TROPPO
A Tropospheric Propagation Simulator

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Overview

- Calculation of microwave propagation losses through the troposphere and lower stratosphere.

- A wealth of detailed literature and software tools exists for calculating losses in geometries which are characteristic of terrestrial satellite and point to point links, and surface based radar installations.

- The more general case is less frequently addressed.

- Need arose in modelling properties of airborne ad hoc networks.

- Tool is adaptable for microwave radar propagation studies.

- Developed for use in libraries or as standalone tool.

- Computational speed was an issue and addressed.

Generalised Propagation Geometries
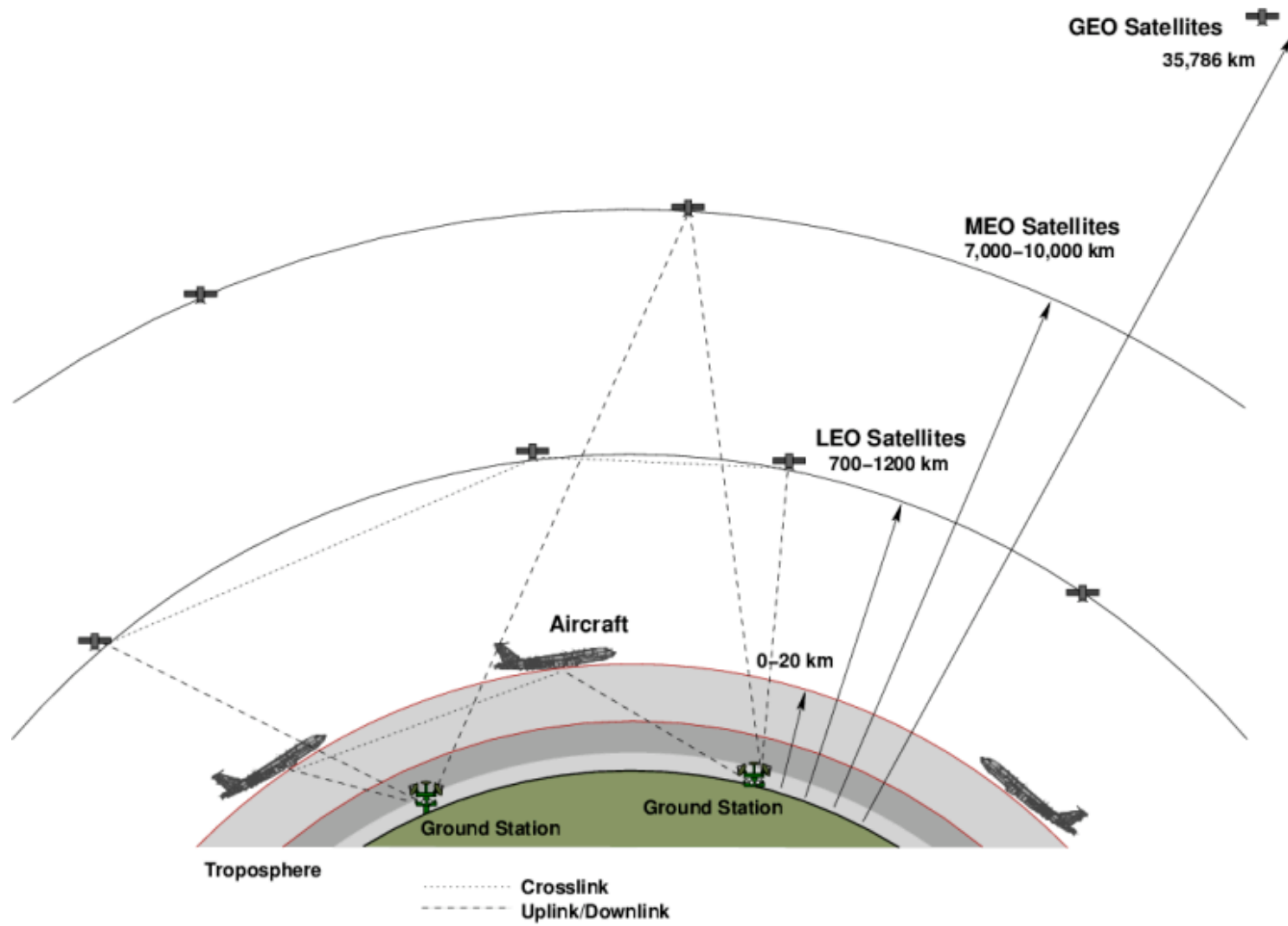
TROPPO Capabilities

- TROPospheric PrOpagation simulator tool (TROPPO), implements a general propagation model for stations with arbitrary altitudes up to the lower stratosphere.

- TROPPO solves:

  - **Nonlinear refractive ODE boundary value problem, using two algorithms;**

  - **Several models for variations of pressure and water vapour density with altitude;**

  - **Water vapour and oxygen resonances;**

  - **Cloud droplet scattering;**

  - **Rain absorption loss;**

  - **lens effect loss;**

  - **The Friis pathlength loss**

- Receiver SNR and link Shannon capacity are calculated.

Design Issues

- Modularity - to allow the incorporation of alternative models for specific propagation effects. Provisions were made for selection of some alternative models in the code.
- Two primary operating modes:
  1. **'point'** mode - simulator calculates the specific attenuation for a point at a given altitude, for a given set of atmospheric conditions.
  2. **'path'** mode - simulator traces the ray path, and then invokes itself in '**point'** mode to calculate the cumulative propagation impairments for each of the internal models.
- Parameters and calculated values are passed to and from the simulator using a large C language structure.
- This was intended to facilitate the addition of parameters as required, and proved to be useful in the latter stages of development.
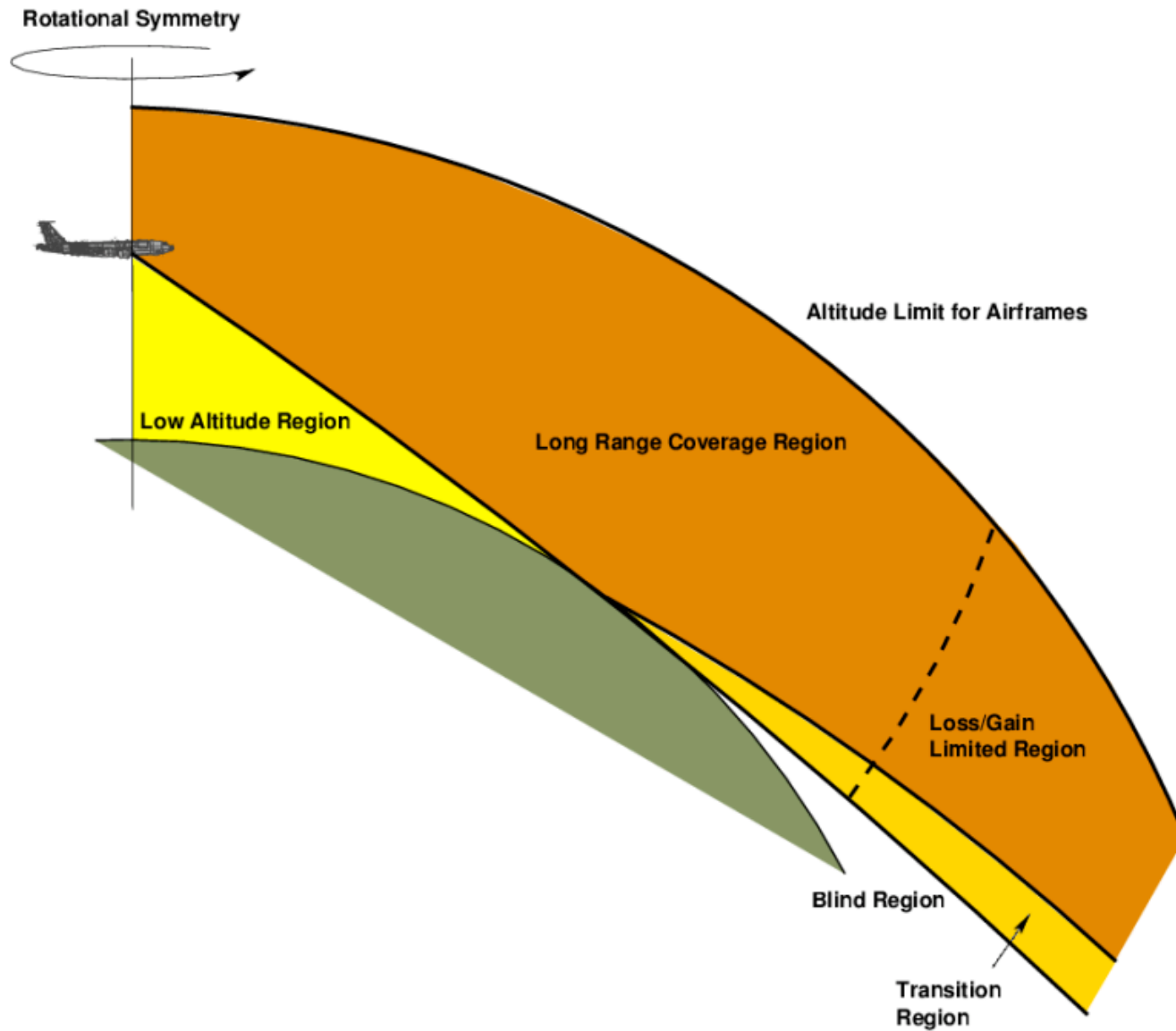
Airborne Ad Hoc Network Geometries
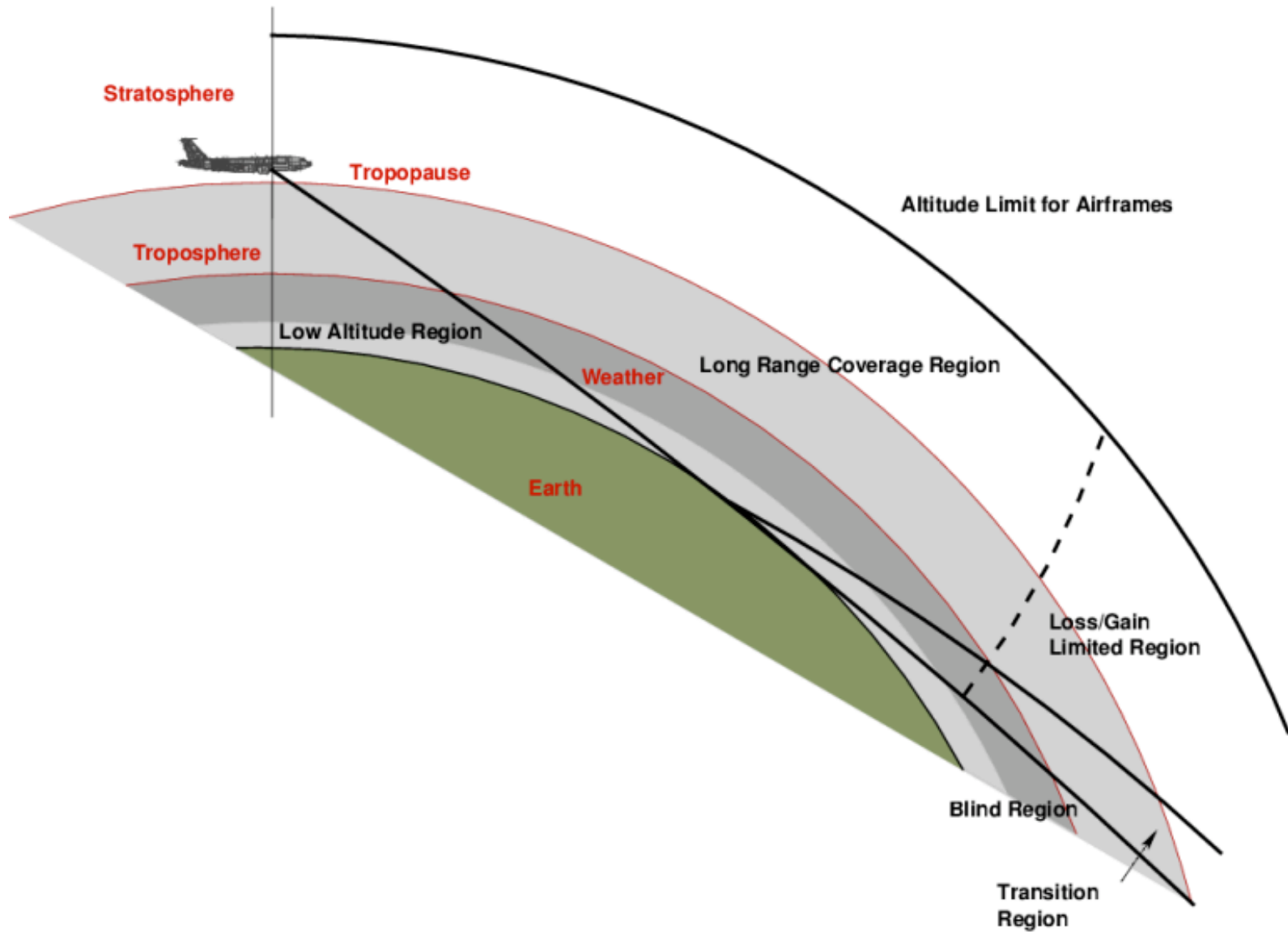
Airborne Ad Hoc Network Propagation Regions

Atmospheric Models / Temperature Profile

- The atmospheric model is divided into three components;

- These calculate the variations of temperature, pressure and water vapour density against altitude;

- The temperature and pressure models at this time conform to the basic ICAO ISA atmospheric model;

- Absolute temperature T [K] is approximated as a piecewise linear function of geopotential altitude h_g [km], defined as:
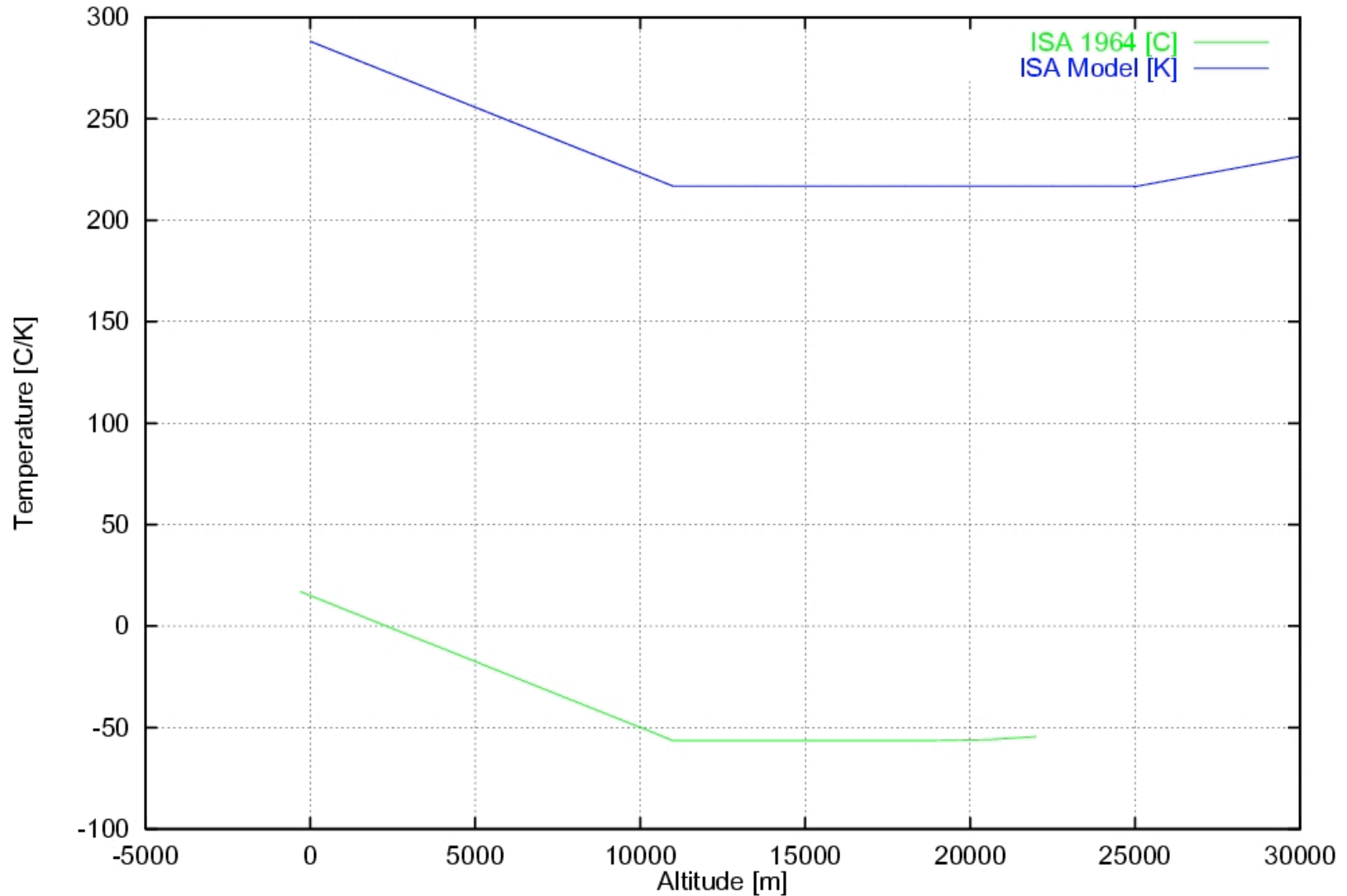
  $T = 288.16 - 6.5h_g$ for $h_g \leq 11$

  $T = 288.16$ for $11 < h_g \leq 25$

  $T = 216.66 + 3.0 (h_g - 25.0)$ for $h_g > 25$

ISA Temperature Profile Model

Atmospheric Pressure Profile Model

- The model for pressure [hPa] variation with altitude is more complex than the temperature

- model, and uses the previously computed temperature variation with altitude:

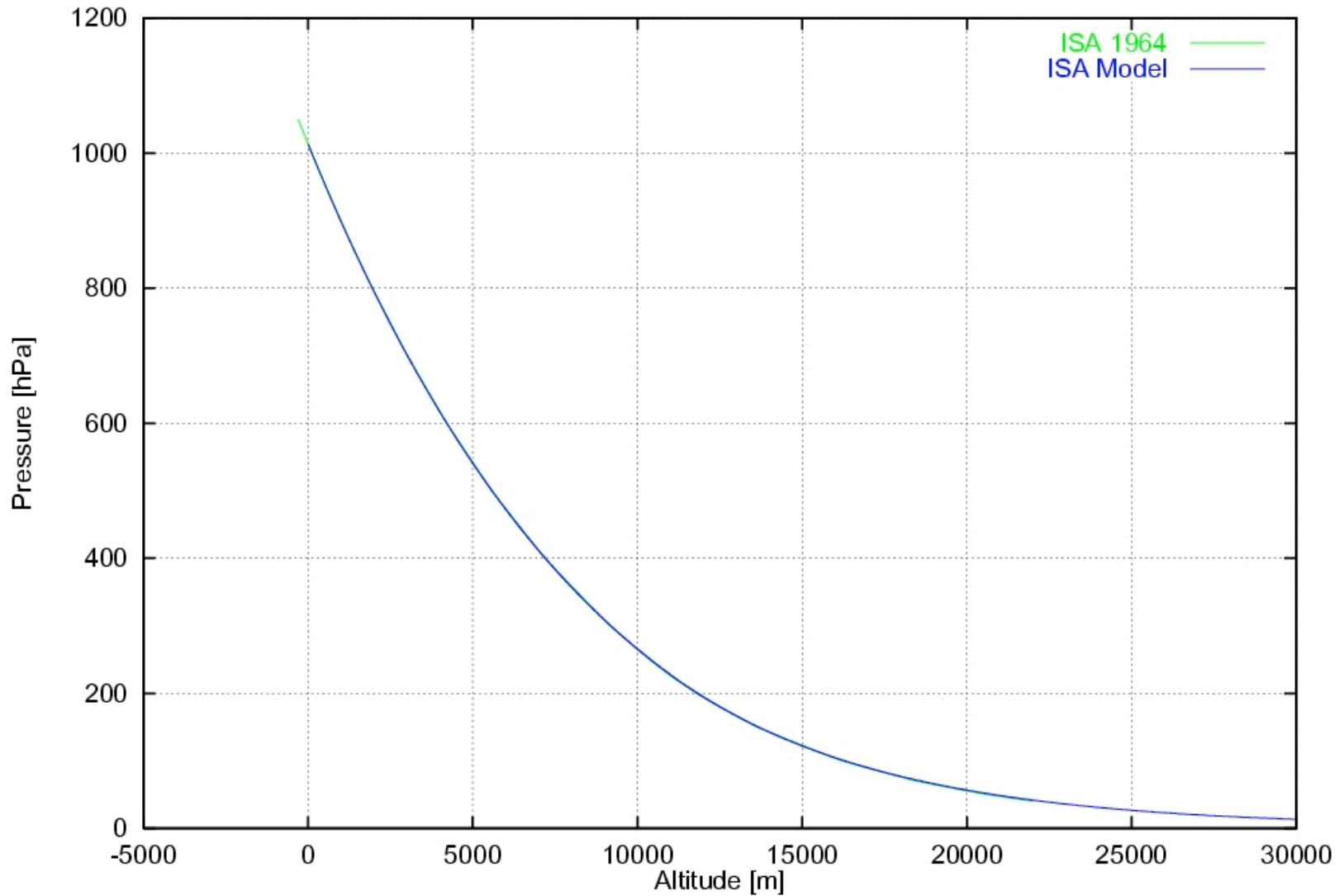$$p = 1013.25 \left(\frac{T}{288.16}\right)^{\alpha} \quad for\ h_g \quad \leq \quad 11$$

$$p = 266.128\, e^{-\beta(h_g - 11)} \quad for\ 11 \quad < \quad h_g \quad \leq \quad 25$$

$$p = 24.886 \left(\frac{216.66}{T}\right)^{\gamma} \quad for\ h_g \quad > \quad 25$$

- Where α = 5.256122, β = 0.157499 and γ = 11.388265.
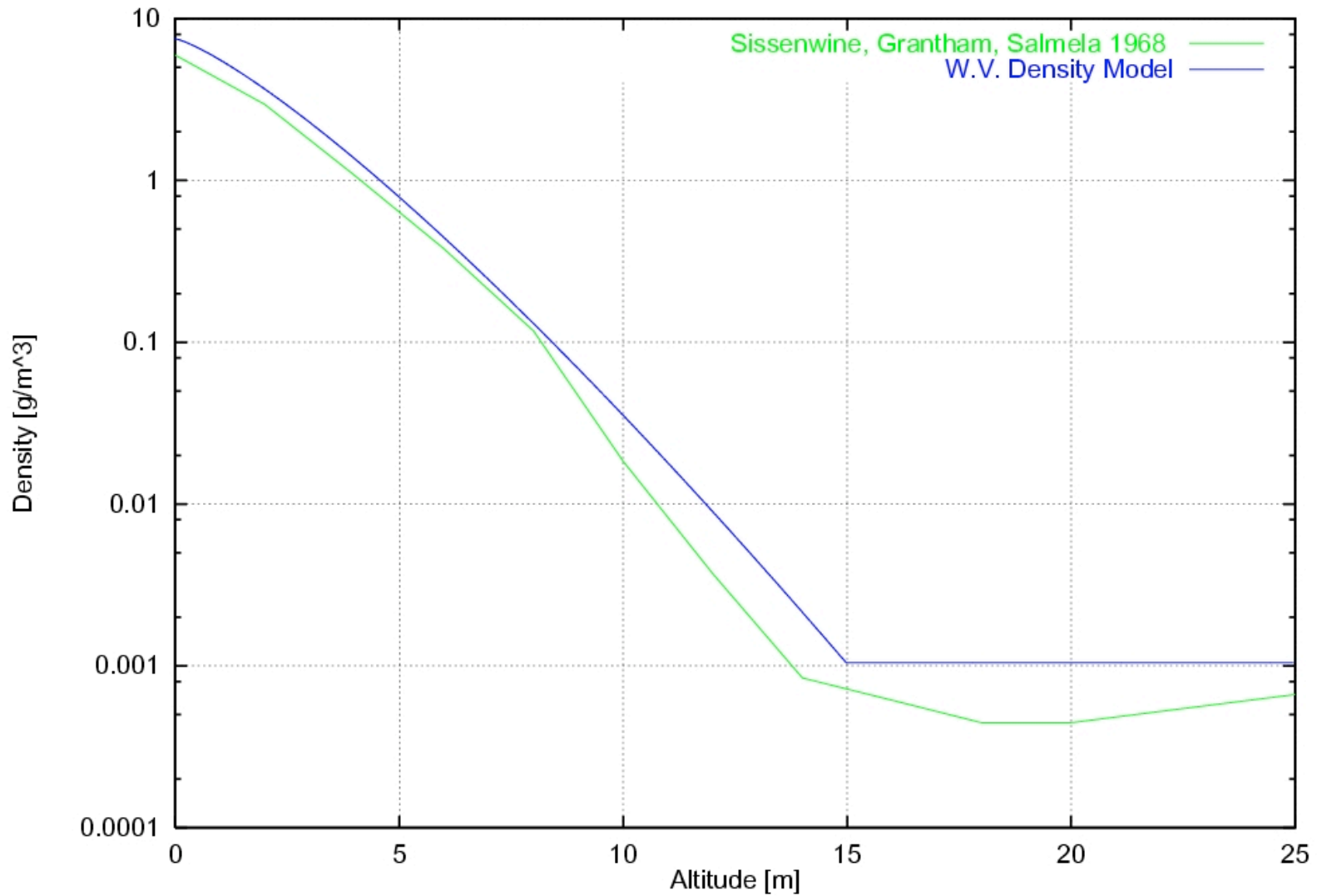
ISA Atmospheric Pressure Model

Water Vapour Density Profile Model

- The water vapour density model was produced by fitting a function to an empirical dataset. The resulting expression relating water vapour density to its sea level value and geopotential altitude is:

$$\rho_{WV} = \rho_{WVSL} \, e^{-\frac{1}{2}(\frac{2h_g}{3})^{\frac{5}{2}}} \qquad f\,or\,h_g \leq \quad 15$$

Water Vapour Density Profile Model

Water Vapour Absorption Model

$$p_T = 0.75\,p$$

$$p_{WV} = \rho_{WV}\,\frac{T}{288.75}$$

Where pressures are in [torr].

The Van Vleck broadening factor is computed for the frequency, temperature and water vapour partial pressure specified, in two steps:

$$\Delta f = 17.99 \times 10^{-3} \times$$

$$\left(p_{WV}\frac{300}{T} + 0.20846(p_T - p_{WV})\left(\frac{300}{T}\right)^{0.63} \right)$$

Water Vapour Absorption Model

$$F = \frac{f}{f_r} \left(\frac{\Delta f}{(f_r - f)^2 + (\Delta f)^2} + \frac{\Delta f}{(f_r + f)^2 + (\Delta f)^2} \right)$$

The loss rate in dB/km is computed, using the Van Vleck broadening factor and the Liebe equation:

$$\gamma_{22} = 2.53397 \times 10^{-3} f p_{WV} \left(\frac{300}{T} \right)^{\frac{7}{2}} e^{2.144 \left(1 - \frac{300}{T} \right)} F$$

The computation of the residual 100 GHz line losses is simpler, and uses the values of water vapour density, pressure, temperature and frequency:

$$\gamma_{100} = 0.4 \frac{\rho_{WV}}{\rho_{WV\ SL}} \frac{p_T}{p_{SL}} \left(\frac{T_{SL}}{T} \right)^{\frac{5}{2}} \left(\frac{f}{f_r} \right)^2$$

The resulting loss contributions for the 22.235 GHz line and residuals from the 100 GHz lines are then summed to yield the total water vapour loss for the given atmospheric conditions.

$$\gamma_{H_2O} = \gamma_{22} + \gamma_{100} \quad [dB/km]$$

Oxygen Absorption Model

$$\Delta f(h_g) = \frac{p}{p_{SL}} \frac{T_{SL}}{T} g(h_g)$$

where:

$$g(h_g) = 0.640 \quad for \quad 0 < h_g \leq 8$$

$$g(h_g) = 0.640 + 0.04218 \, (\, h_g - 8 \,)$$
$$for \quad 8 < h_g \leq 25$$

$$g(h_g) = 1.357 \quad for \quad 25 < h_g$$

$$\mu_{N0}^2 = \frac{2(N^2 + N + 1)(2N + 1)}{N(N + 1)}$$

Oxygen Absorption Model

The resonant terms are then:

$$F_{N\pm} = \frac{\Delta f}{(f_{N\pm} - f)^2 + (\Delta f)^2} + \frac{\Delta f}{(f_{N\pm} + f)^2 + (\Delta f)^2}$$

$$\mu_{N+}^2 = \frac{N(2N+3)}{N+1}$$
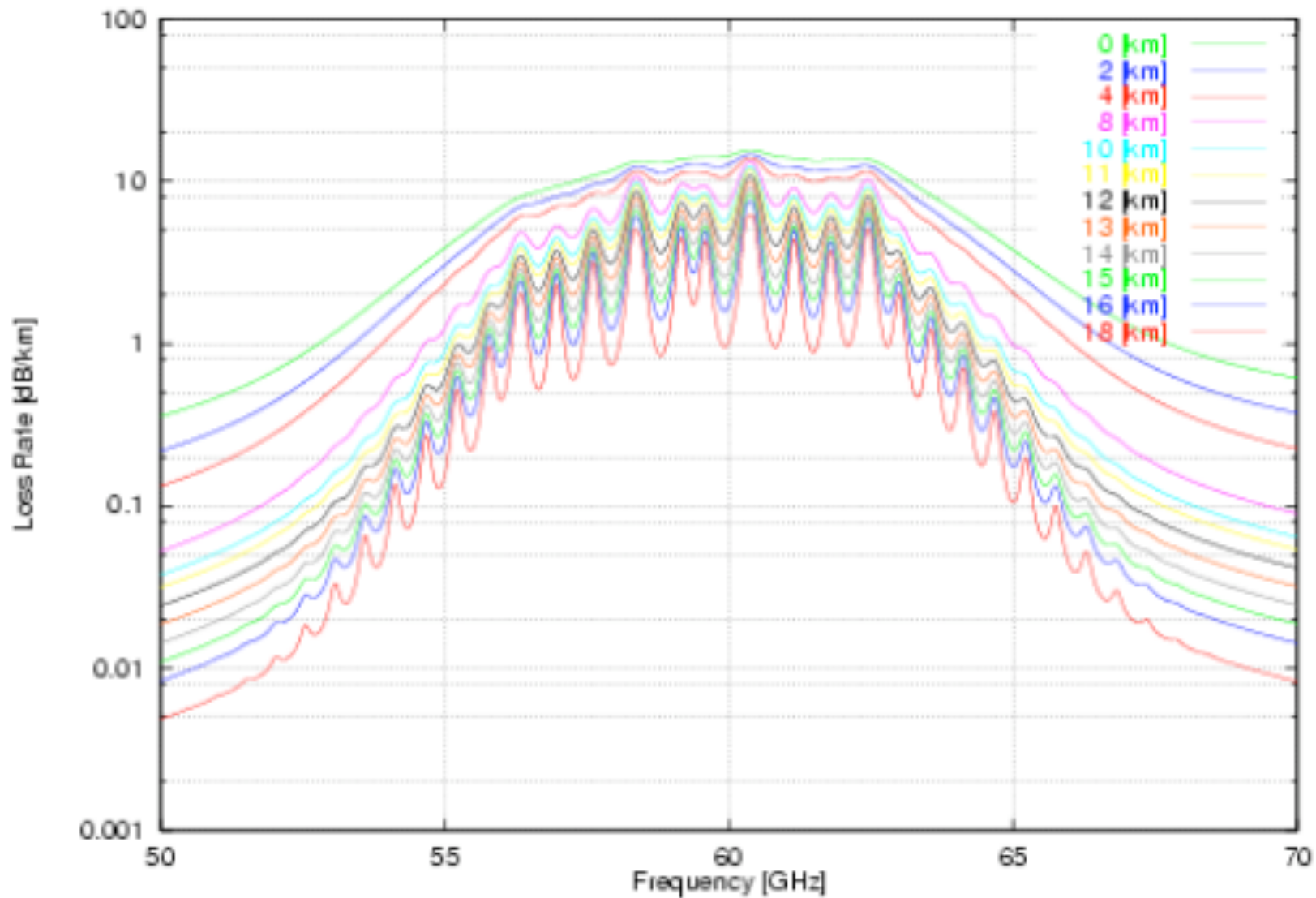
$$\mu_{N-}^2 = \frac{(N+1)(2N-1)}{N}$$

The resonant and nonresonant contributions are then combined to produce the total contribution for the line, and the contributions for all lines are summed:

$$\gamma_{O_2} = 2.0058 \, \frac{pT}{T^3} f^2 \times$$

$$\sum_N (\mu_{N+}^2 \, F_{N+} + \mu_{N-}^2 \, F_{N-} + \mu_{N0}^2 \, F_0) \, e^{-\frac{2.06844N(N+1)}{T}}$$
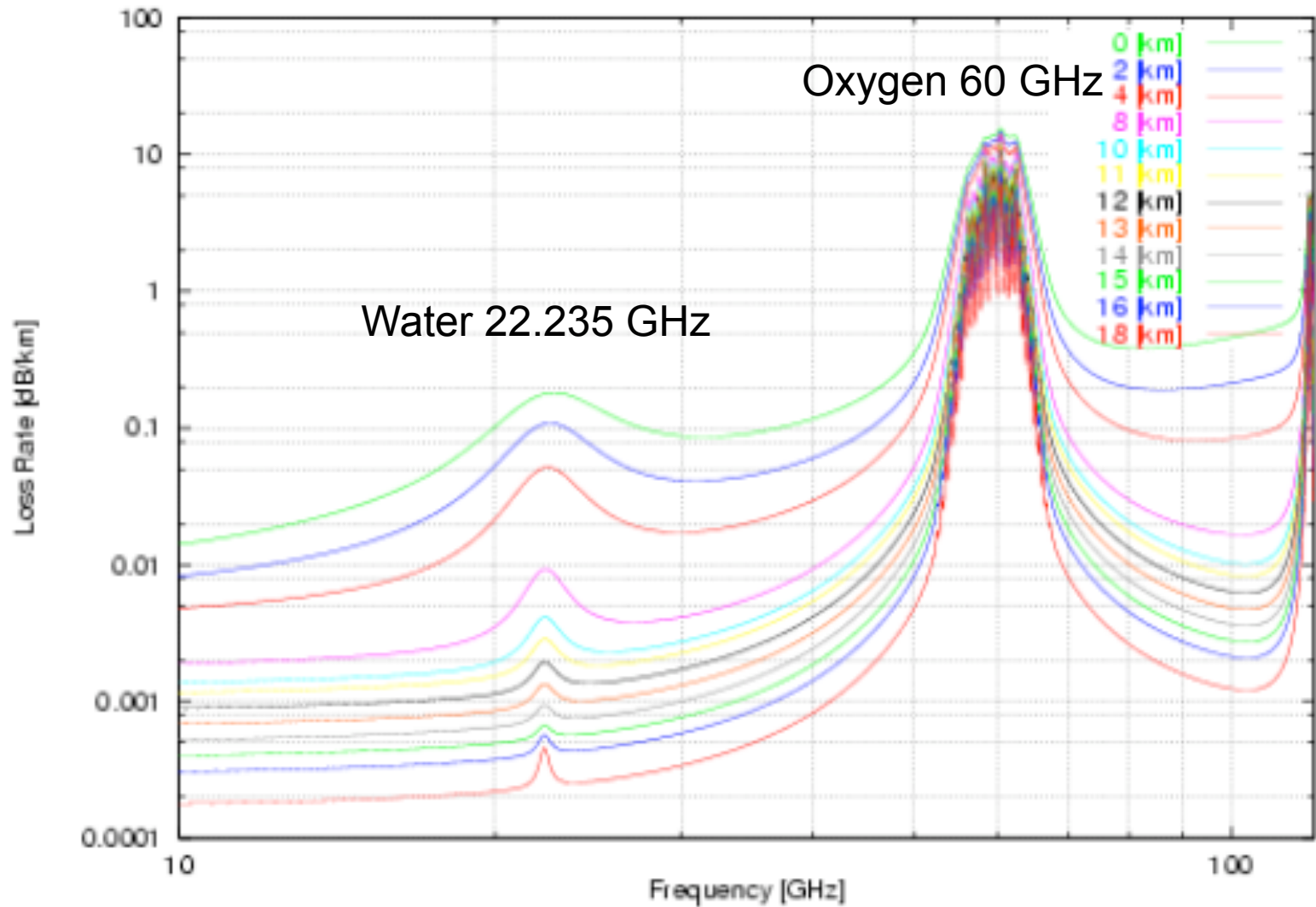
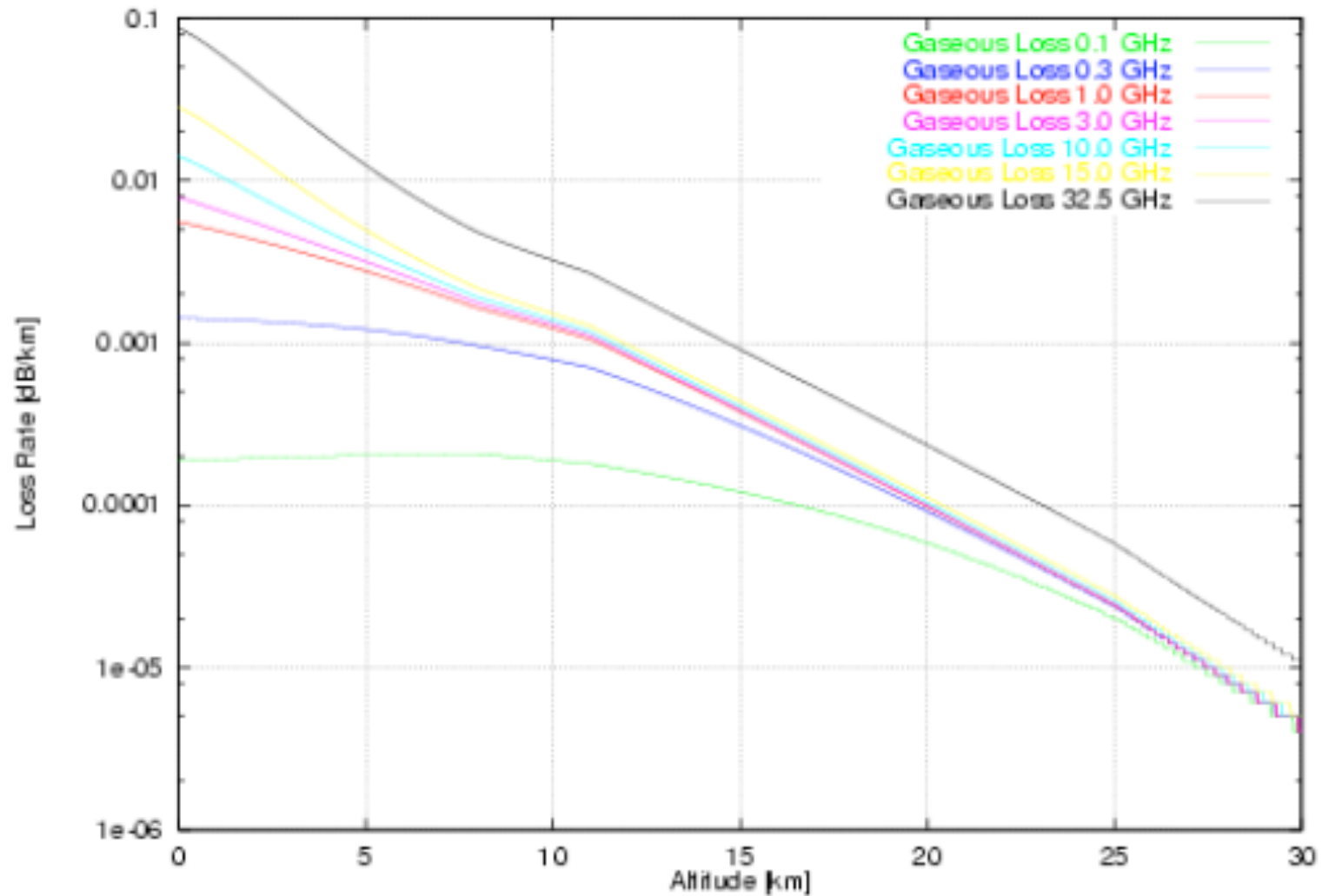$$[dB/km]$$

Oxygen Band Loss vs Frequency; Altitude

Gaseous Loss vs Frequency; Altitude

Gaseous Loss vs Altitude; Frequency

Lens Effect Loss Model

- The model used Blake was adopted, but its implementation was unconventional.

- The classical approach is to raytrace the paths corresponding the upper and lower vertical extents (eg -3 dB mainlobe width) and employ these to evaluate the loss incurred.

- Our strategy exploited the BVP shooting method, inserting the initial and final BVP shots into the loss model. In this manner no penalty is incurred in compute effort. Because the launch angles of the initial and final BVP shots are of a similar order of magnitude in size to the beamwidth, the error is negligible in magnitude. The equation for calculating the loss is:

$$L_{LE} = 10 \, \log_{10}(\frac{\epsilon}{\delta \, R}) \; [dB]$$

- Where ε is the difference in launch angles, δ the difference in final beam positions, and R the mean pathlength. The results were found to be in close agreement with Blake's results.

Cloud Droplet Scattering Loss Models

The revised Staelin model is used to calculate the density specific attenuation in for a given frequency and temperature:

$$K_c = 12.8889 \times 10^{-3} \times$$
$$\log_{10}(e) \ 10^{0.0122 \ (292.0 - T) - 1} \ f^2$$
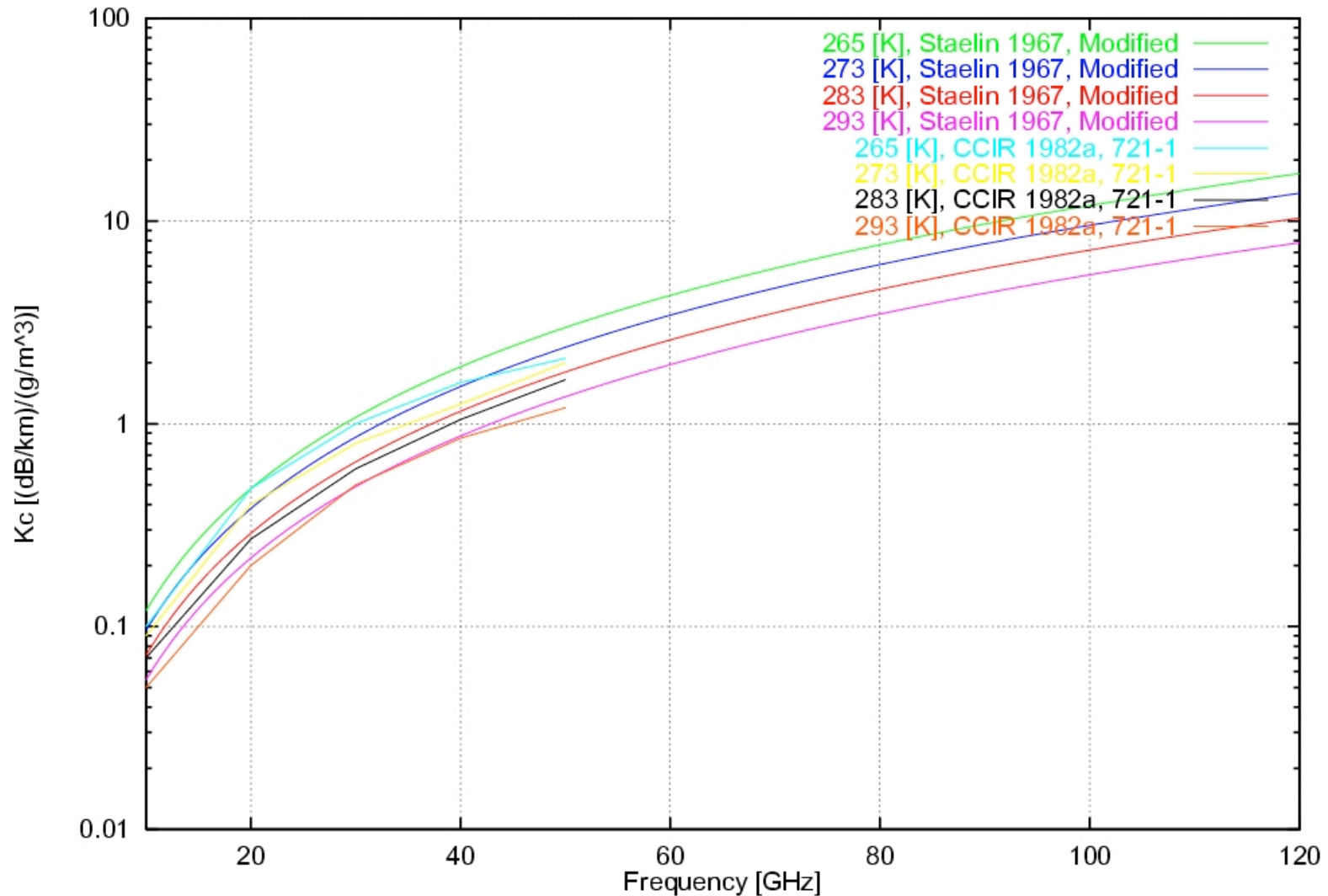$$[(dB/km)/(g/m^3)]$$

The density specific attenuation is then used to calculate the specific attenuation for the given conditions, and this is used to find the loss:

$$A_c = K_c \ \rho_c \ [dB/km], \qquad L_c = A_c \ d \ [dB]$$

Cloud Droplet Scattering Loss Models

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Rain Rate Loss Models

$$A_r = \alpha(f)\, R^{\beta(f)}$$

R is the rain rate in mm/hr, the coefficient α and exponent β are defined as:

$$\alpha(f) = \frac{3.1 \times 10^{-5} f^2 \left(1 + \frac{f^2}{f_1^2}\right)^{\frac{1}{2}}}{\left(1 + \frac{f^2}{f_2^2}\right)^{\frac{1}{2}} \left(1 + \frac{f^2}{f_3^2}\right)^{\frac{1}{2}} \left(1 + \frac{f^2}{f_4^2}\right)^{\frac{1}{2}}}$$

$$f_1 = 3.0,\ f_2 = 35.0,\ f_3 = 50.0,\ f_4 = 110.0\ [GHz]$$

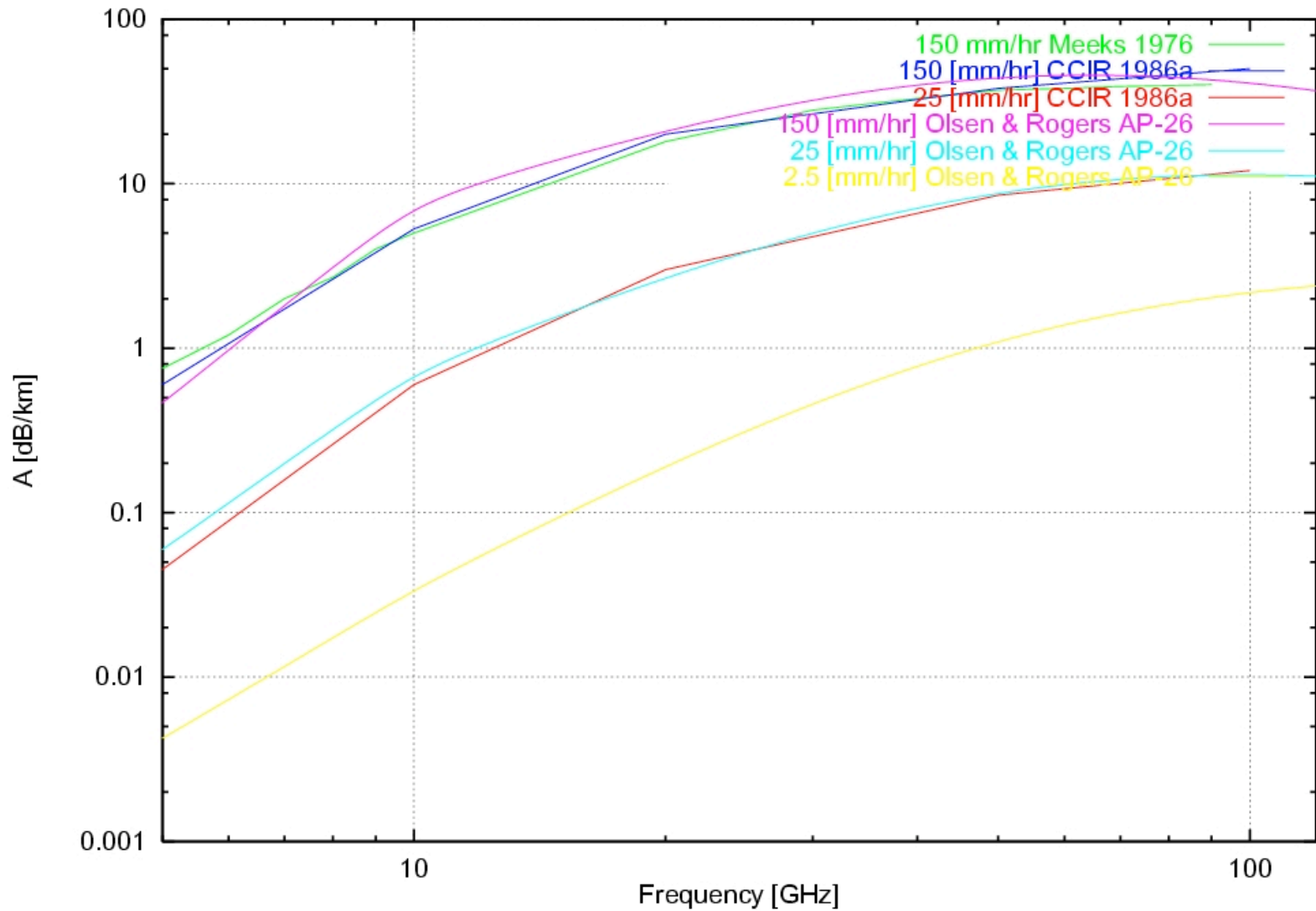$$\beta(f) = 1.30 + 0.0372\,(\,1 - (\,1 + x^2\,)^{\frac{1}{2}}\,),$$

$$x = \frac{\log_{10}\left(\frac{f}{10.0}\right)}{0.06}$$

The Rice model for rain rate variation with altitude is a simple scale height model:

$$r(h) = r_{SL}\, e^{-\left(\frac{h}{h_s}\right)^2}$$

Rain Rate Loss Models

Refraction in the Atmosphere

- The requirement for accurate modelling of cloud and rain losses introduced the need for ray path tracing of reasonable accuracy.
- Geometries with shallow depression or elevation angles experience a large error in cloud or rain penetration distance with even a modest error in ray path elevation.
- The refractive properties of the atmosphere were modelled with the CRPL exponential model using a sea level refractivity of 313 and scale height of 6.95 km. The nonlinear second order differential equation describing the ray path is:

$$\frac{\partial^2 y}{\partial x^2} = \left(1 + \left(\frac{\partial y}{\partial x}\right)^2\right)\left(\frac{1}{R} + \frac{\partial}{\partial y}\log(n(y))\right)$$

- An attempt was made to solve the equation analytically, using a nine term series to approximate the exponential as this removed the analytical difficulties with the exponential. This failed

Non-Linear Ray Tracing BVP Solution

- The numerical technique chosen to solve this BVP was the shooting method [6], [7], [8], employing a numerical integration algorithm to solve the ray path Initial Value Problem (IVP) for a known initial height and variable ray launch angle.

- Two techniques were employed for the IVP integration. Initially a second order predictor-corrector algorithm was used [6], [7], this yielded satisfactory results for modest increment sizes of the order of a kilometre, but its speed performance was not satisfactory for traces with aggregate lengths of the order of hundreds of kilometres.

- A more elaborate fourth order multi-step technique by Wallace and Gupta was then implemented and tested [9], achieving an order of magnitude better speed performance with increments of 20 km size still yielding suitable accuracy.
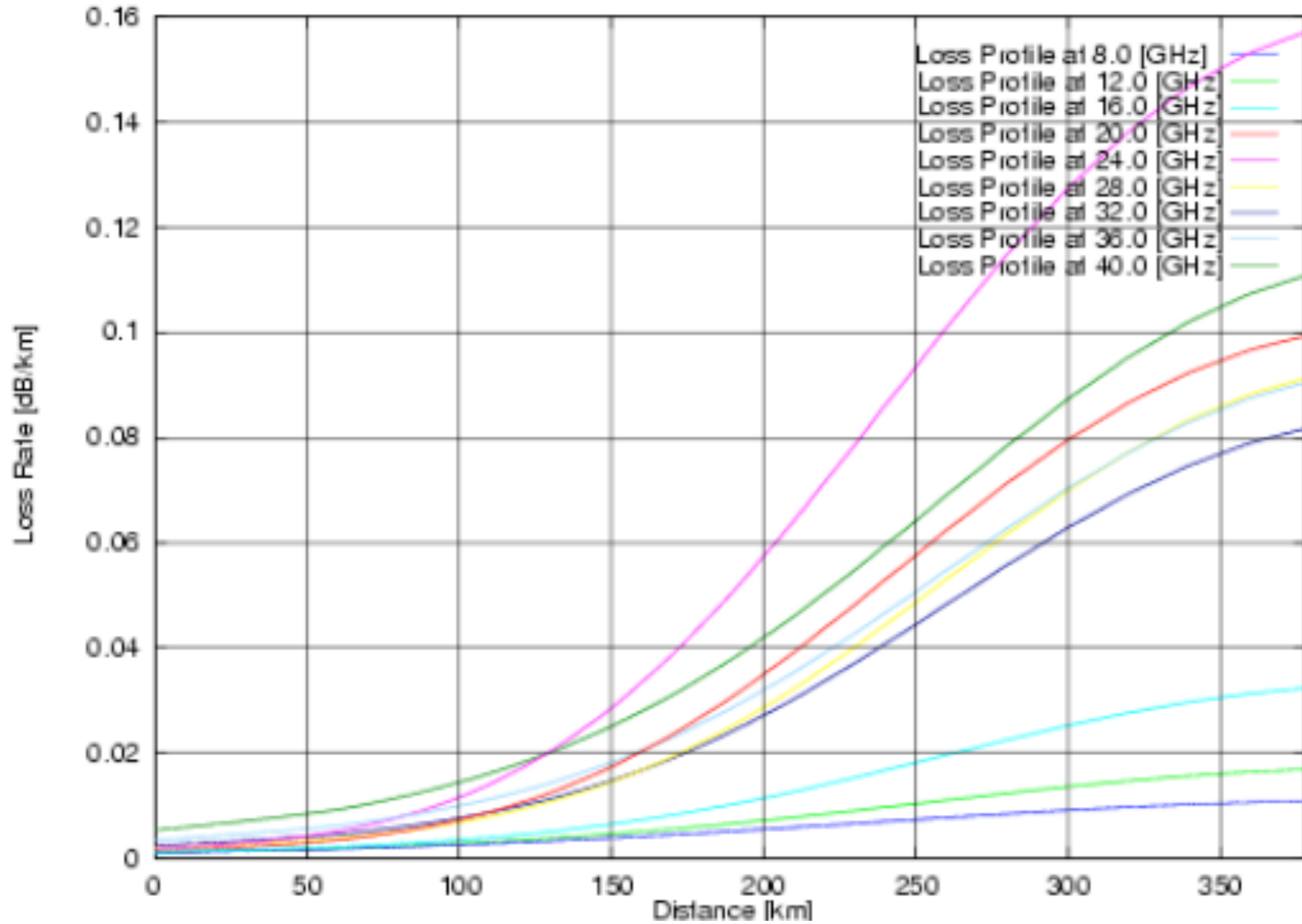
Non-Linear Ray Tracing BVP Solution

- A simple linear interpolation was employed to provide the intermediate 1 km sample points between the computed 20 km intervals, this still provided a less than 0.1% error against the second order method.

- Testing indicated that the fourth order method would require further refinement for shorter distance ray paths, in the interest of expediency the TROPPO simulator uses the second order method for distances up to 150 km, and the fourth order method for all greater distances.

- The BVP is solved using a secant method for convergence, which under best case conditions achieves a final height error of the order of 0.05% in 3 iterations.

- During the computation the values of initial and final launch angles and heights are saved to provide values for the lens effect loss calculation.

Example Loss Profiles

Legend:
- Loss Profile at 8.0 [GHz]
- Loss Profile at 12.0 [GHz]
- Loss Profile at 16.0 [GHz]
- Loss Profile at 20.0 [GHz]
- Loss Profile at 24.0 [GHz]
- Loss Profile at 28.0 [GHz]
- Loss Profile at 32.0 [GHz]
- Loss Profile at 36.0 [GHz]
- Loss Profile at 40.0 [GHz]

Axes: Loss Rate [dB/km] vs Distance [km]

Parametrised Loss Profile

Launch Angle = -3.1 [deg]
Pathlength = 380.2 [km]
Absorption Loss = 71.9 [dB]
Pathlength Loss = 172.0 [dB]
Total Loss = 244.3 [dB]
Rain Rate SL = 2.5 [mm/hr]
Cloud Density (1) = 0.5 [g/m^3] Base @ 3.0 [km]
Cloud Density (2) = 0.1 [g/m^3] Base @ 0.6 [km]
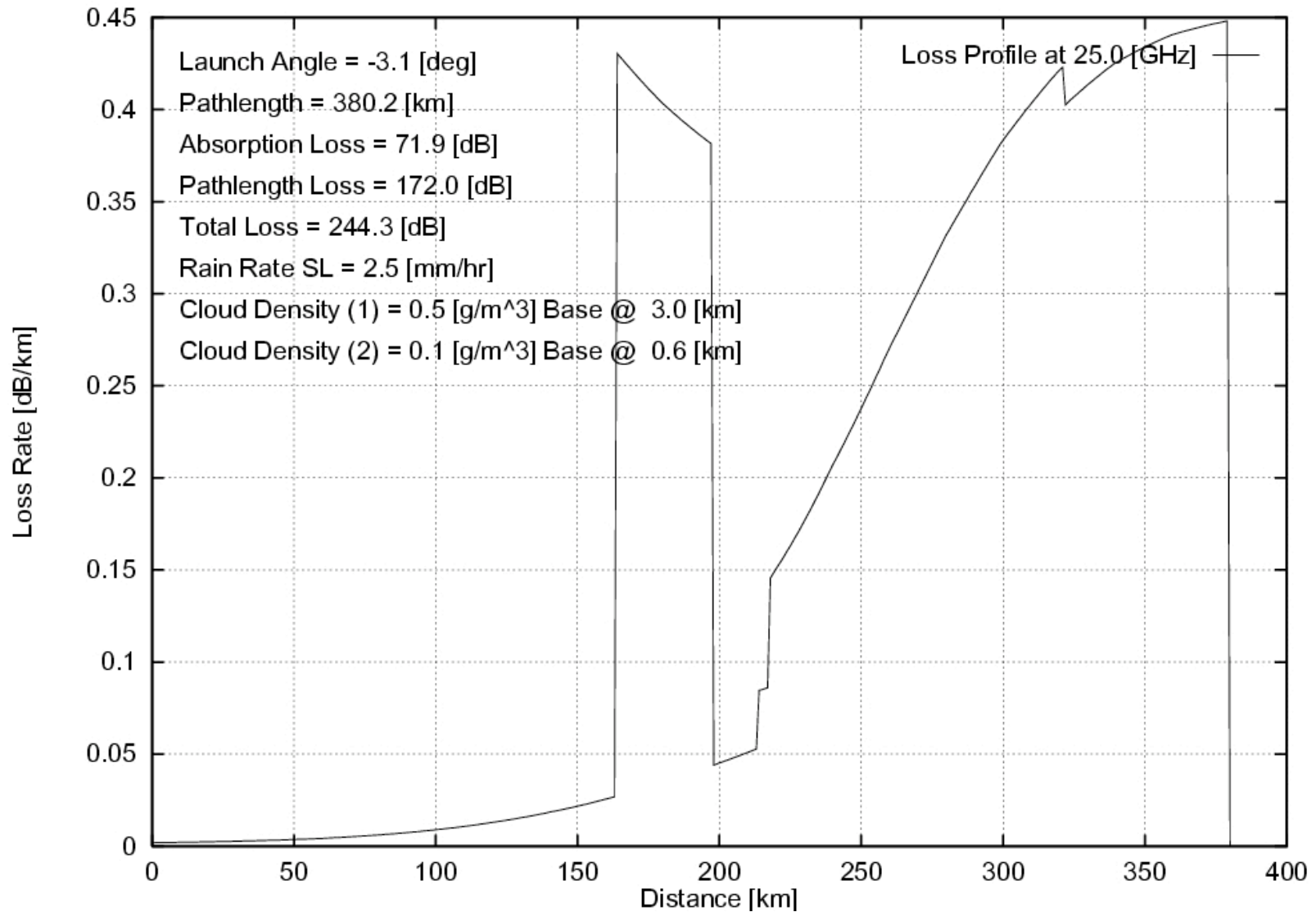
Loss Profile at 25.0 [GHz]

TROPPO Capabilities and Application

- Highly modular software design permitting addition of specific models and configuration to use or exclude models.

- Calculates both SNR for configurable R/T parameters, and Shannon channel capacity for specified bandwidth.

- Capable of solving the generalised point to point problem required for two airborne stations.

- Used extensively for large scale simulations of airborne ad hoc networks with thousands of nodes.

- Standalone use or can be integrated as library object.

- *FAST computation compared to legacy simulators; caching techniques used where possible to minimise computational loads, BVP method inherently fast.*

Limitations – Future Tasks

- Current suite of models does not include a Melting Layer model – planned for future inclusion.

- Existing model suite requires updating with additional loss models adopted during the late 1990s and since.

- No Graphical User Interface thus requiring command line operation and configuration files.

- Requires extension to permit satellite communications applications – both ray tracing and ionospheric losses.