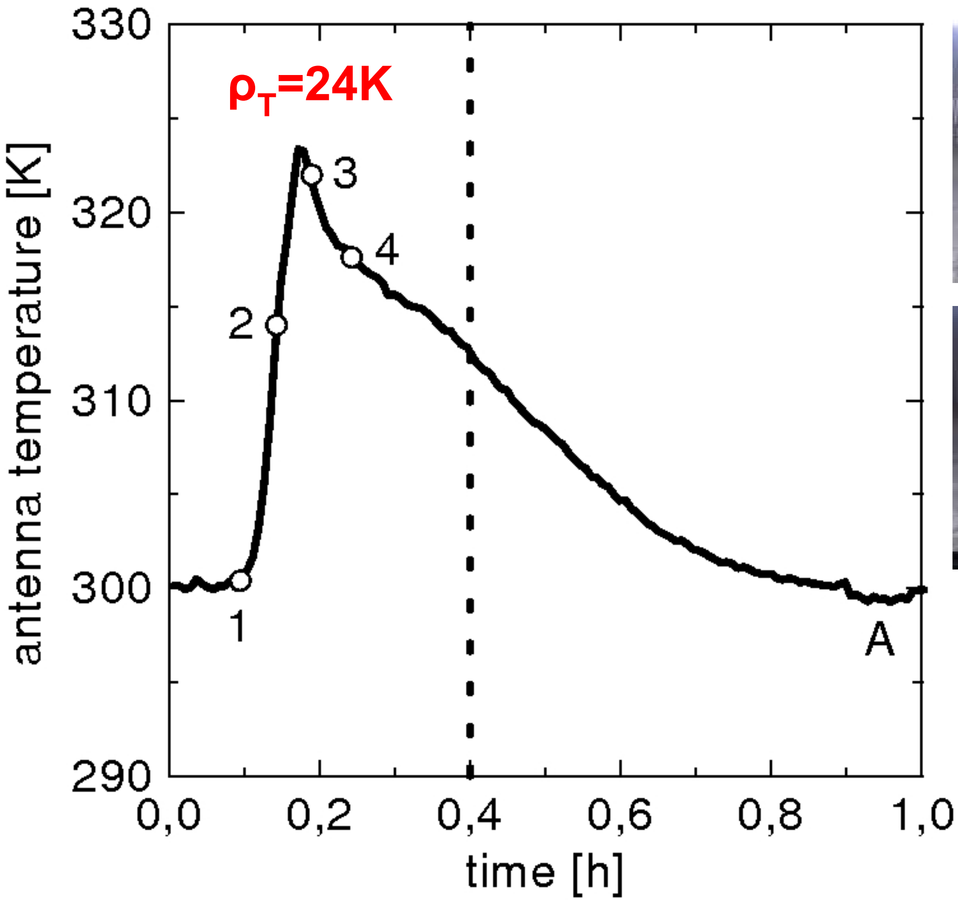
Fire experiments (laboratory)

radiometer



- Antenna to fire distance 2m; modified TF1 with 21 beechwood sticks; fire side 25cm; 15dBi standard gain horn; HPBW 30°; incidence angle 58°; filling factor 2.7%; estimated fire temperature 1100K; soil temperature 302K; vertical polarization.

Fire experiments (laboratory)

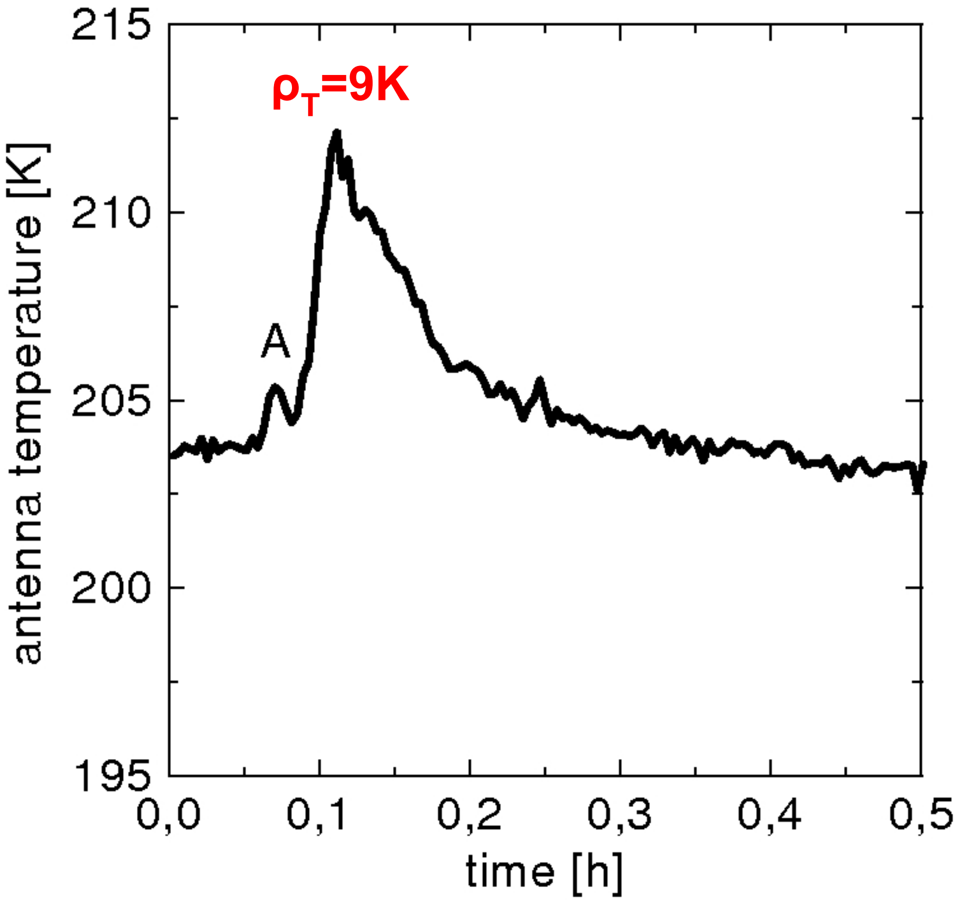


- Maximum microwave emission associated to embers.

Fire experiments (open-space)

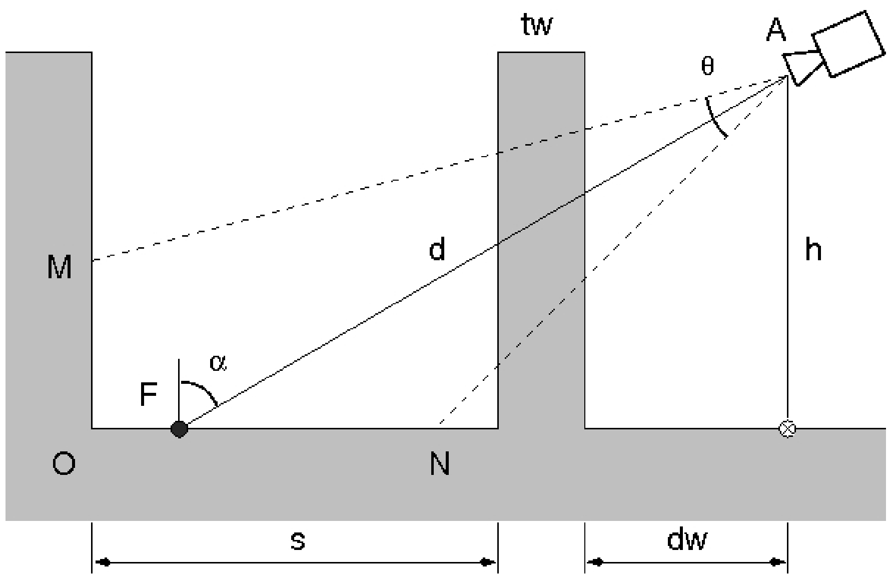
- Antenna to fire distance 31m; fire diameter 50cm; TV-SAT dish antenna; HPBW 3°; incidence angle 84°; filling factor 0.9%; estimated fire temperature 1100K; soil temperature 298K; horizontal polarization.

Fire experiments (open-space)



- The fire has been clearly detected with radiometric contrast of about 9K.
- The point A in the graph is due to the operators crossing the antenna beam.

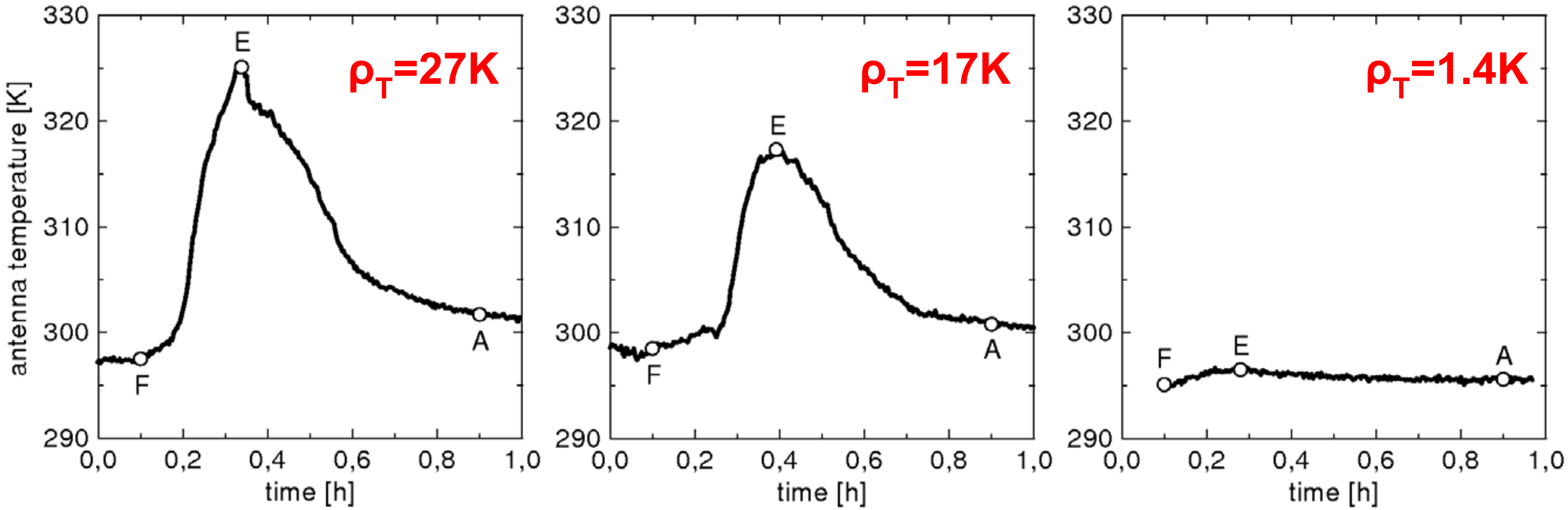
Fire experiments (obstacle penetration)



- Obstacle penetration capabilities studied in indoor environment with walls of concrete material.
- Scene sensed with the 15dBi standard gain horn antenna; vertical polarization.
- Antenna to fire distance 2.4m; incidence angle 78°; fire side 25cm.

Fire experiments (obstacle penetration)

wall thickness 12.5cm



no wall	**plasterboard wall**	**concrete wall**
filling factor 3.2%	**112kg/m^3**	**2063kg/m^3**

- Microwaves can penetrate obstacles such as wall of buildings that completely mask optical or IR sensors. Obstacle transmissivity is related to bot material conductivity and mass density.

Conclusions

- This work experimentally demonstrates that forest fires with filling factors below 1% can easily be detected by 13GHz radiometers. Obstacles of different nature can also been penetrated.
- The maximum microwave emission is related to the embers whereas the flame has never been detected. The mass density of the embers is around 700kg/m^3 and their peak temperature is in excess to 1000K.
- System simulations with a 60cm dish antenna, give a maximum range of about 1km without vegetation and of about 400m with vegetation.
- A microwave radiometer has customarily been developed for fire detection. It features a component cost of about $1800 and can operate at ambient temperature (I.e. saving the electrical power needed by a thermal control unit) with a stability of about 2K.

Acknowledgements

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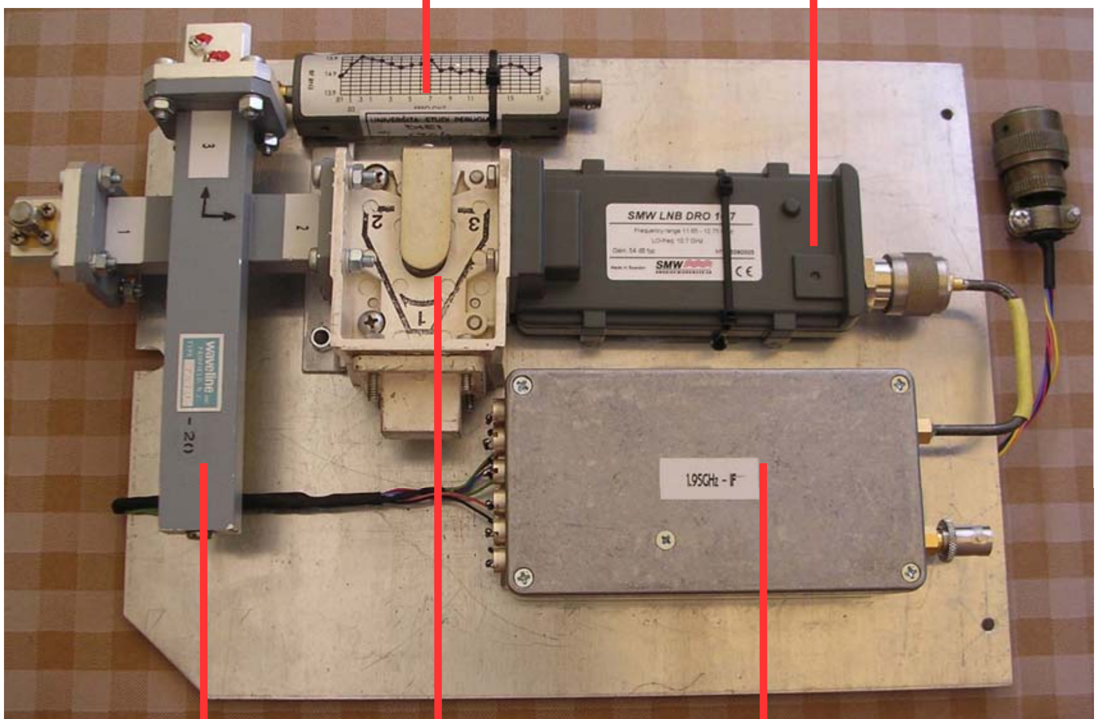
Sensor architecture (receiver)

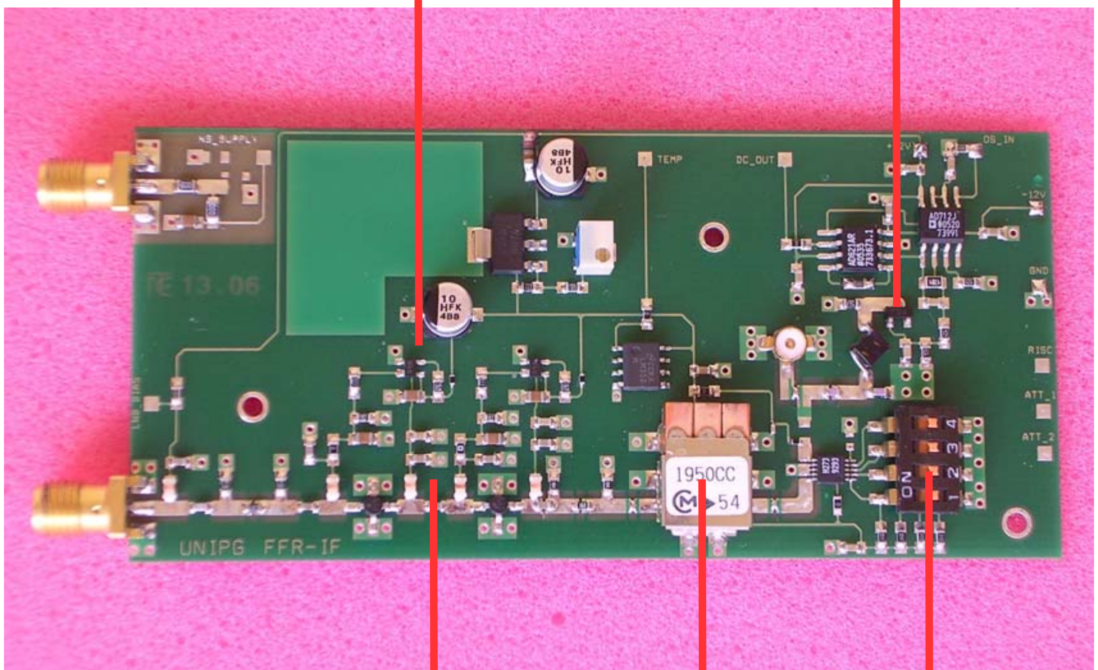


- TV-SAT low-noise block (LNB) used as microwave down-converter.
- 12.65GHz input in WR75 waveguide.
- 10.70GHz local oscillator (DRO).
- 1.95GHz IF with 100MHz noise bandwidth.
- 8051 CPU unit with 10bit ADC not shown in the figure.

Sensor architecture (custom IF)

active bias circuitry

square-law detector



2-stage amplifier

1.95GHz filter

digital attenuator

- Two stages IF amplifier (SGA4486) working at 1.95GHz.
- Noise bandwidth determined by a 3-cells ceramic filter.
- Schottky diode square-law detector with 7mV/μW sensitivity (narrow-band design).
- Fine control of the IF (receiver) gain by digital attenuator.

Sensor architecture (measurement cycle)

state 1 integrate V_{OFF} for τ seconds, go to state 2;

state 2 switch ON the noise source and wait Δt seconds in order to let the transients to vanish, go to state 3;

state 3 integrate V_{ON} for τ seconds, go to state 4;

state 4 switch OFF the noise source and wait Δt seconds in order to let the transients to vanish, in the mean time evaluate the Y factor, go to state 5;

state 5 wait Δt seconds - free measurement slot for internal use, go to state 6;

state 6 measure the physical temperture T_{pr} of the LNB for Δt seconds, go to state 7;

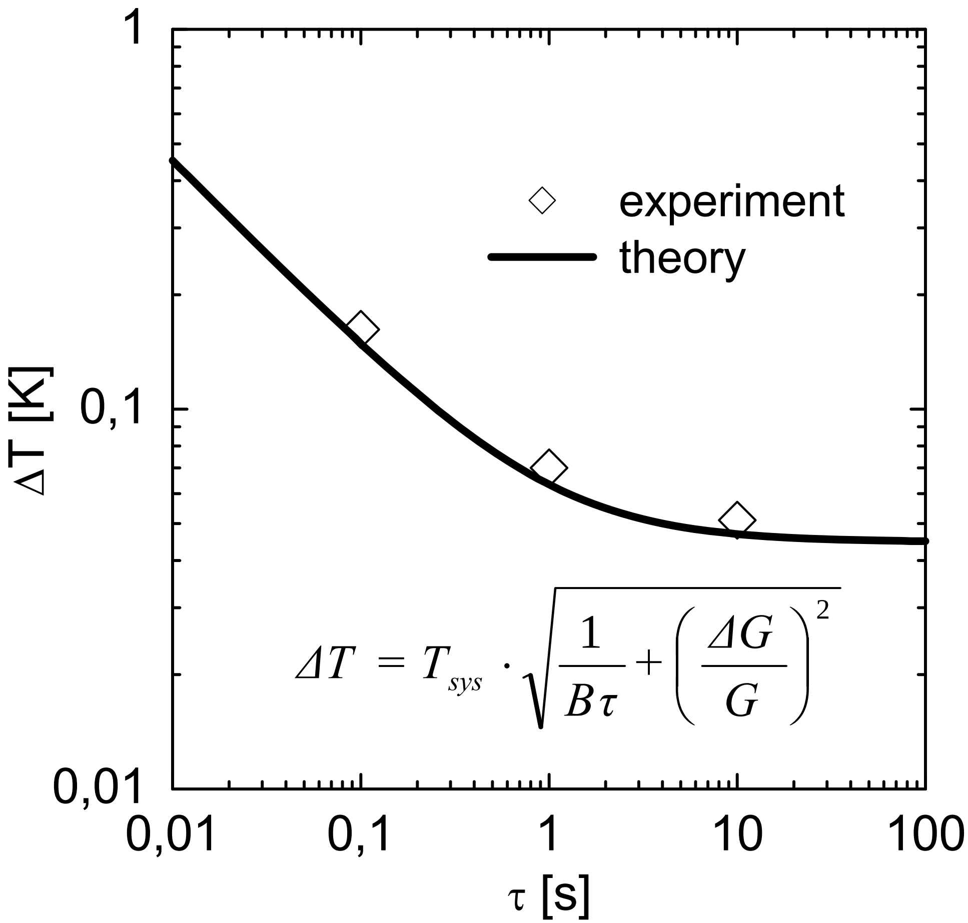
state 7 measure the physical temperture T_{pn} of the noise source for Δt seconds, go to state 8;

state 8 measure the external temperture T_{pl} for Δt seconds, go to state 9;

state 9 wait Δt seconds, in the mean time evaluate T_B and upload all the measured data to the desktop computer via RS232 serial connection, return to state 1;

- Integration for τ seconds performed numerically by the CPU.
- τ set to 1s.
- Δt set to 0.1s
- Temporal duration of each measurement cycle equal to 2.7s.

Radiometer calibration (sensitivity)



- Sensitivity measured as a function of the integration time τ with the radiometer in total power mode.
- ΔT=70mK for τ=1s.
- Agreement between experiment and theory for T_{sys}=400K and ΔG/G=1.3x10^{-4}.

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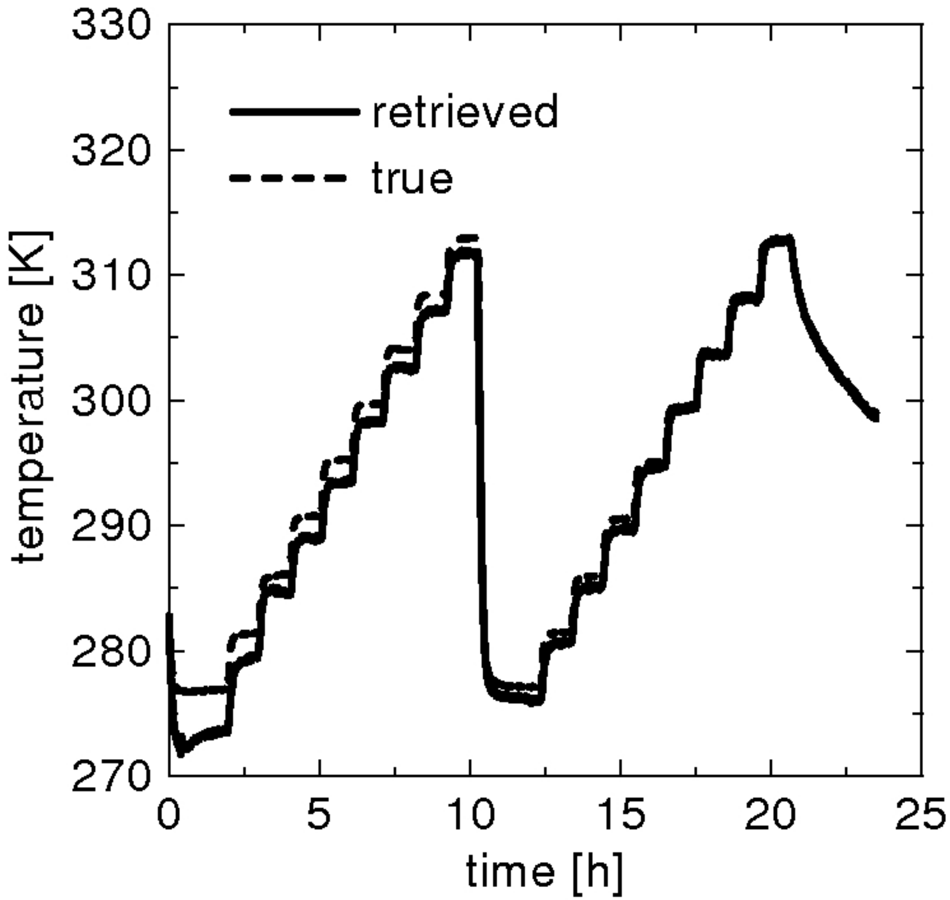
Radiometer calibration (waveguide load)



- Climatic chamber results versus time.
- Comparison between antenna and physical (WR75 load) temperature.
- Maximum error between brightness and physical load temperature ~2K after the transient.