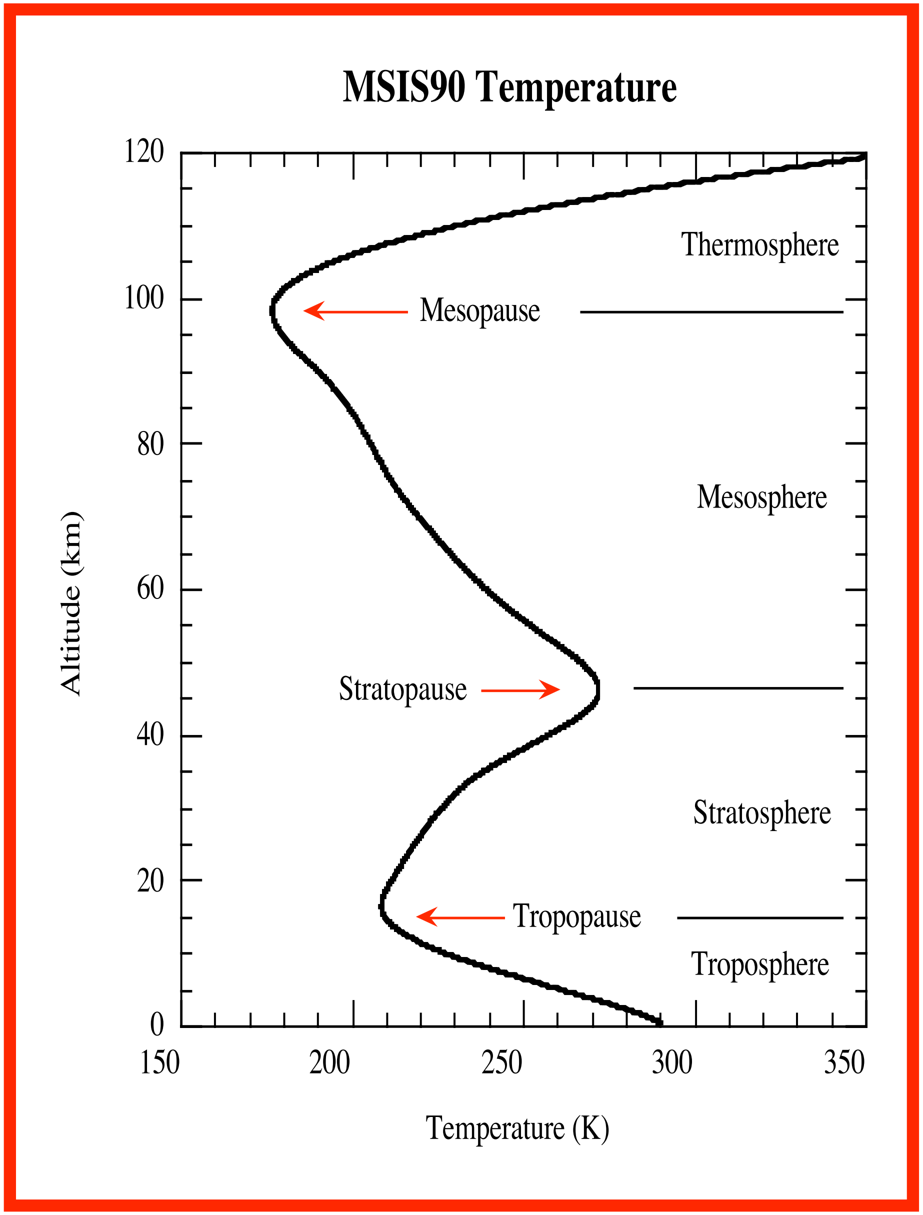
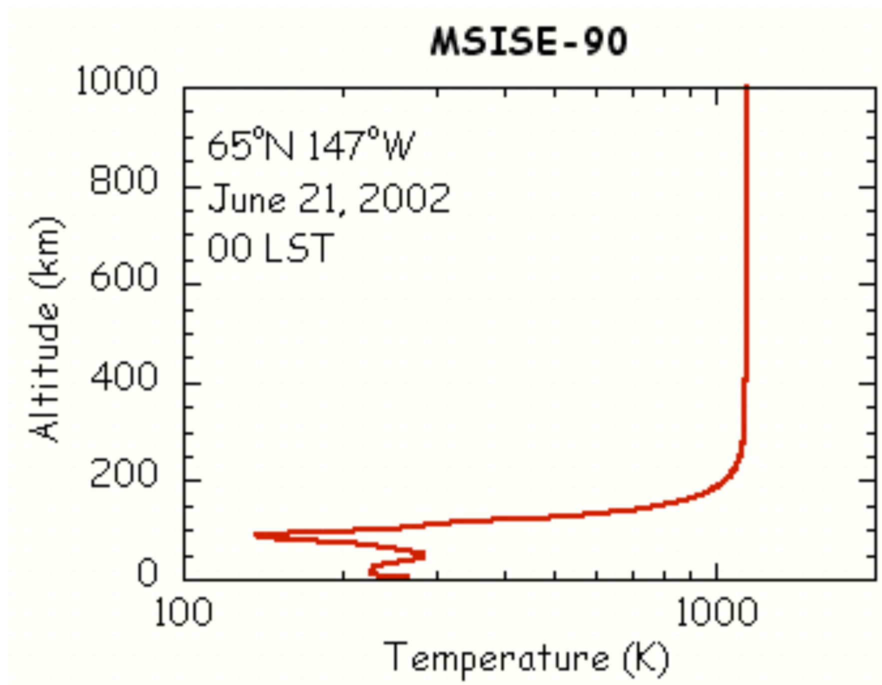
Lecture 16. Temperature Lidar (5)
Boltzmann Technique

- Introduction
- Boltzmann temperature technique
- Fe Boltzmann temperature lidar
- N_2^+ Boltzmann temperature lidar
- Summary

Introduction

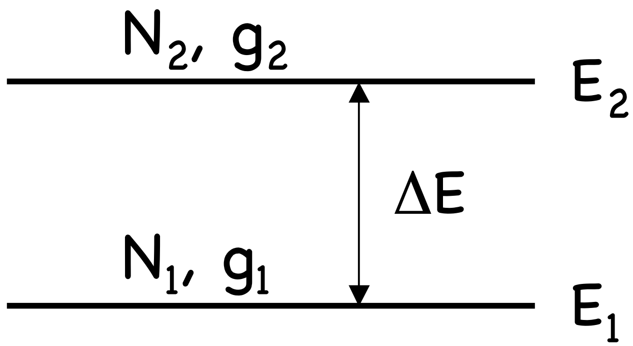


- Resonance fluorescence lidar technique can be used in MLT region, and also extended to thermosphere on molecular species, like N_2^+



Boltzmann Temperature Technique

- Boltzmann distribution is the law of particle population distribution according to energy levels under thermodynamic equilibrium (Maxwell-Boltzmann distribution law)



$$\frac{N_k}{N} = \frac{g_k \exp(-E_k / k_B T)}{\sum_i g_i \exp(-E_i / k_B T)}$$

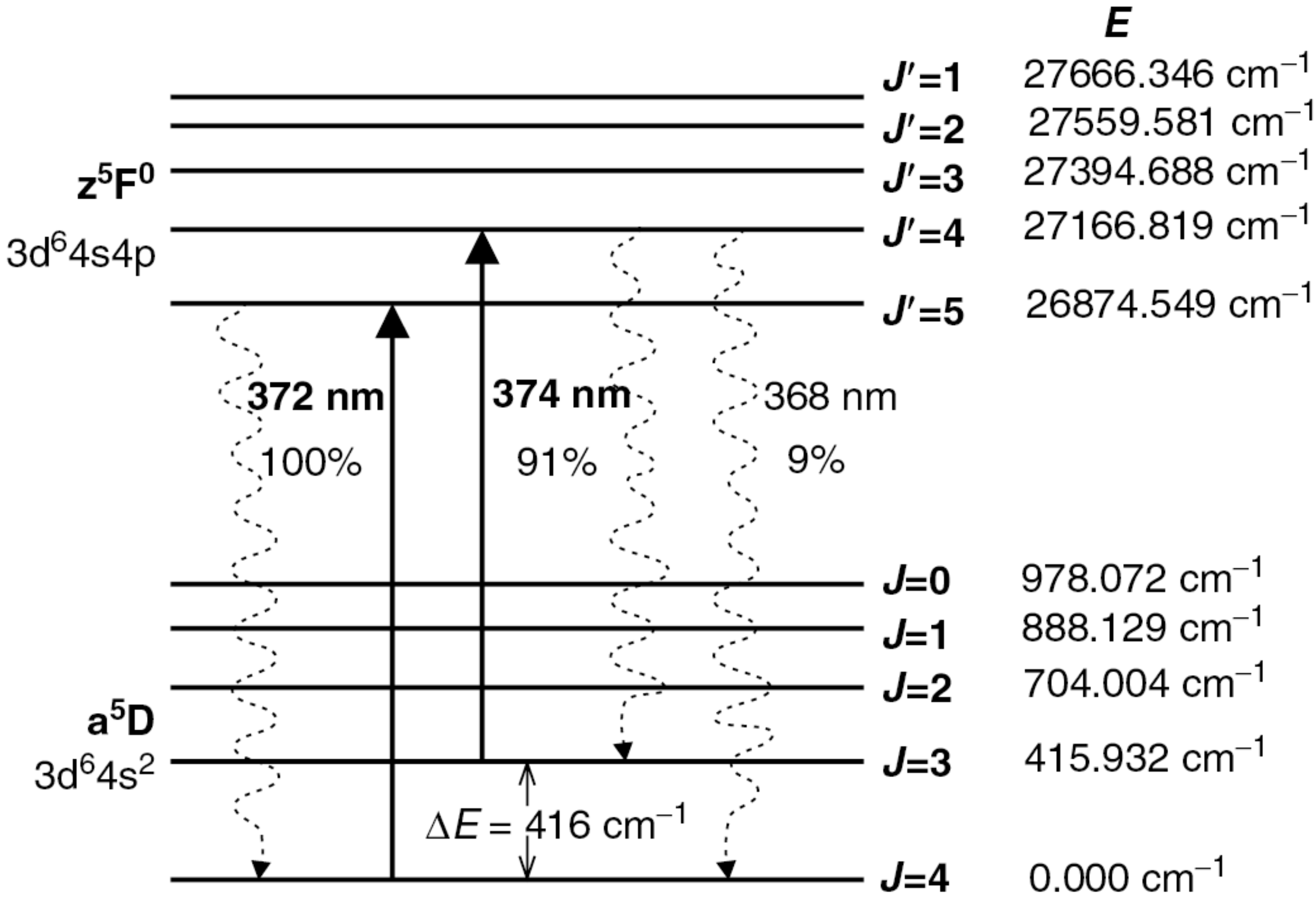
$$\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\left\{-\left(E_2 - E_1\right)/k_B T\right\}$$

$$T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2}{g_1} \cdot \frac{N_1}{N_2}\right)}$$

N_1 and N_2 - particle populations on energy levels E_1 and E_2
g_1 and g_2 - degeneracy for energy levels E_1 and E_2, $\Delta E = E_2 - E_1$
k_B - Boltzmann constant, T - Temperature, N - total population

Population Ratio ⇨ Temperature

Fe Atomic Energy Levels



Fluorescence Intensity Ratio ⇨ Population Ratio ⇨ Temperature

Fe Atomic Parameters

Table 5.3 Isotopic Data of Fe Atoms

	^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe
Z	26	26	26	26
A	54	56	57	58
Nuclear spin	0	0	1/2	0
Natural abundance	5.845%	91.754%	2.119%	0.282%

Table 5.4 Fe Resonance Line Parameters

Transition wavelength λ	372.0993 nm	373.8194 nm
Degeneracy for ground state	$g_1 = 9$	$g_2 = 7$
Degeneracy for excited state	$g_1' = 11$	$g_2' = 9$
Radiative lifetime of excited state (ns)	61.0	63.6
Einstein coefficient A_{ki} (10^8 s^{-1})	0.163	0.142
Oscillator strength f_{ik}	0.0413	0.0382
Branching ratio R_B	0.9959	0.9079
σ_0 (10^{-17} m^2)	9.4	8.7

Fe Boltzmann Lidar Principle

$$N_{\mathrm{Fe}}(\lambda,z)=\left(\frac{P_{\mathrm{L}}\Delta t T_{\mathrm{a}}}{hc/\lambda}E(\lambda,z)\right)\sigma_{\mathrm{eff}}(\lambda,T,\sigma_{\mathrm{L}})R_{\mathrm{B}\lambda}\rho_{\mathrm{Fe}}(\lambda,z)$$
$$\times\Delta z\left(E(\lambda,z)T_{\mathrm{a}}\frac{A_{\mathrm{R}}}{4\pi z^2}\eta\right) \tag{5.92}$$

$$N_{\mathrm{norm}}(\lambda,z)=\frac{N_{\mathrm{Fe}}(\lambda,z)+N_{\mathrm{B}}(\lambda,z)-\hat{N}_{\mathrm{B}}(\lambda)}{N_{\mathrm{R}}(\lambda,z_{\mathrm{R}})+N_{\mathrm{B}}(\lambda,z_{\mathrm{R}})-\hat{N}_{\mathrm{B}}(\lambda)}$$
$$=\frac{z_{\mathrm{R}}^2E^2(\lambda,z)R_{\mathrm{B}\lambda}\sigma_{\mathrm{eff}}(\lambda,T,\sigma_{\mathrm{L}})\rho_{\mathrm{Fe}}(\lambda,z)}{z^2\sigma_{\mathrm{R}}(\lambda)\rho_{\mathrm{atmos}}(z_{\mathrm{R}})}$$

Fe Boltzmann Lidar Principle

$$R_T(z) = \frac{N_{norm}(\lambda_{374}, z)}{N_{norm}(\lambda_{372}, z)}$$

$$= \frac{g_2}{g_1} \frac{R_{B374}}{R_{B372}} \left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117} \frac{E^2(\lambda_{374}, z)}{E^2(\lambda_{372}, z)}$$

$$\times \frac{\sigma_{eff}(\lambda_{374}, T, \sigma_{L374})}{\sigma_{eff}(\lambda_{372}, T, \sigma_{L372})} \exp(-\Delta E / k_B T)$$

$$R_\sigma = \frac{\sigma_{eff}(\lambda_{374}, T, \sigma_{L374})}{\sigma_{eff}(\lambda_{372}, T, \sigma_{L372})}$$

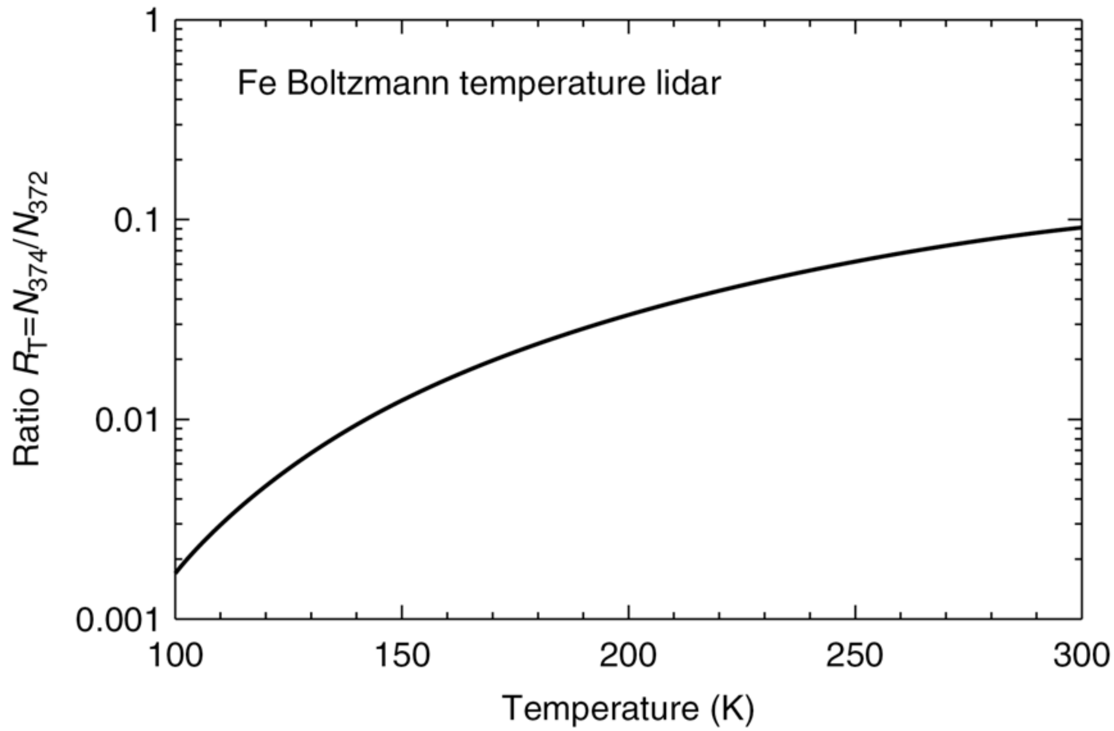
$$R_E(z) = \frac{E(\lambda_{374}, z)}{E(\lambda_{372}, z)}$$

$$T(z) = \frac{\Delta E / k_B}{\ln\left[\frac{g_2}{g_1} \frac{R_{B374}}{R_{B372}} \left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117} \frac{R_E^2(z) R_\sigma}{R_T(z)}\right]}$$

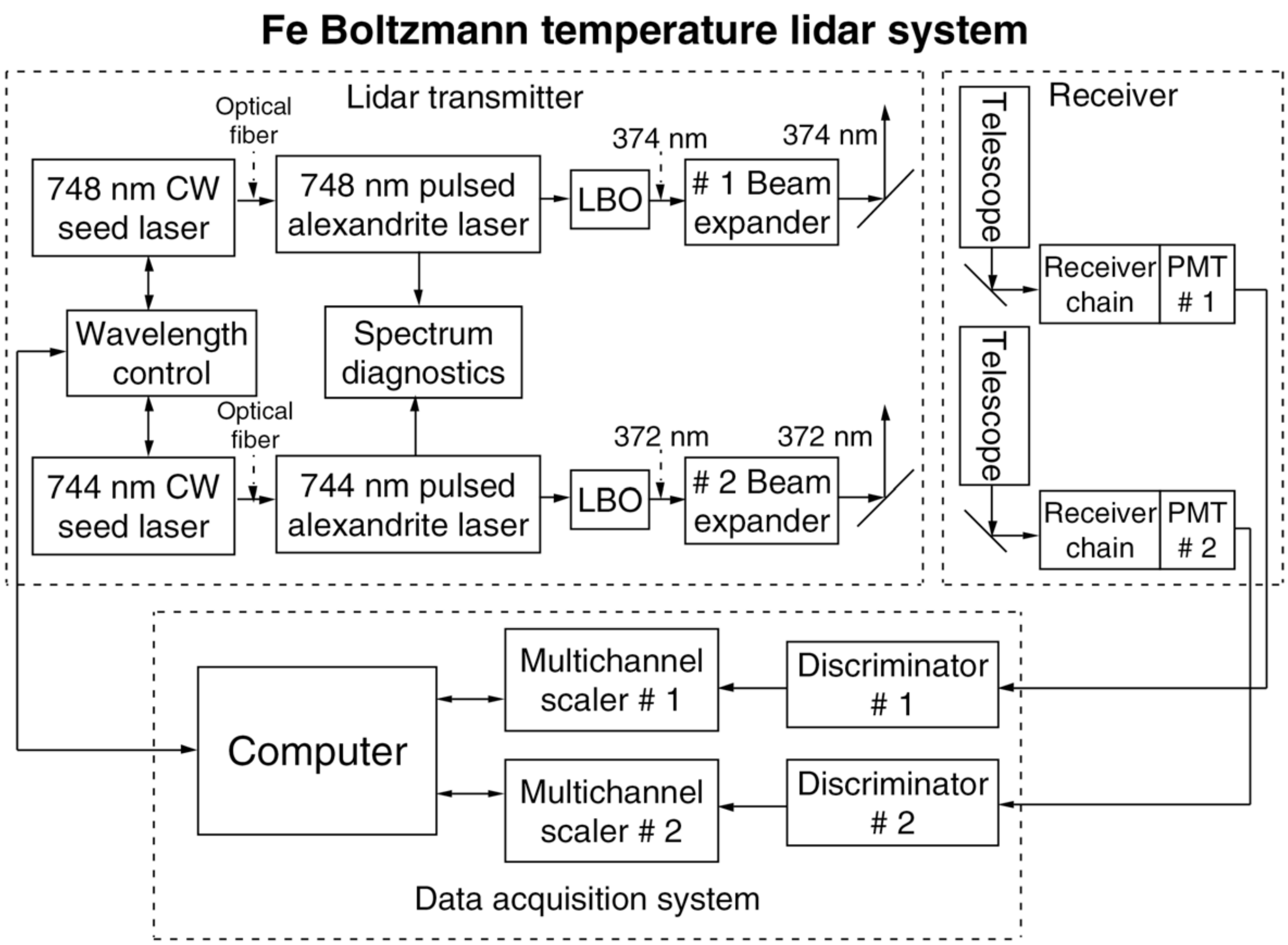
$$= \frac{598.44K}{\ln\left[\frac{0.7221 R_E^2(z) R_\sigma}{R_T(z)}\right]}$$

Fe Boltzmann Lidar Calibration

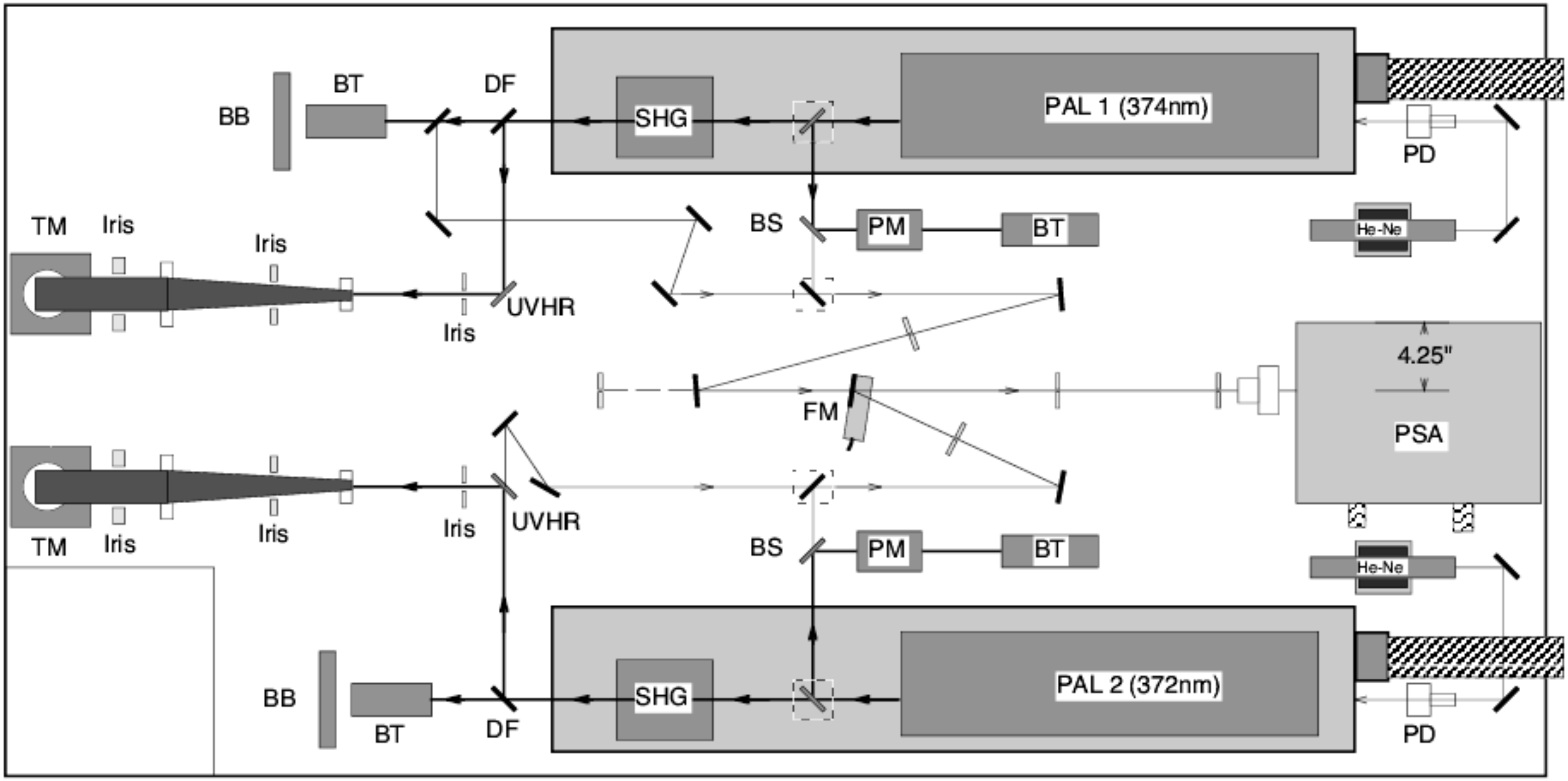
$$R_T(z) = \frac{N_{norm}(\lambda_{374}, z)}{N_{norm}(\lambda_{372}, z)}$$
$$= \frac{g_2}{g_1}\frac{R_{B374}}{R_{B372}}\left(\frac{\lambda_{374}}{\lambda_{372}}\right)^{4.0117}\frac{E^2(\lambda_{374}, z)}{E^2(\lambda_{372}, z)}$$
$$\times \frac{\sigma_{eff}(\lambda_{374}, T, \sigma_{L374})}{\sigma_{eff}(\lambda_{372}, T, \sigma_{L372})}\exp(-\Delta E/k_B T)$$



Fe Boltzmann Lidar Instrumentation



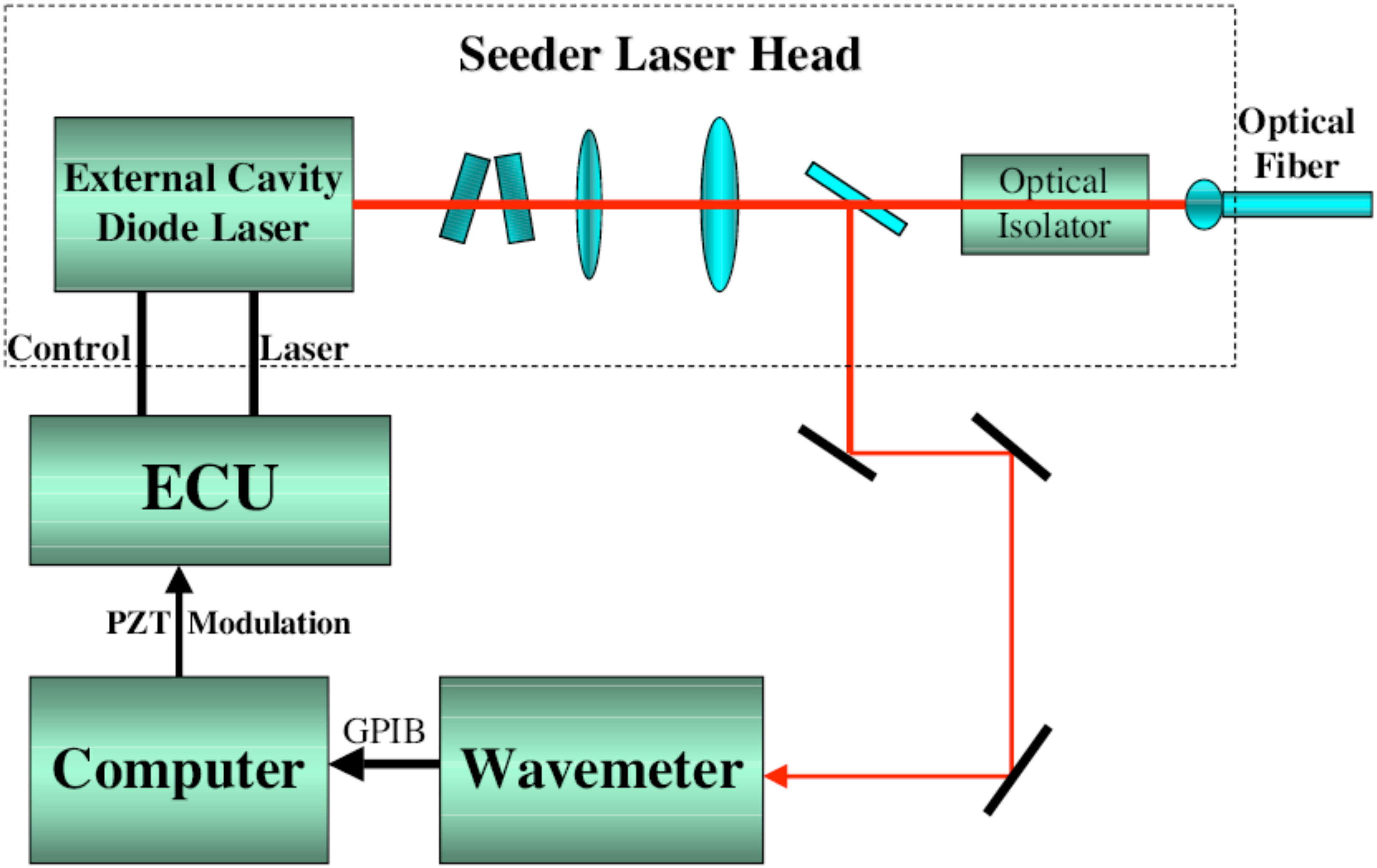
Fe Boltzmann Lidar Transmitter



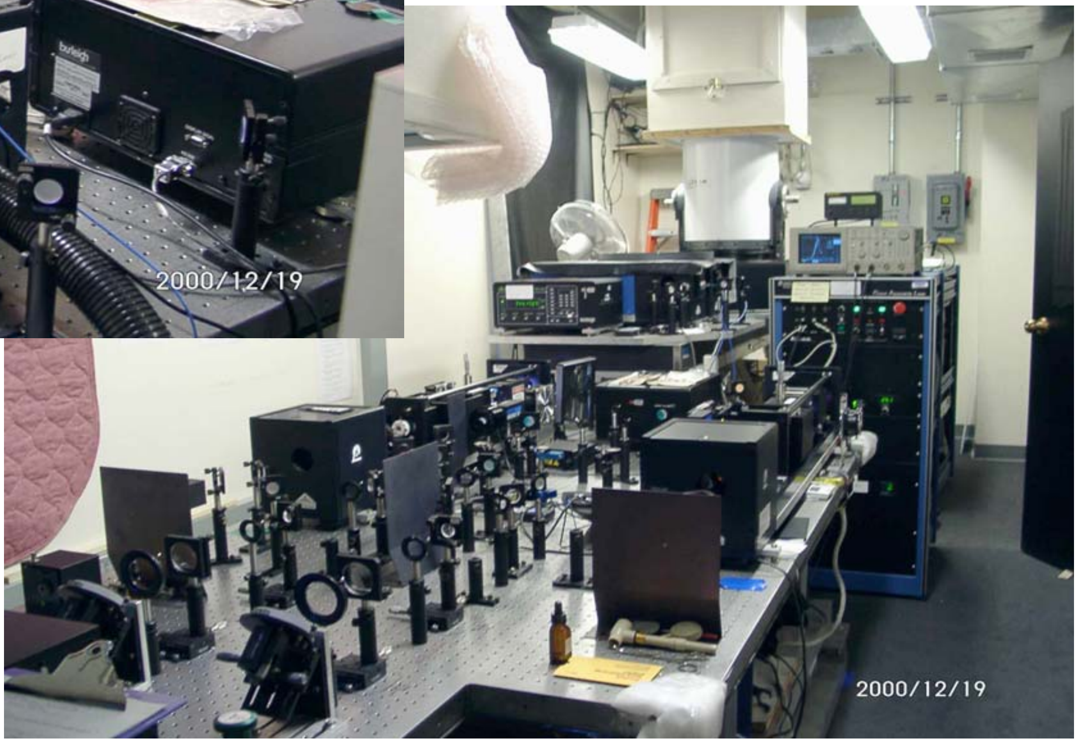
- Based on injection-seeded, frequency-doubled, pulse Alexandrite laser systems (372 and 374 nm output)

Fe Lidar Seeder Laser System

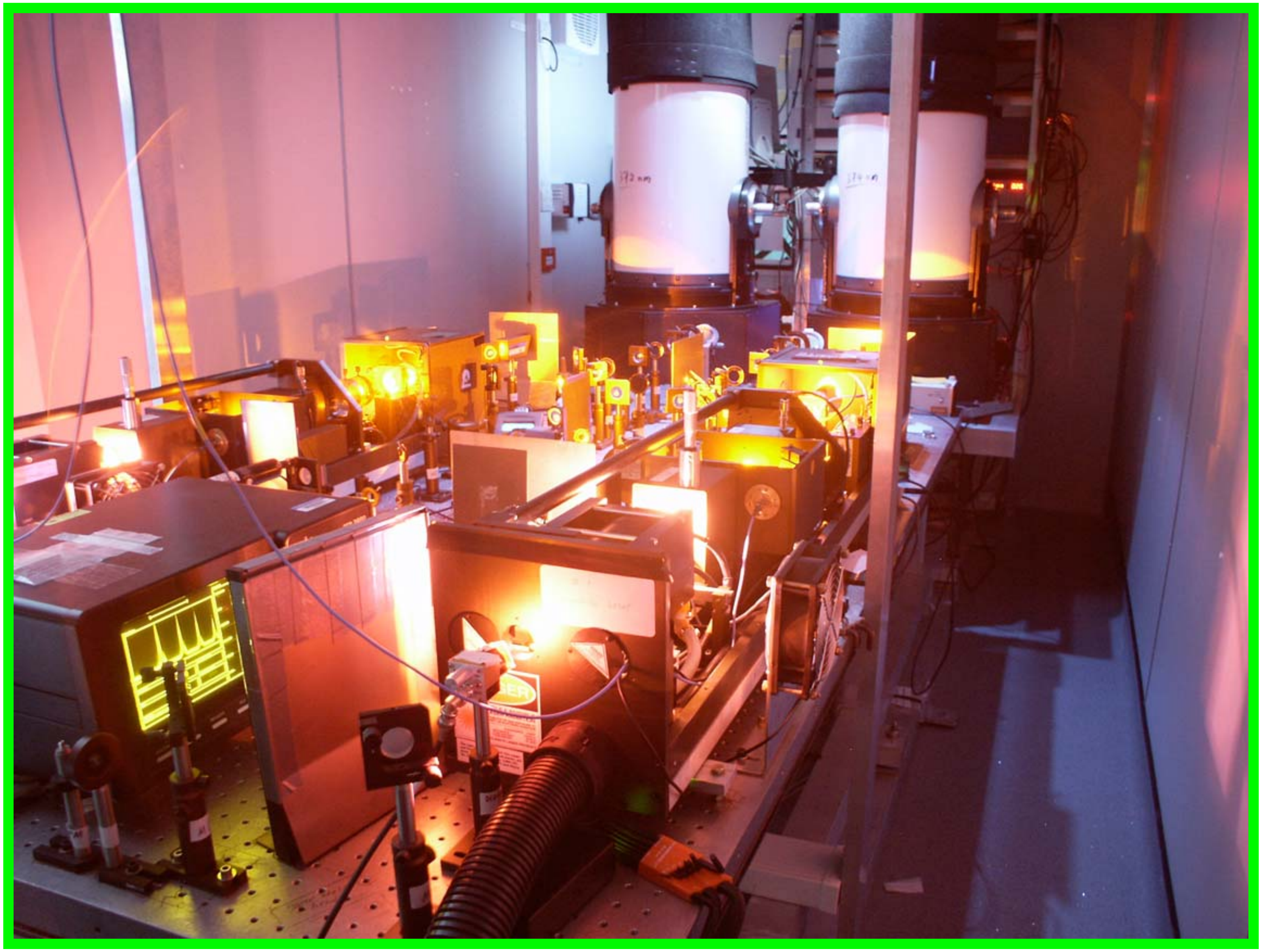
Seeder Laser Structure and Wavelength Control



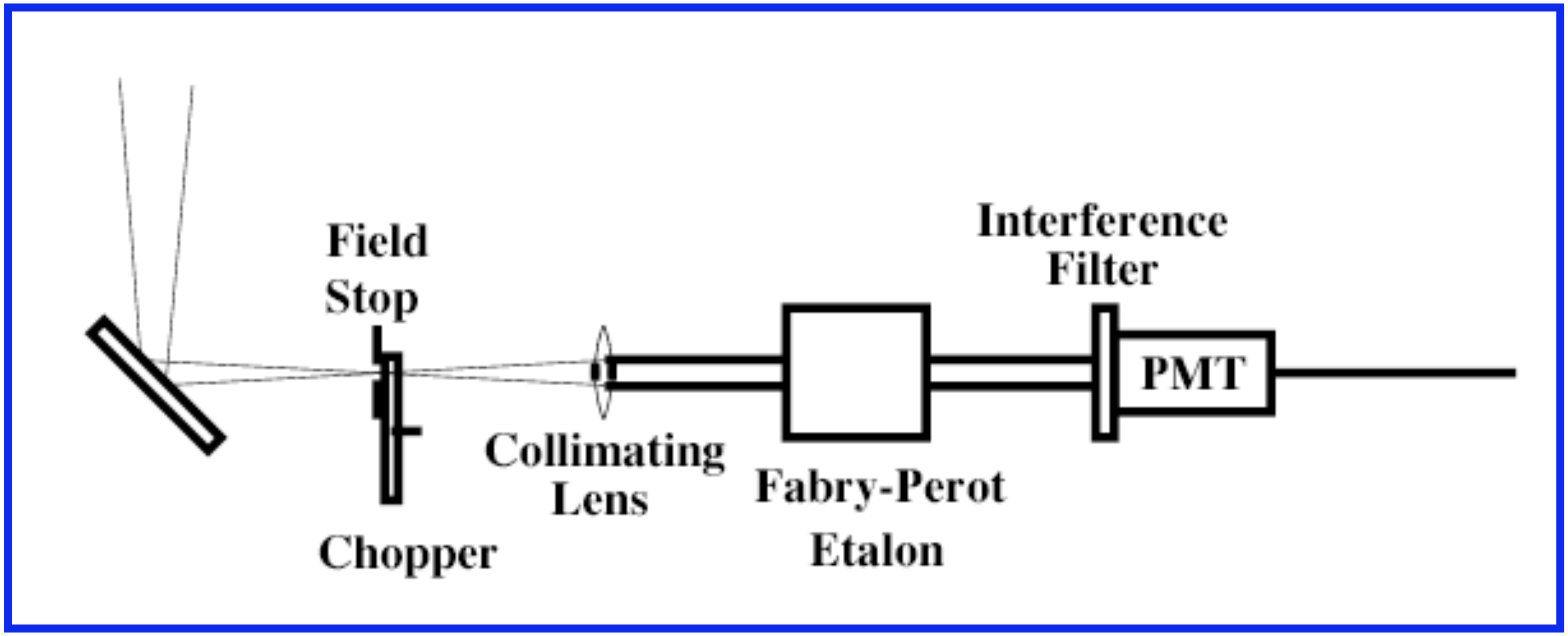
Fe Boltzmann Lidar @ South Pole

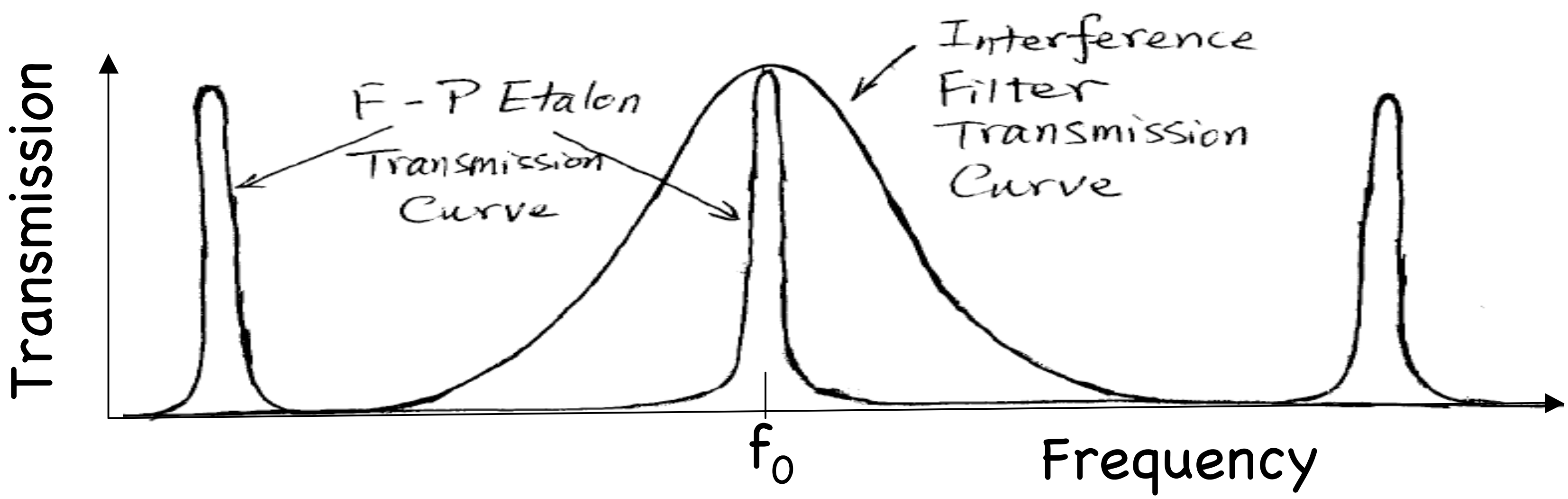


Fe Boltzmann Lidar @ Rothera

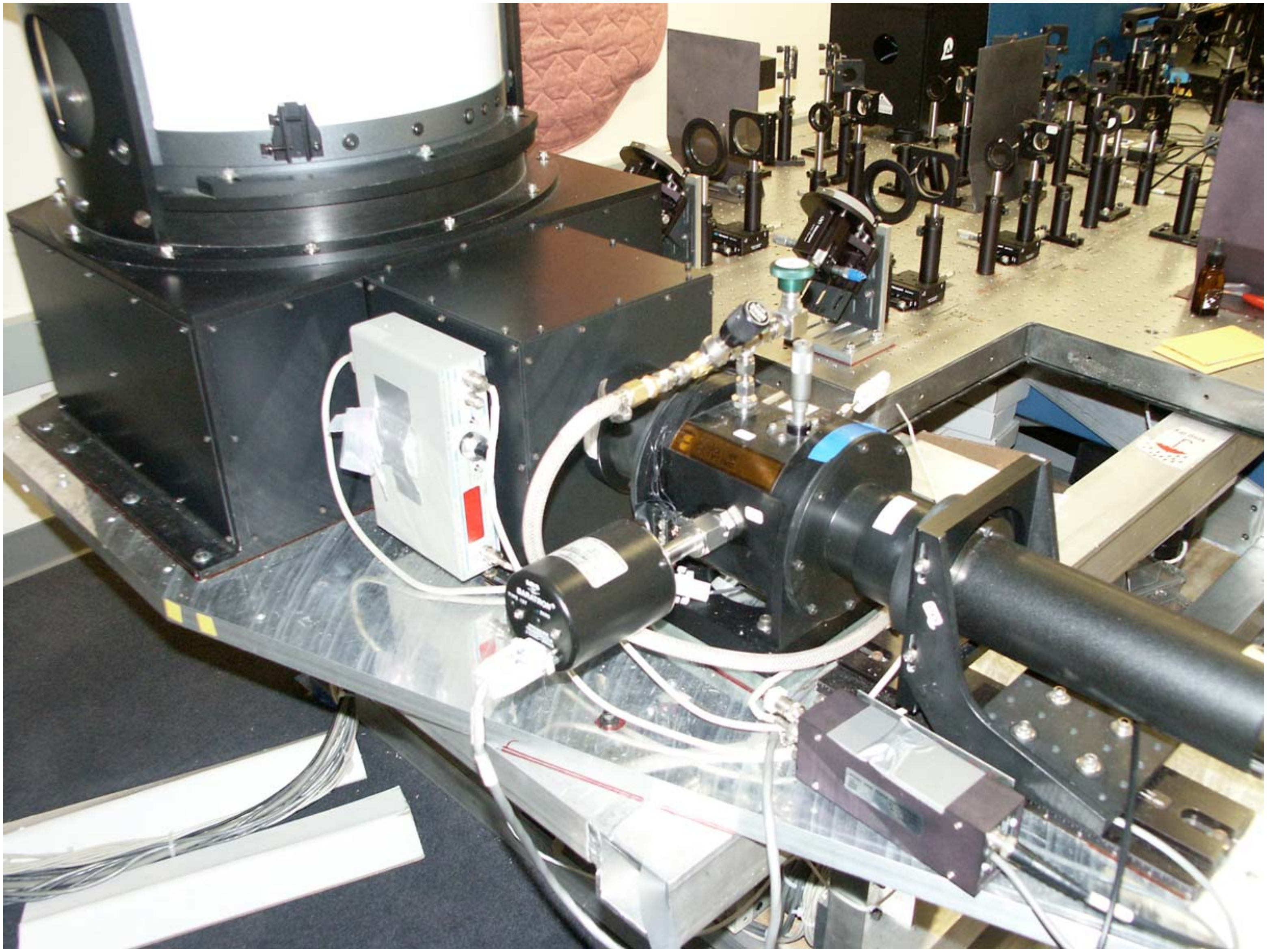


Fe Boltzmann Lidar Receiver



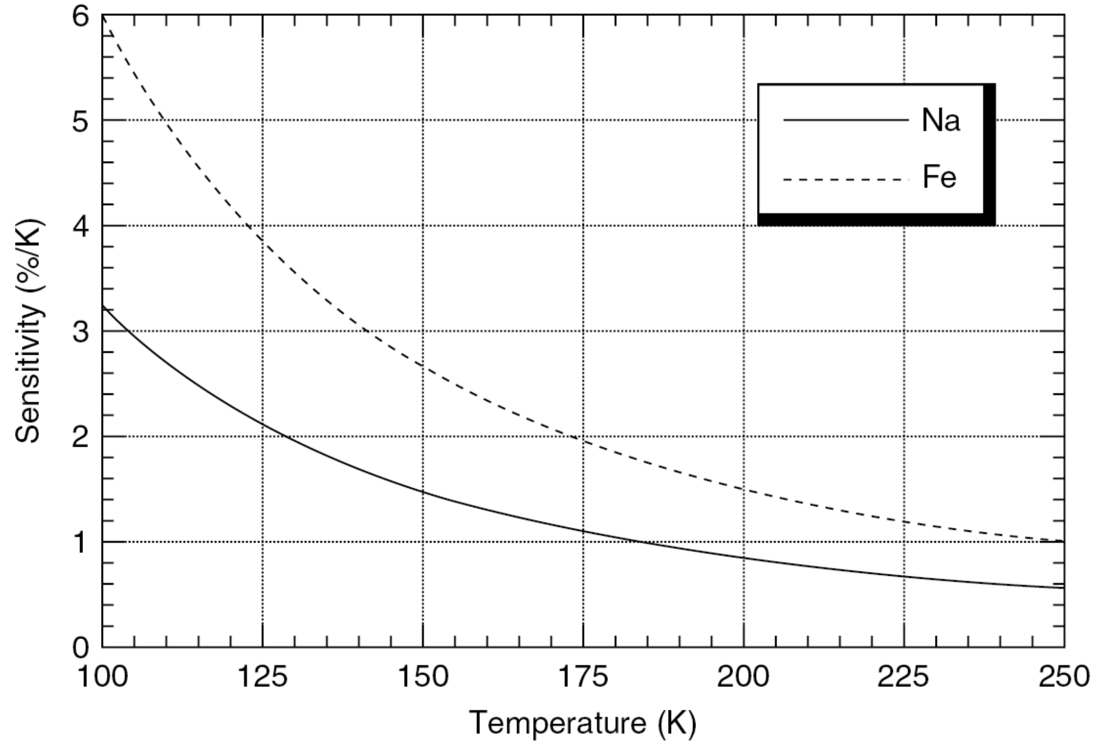


Fe Boltzmann Lidar Receiver

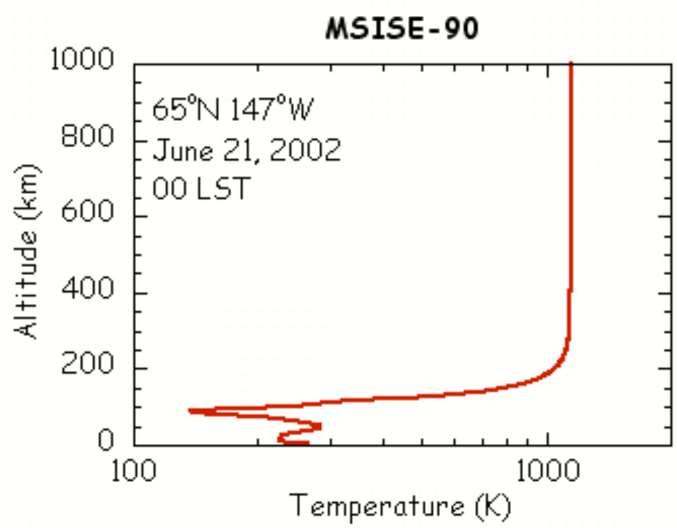


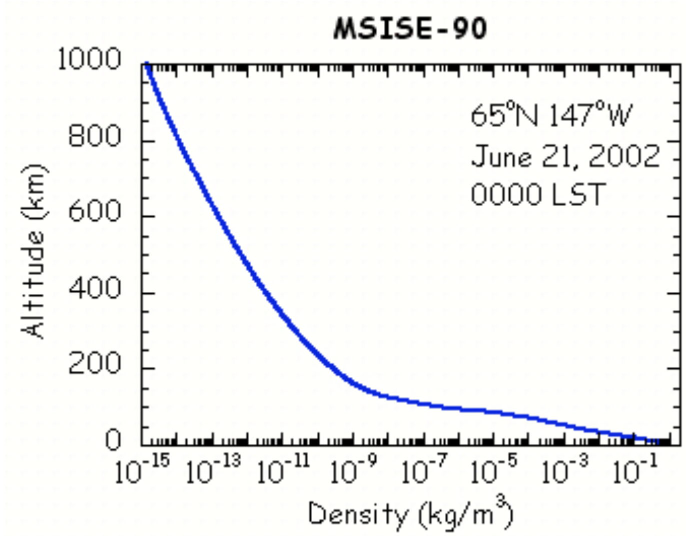
Sensitivity Analysis

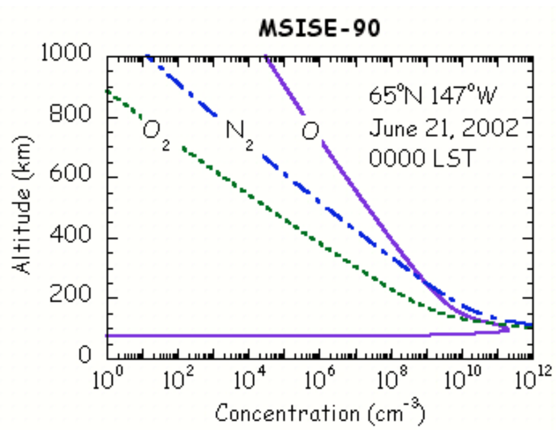
$$S_{\mathrm{T}} = \frac{\partial R_{\mathrm{T}}/\partial T}{R_{\mathrm{T}}}$$

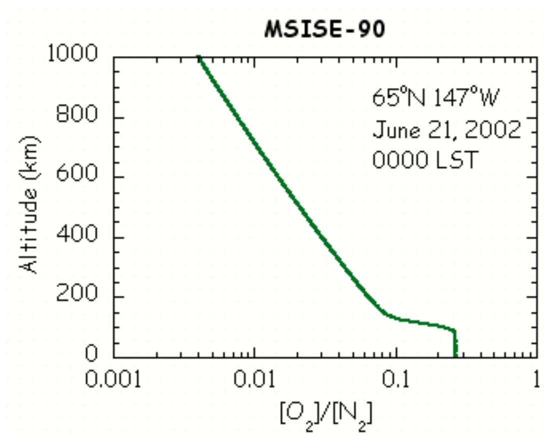


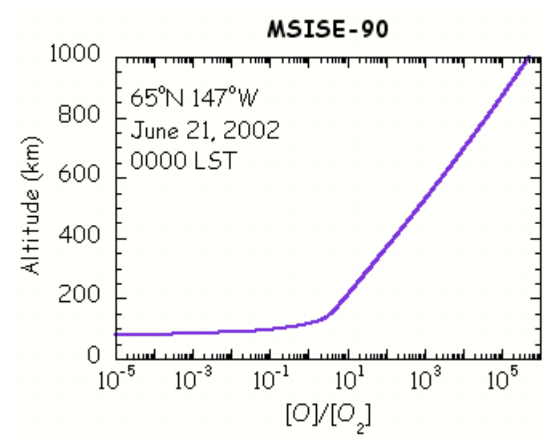
The Ionosphere and Thermosphere





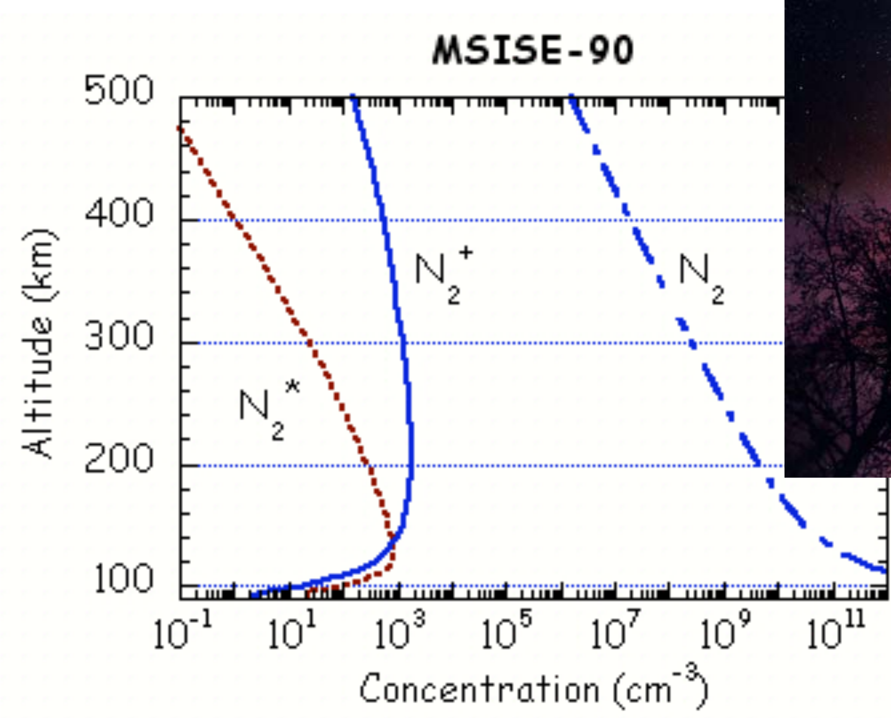






Courtesy to Richard Collins of UAF

The Aurorally-Modified Ionosphere



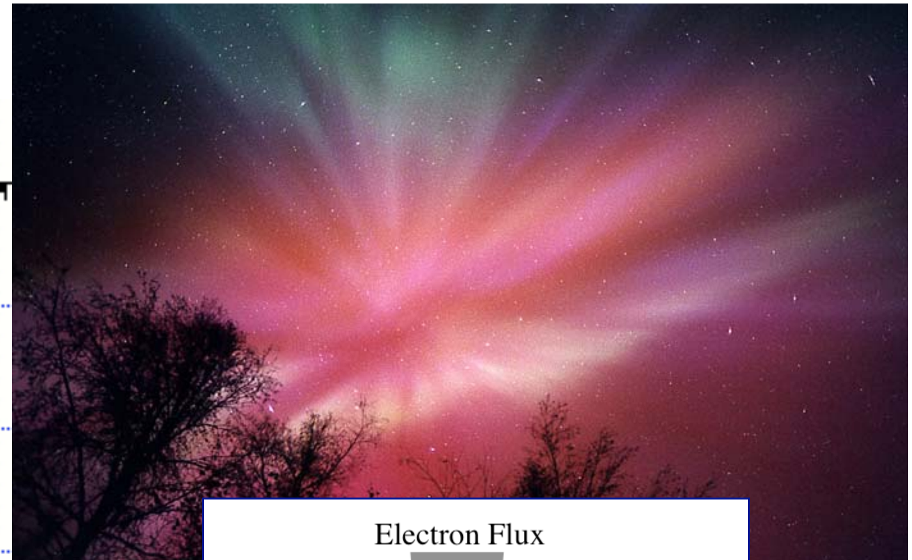
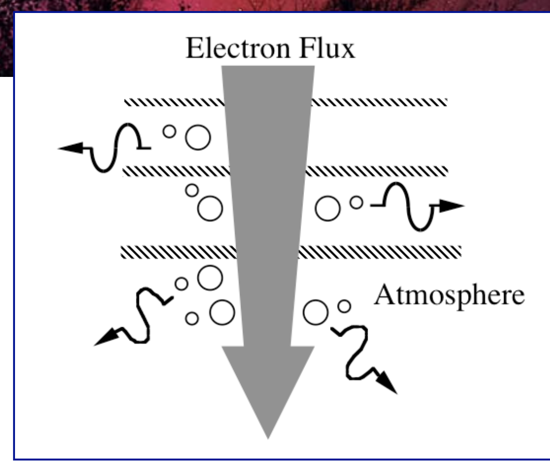


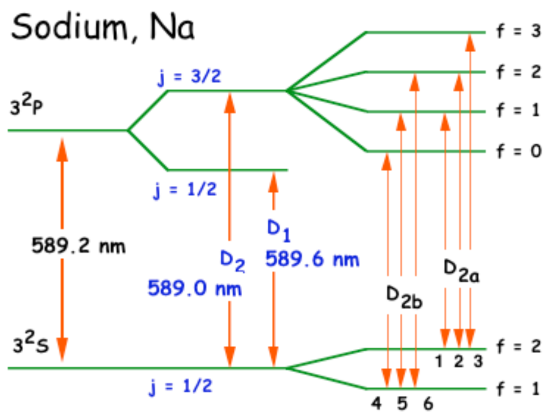
Photo courtesy of GI-UAF by Jan Curtis



The aurora modifies the composition of the ionosphere.

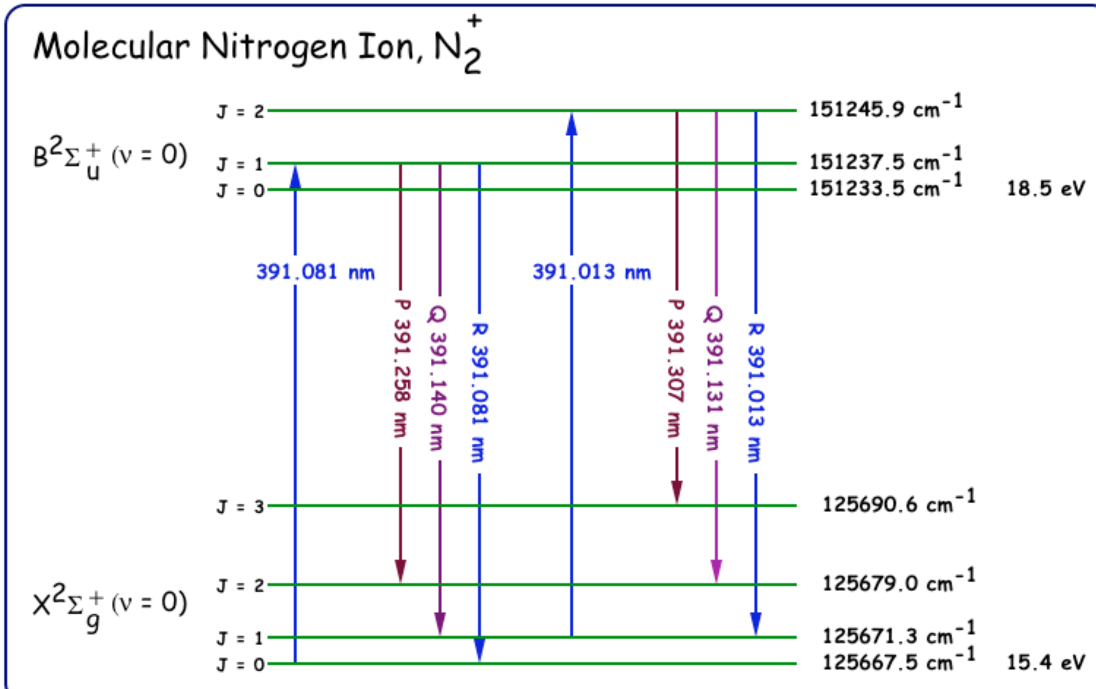
Courtesy to Richard Collins of UAF

The Spectroscopy of Molecules vs. Atoms



Frequency Shifts

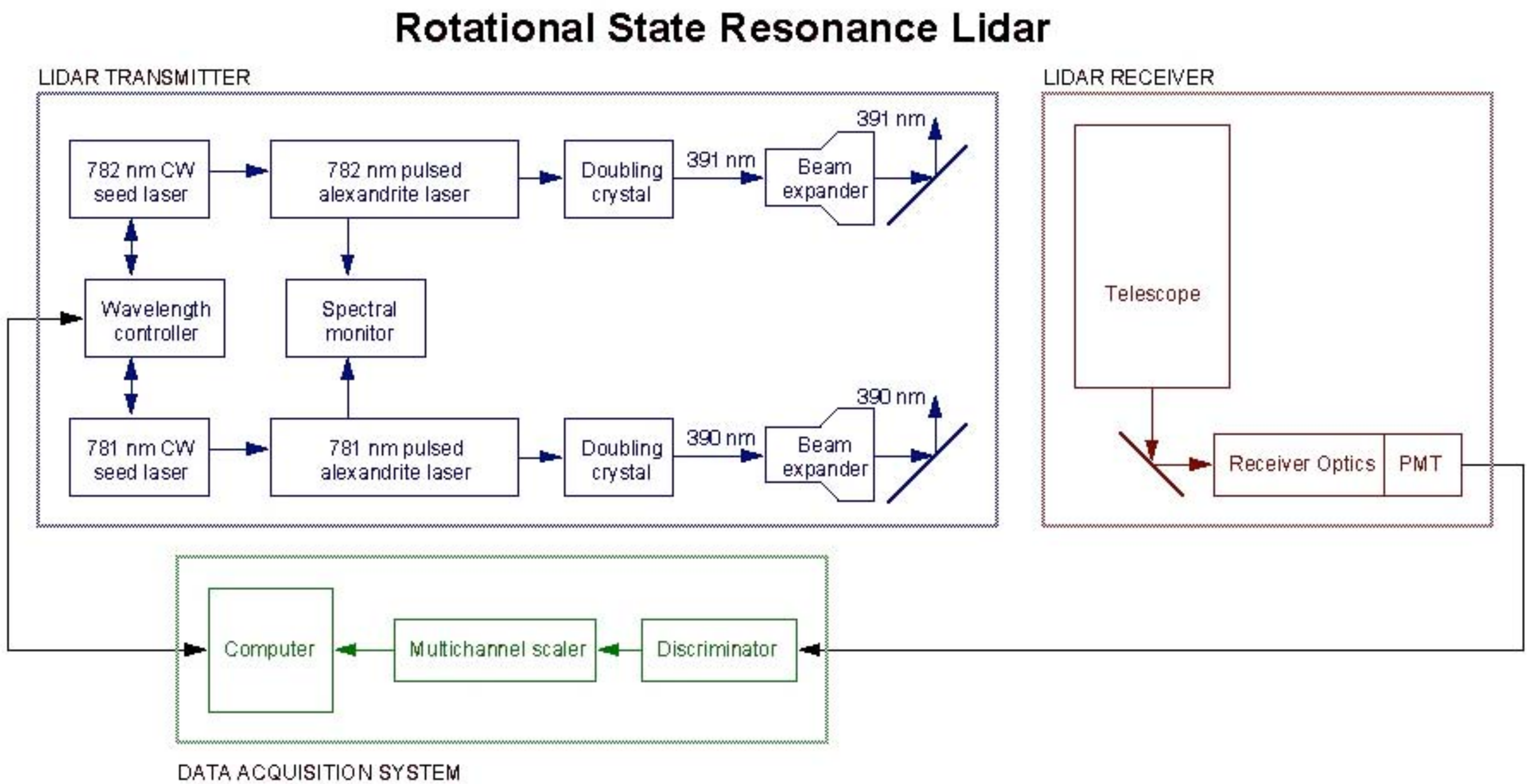
	D2a		D2b
1	-715.0 MHz	4	1040.8 MHz
2	-680.8 MHz	5	1056.6 MHz
3	-621.6 MHz	6	1091.1 MHz



Molecular spectroscopy has vibrational and rotational states.

Courtesy to Richard Collins of UAF

N_2^+ Boltzmann Temperature Lidar



A dual laser lidar system employing solid-state lasers could be used to profile two rotational states simultaneously and hence study the energy deposition in the auroral ionosphere.

Courtesy to Richard Collins of UAF

Summary

- Boltzmann technique utilizes Maxwell-Boltzmann distribution of atomic or molecular populations along different energy levels, which is directly temperature dependent.
- The temperature-dependent population ratio is inferred through the intensity ratio of two resonance fluorescence lines whose lower energy levels are the two energy levels that we concern.
- The key is to find the right energy level diagrams that are suitable to this measurement - energy separation is not too large or too small, and wavelengths fall in the laser reachable range.
- Boltzmann technique can be applied to not only the Fe Boltzmann lidar but also potentially to other molecular species like N_2^+.
- Boltzmann technique is also used in rotational Raman lidar and in airglow temperature mappers, like Bomem.