Lidar Measurements of Metal Atoms in the Middle Atmosphere: Plans for Detection of Space Debris Impact

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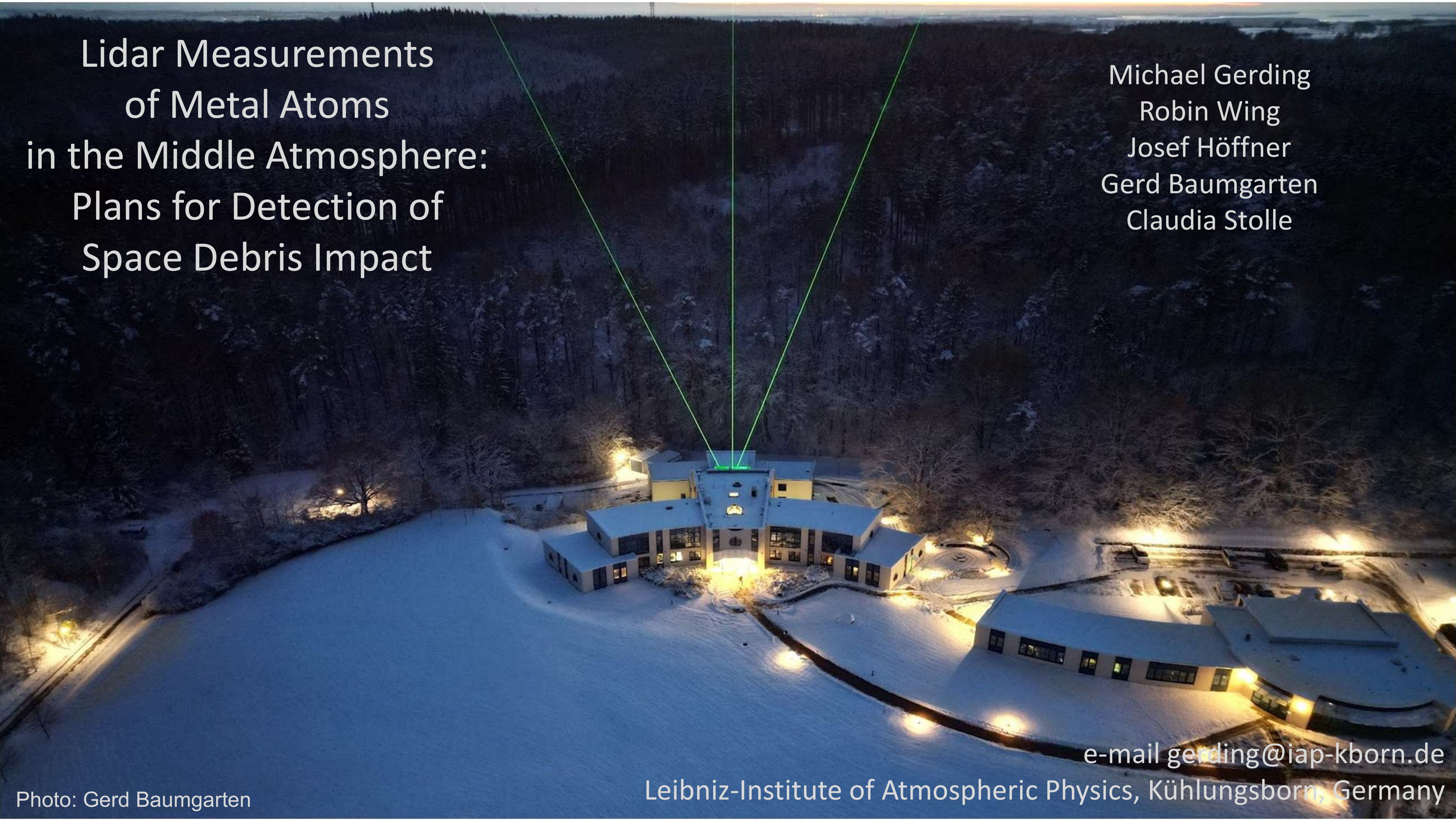
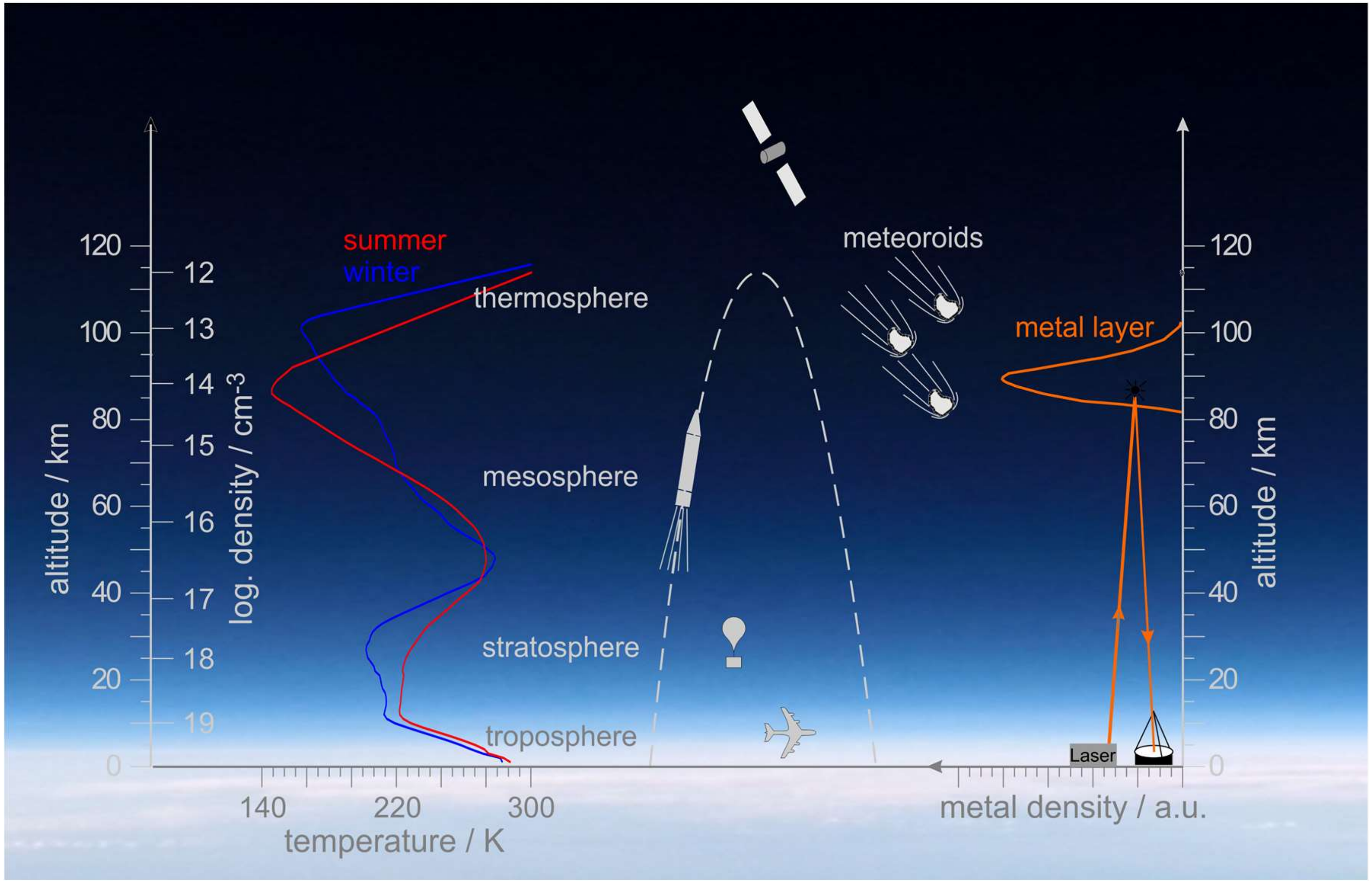
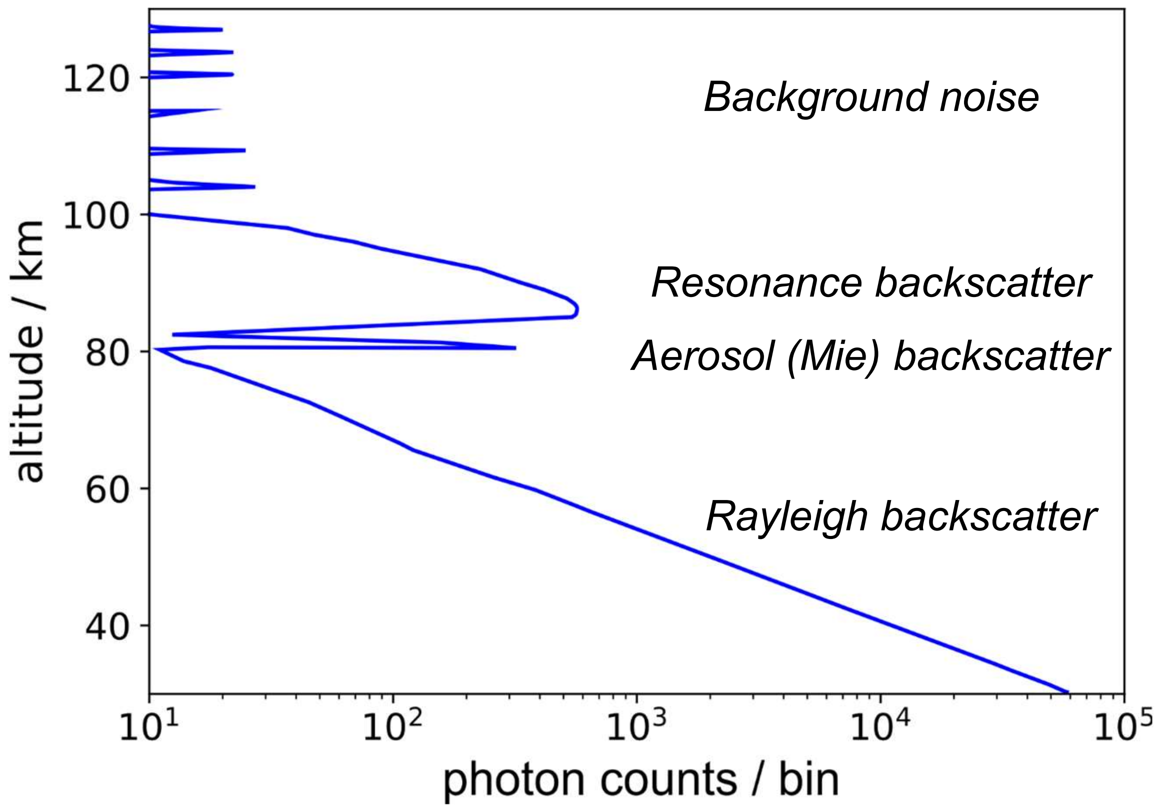


Photo: Gerd Baumgarten

Sounding of the atmospheric metal layer by lidar



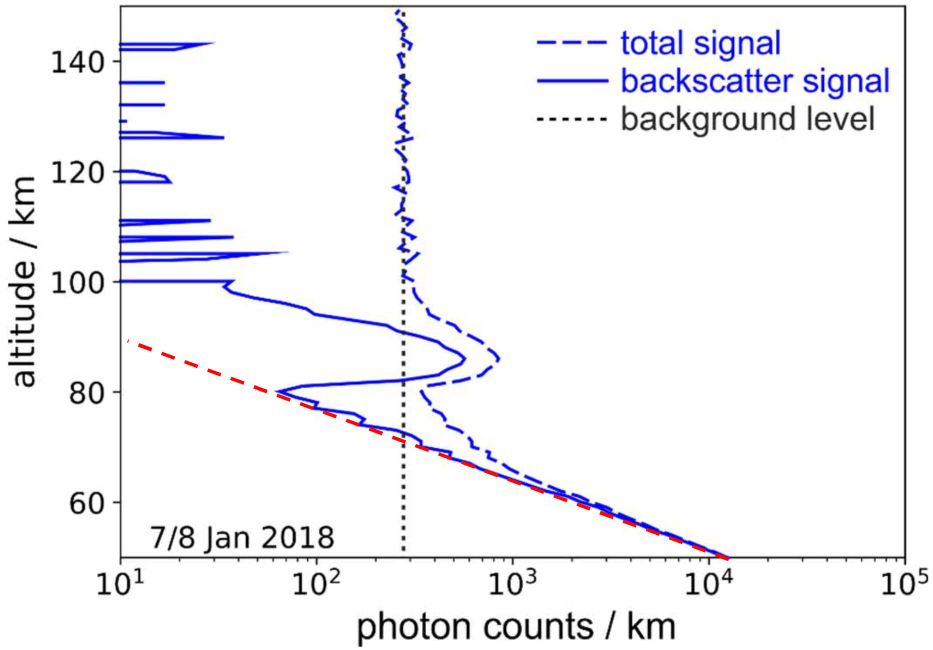
Lidar elastic backscatter profiles



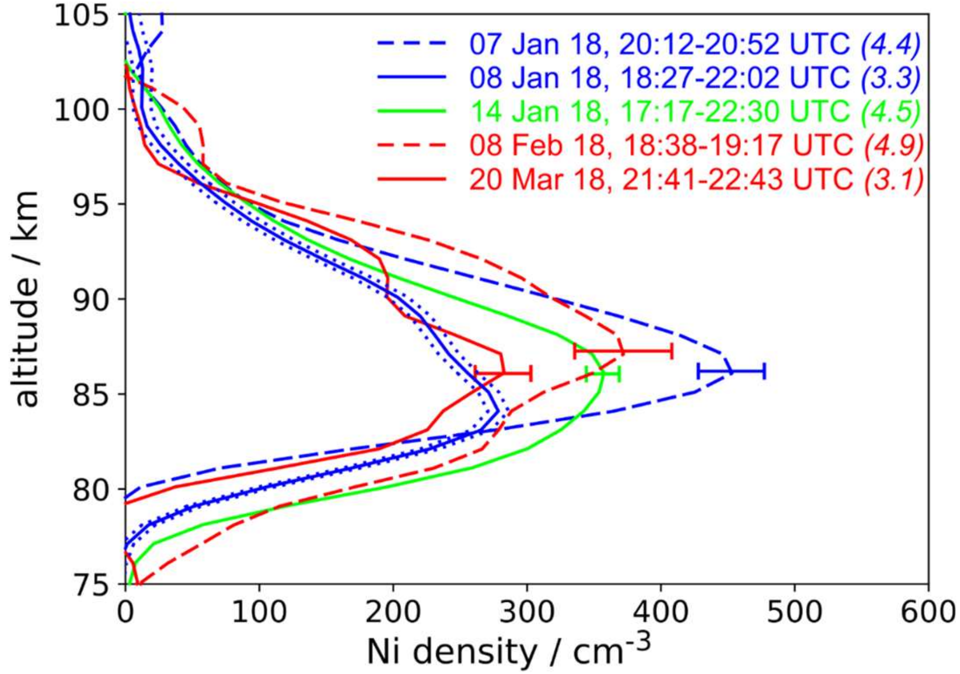
Photon budget:
- laser emission: 10^{18} photons / pulse
- 90% exported to space
- 10% scattered below 20 km
- 0.01% scattered between 20-100 km

Data products:
- *Air density variations*
- *Temperature*
- *Wind*
- *Aerosol load*
- *Metal densities*

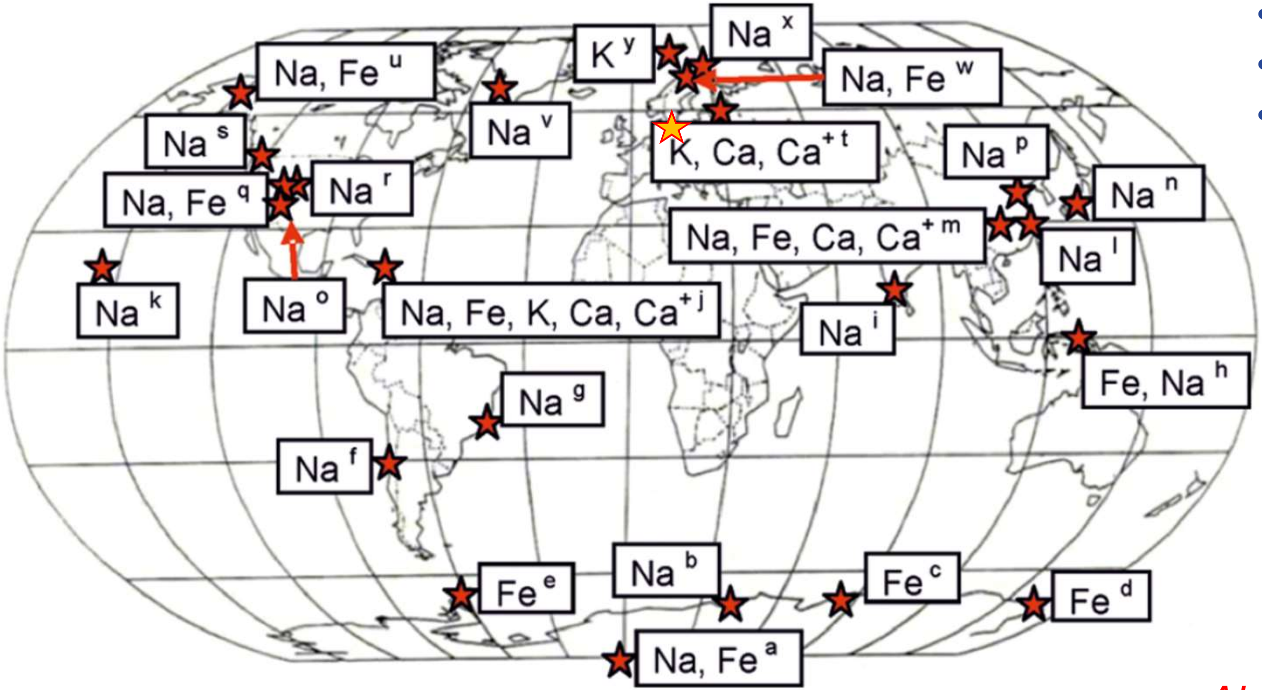
Ni observations at Kühlungsborn/Germany (54°N)



Gerding et al., GRL, 2019
(50 years after the first metal lidar measurements by Bowman, 1969)



Lidar soundings of different metals



Plane et al., Chem. Rev., 2015

Additional observations:

- Lithium (Jegou et al., 1980)
- Nickel (Gerding et al., 2019; Wu et al., 2021)
- AlO upper limit (Plane et al., 2021)

About 10 stations still active.
➔ Most metal lidars are dedicated to Na or Fe for Doppler temperature and wind soundings, not primarily for metal density measurements

Anthropogenic metals in the atmosphere

Schulz and Glassmeier, Adv. Space Res., 2021

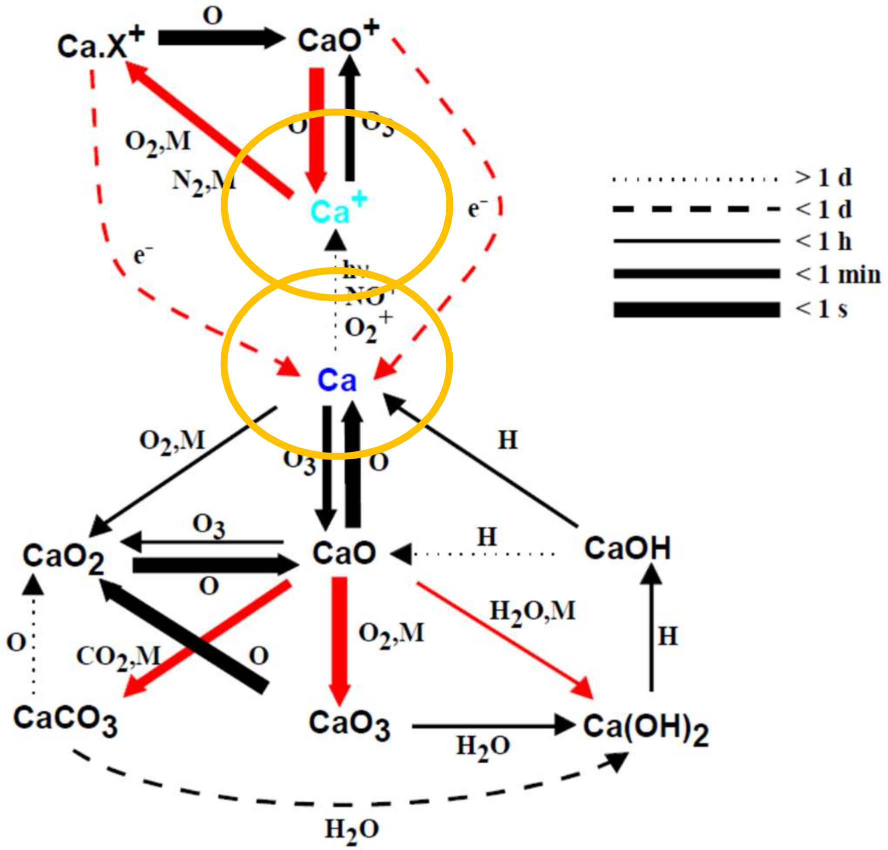
El.	Anthropogenic Today		Scenario 1		Scenario 2		Natural injection
H							220
C	0.1	(0)	0.2	(0)	0.5	(0)	1,054
O							3,851
Mg	0.04	(0)	0.1	(0)	0.3	(0)	1,300
Al	211	(161)	807	(614)	2,467	(1,877)	131
Si	8	(0)	76	(5)	251	(15)	1,654
S							513
Ti	7	(100)	52	(754)	171	(2,459)	7
Cr	7	(20)	17	(47)	48	(131)	37
Fe	36	(2)	160	(7)	496	(22)	2,295
Ni	23	(25)	89	(99)	272	(304)	90
Cu	15	(720)	38	(1,747)	106	(4,923)	2
Ge	4	(776)	37	(7,973)	124	(26,435)	0.5

Table 6: Anthropogenic and natural injection of some selected elements. Masses are given in t/yr. The numbers in parenthesis depict the percentage compared to the natural injection value in the respective row. Note that percentages larger than 100 % indicate that these elements are mainly of anthropogenic origin. For some elements, no anthropogenic abundances were calculated.

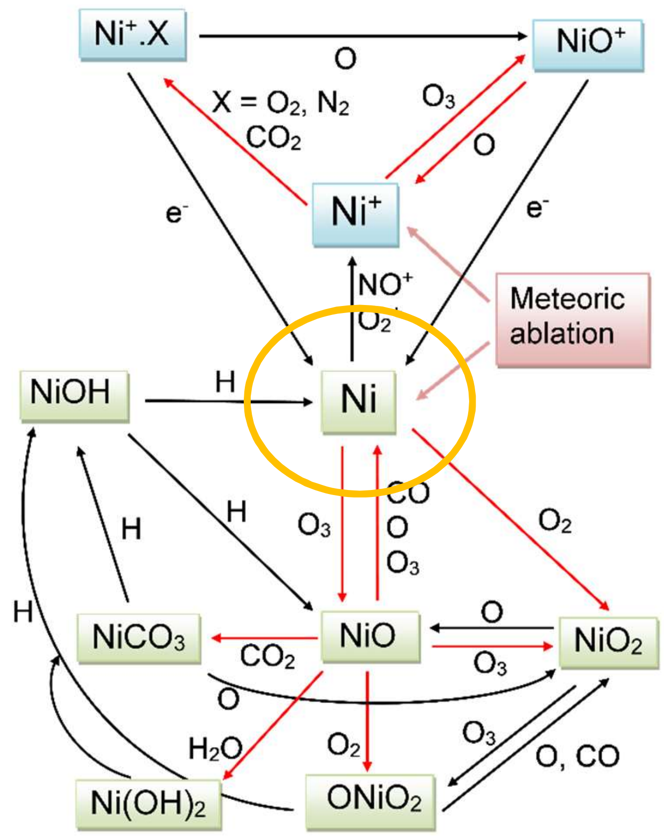
Further candidates
(not abundant in cosmic dust)

- Lithium — *observed by lidar*
- Niobium
- Hafnium
- Silver
- Lead

Metals exist in compounds and as atoms

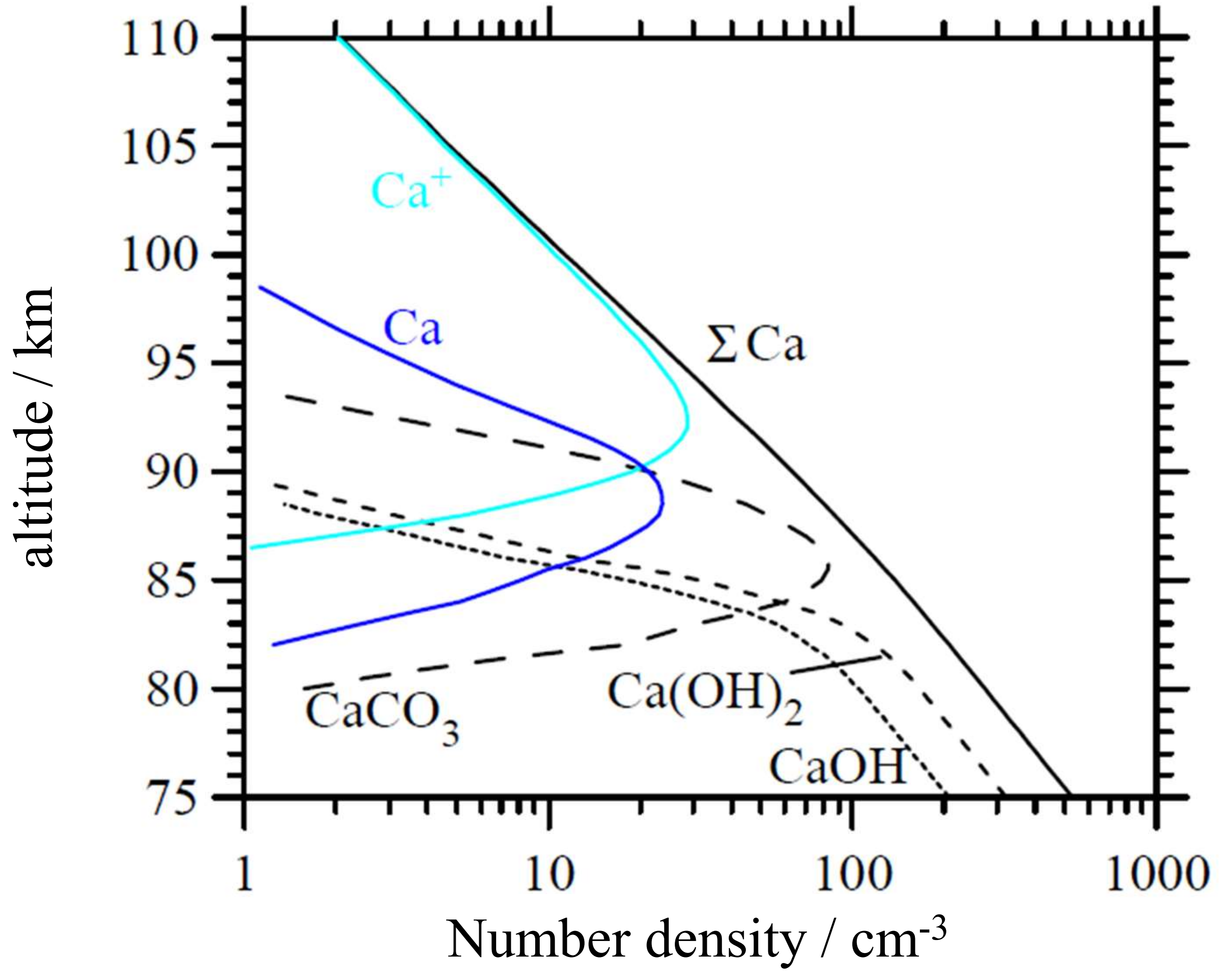


Gerding et al., JGR, 2000



Daly et al., JGR, 2020

Altitude variation of metal atoms and compounds



Metals in the lower mesosphere and stratosphere do not exist as atoms but compounds.

→ *Upward transport by diffusion and global circulation needed for detection*

Gerding et al., JGR, 2000

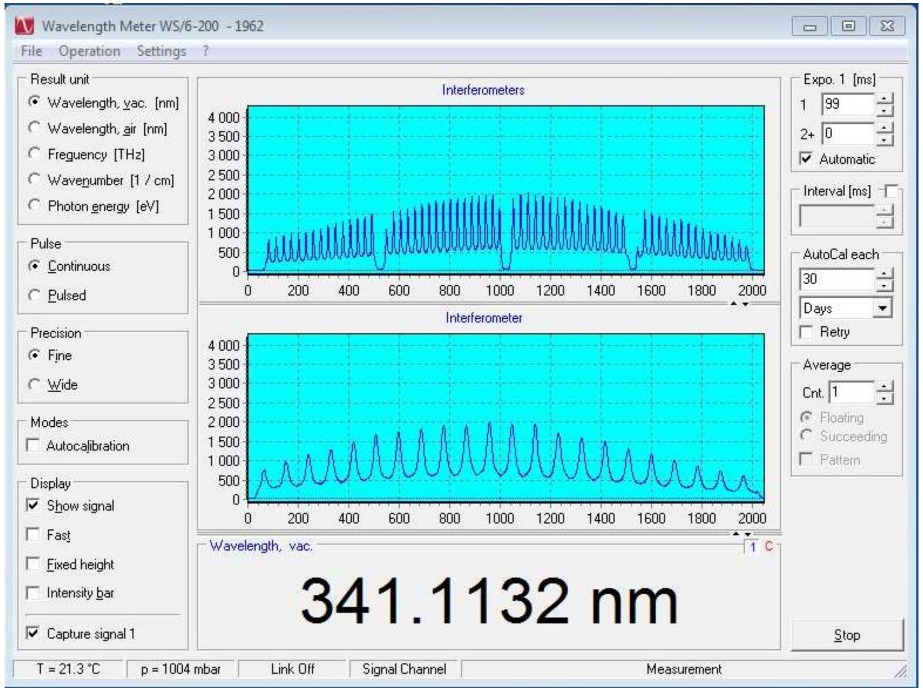
What do we need for space debris detection?

Geophysical prerequisites:

- Metals in atomic state (no metal compounds)
- Low natural abundance
- Anthropogenic abundance above detection limit

Technical prerequisites:

- Powerful and tunable metal resonance lidar, e.g. with dye laser ✓
- Second metal resonance lidar, e.g. Na (for detection of natural trends) ?
- Calibrated wavelength meter ✓
- Capabilities for long-term measurements (✓)

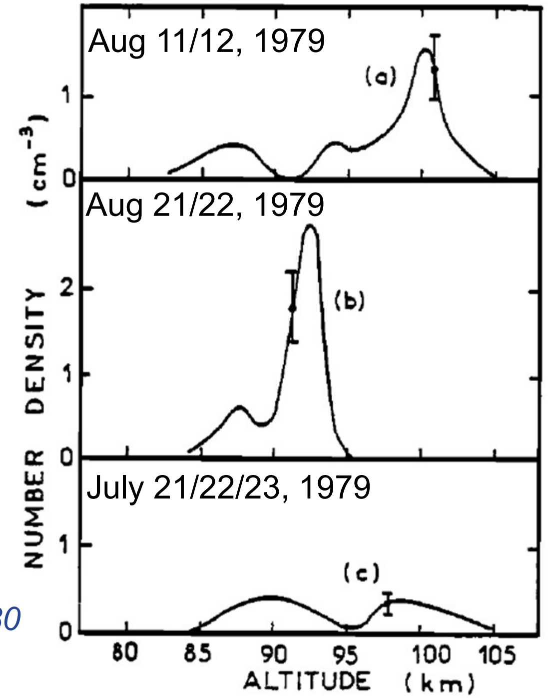


Calibrated wavemeter (accuracy 0.2 pm / 500 MHz)

Candidate metals

Lithium:

- very low natural abundance
- detected >40y ago with specialized (powerful) lidar



Jegou et al., GRL, 1980

Lithium signal estimate		
	Jegou 1980	IAP
Laser power /mJ	800	30
Laser reprate /Hz	2	30
tel. area /m^2	0.5	0.5
Quantum efficiency /%	30	70
IF transmission /%	100	90
sigma_eff / m^2/sr	4.15E-17	7.66E-17
product	9.96789E-11	2.1727E-10
factor		2.18

Candidate metals

Lithium:

- very low natural abundance
- detected >40y ago with specialized (powerful) lidar

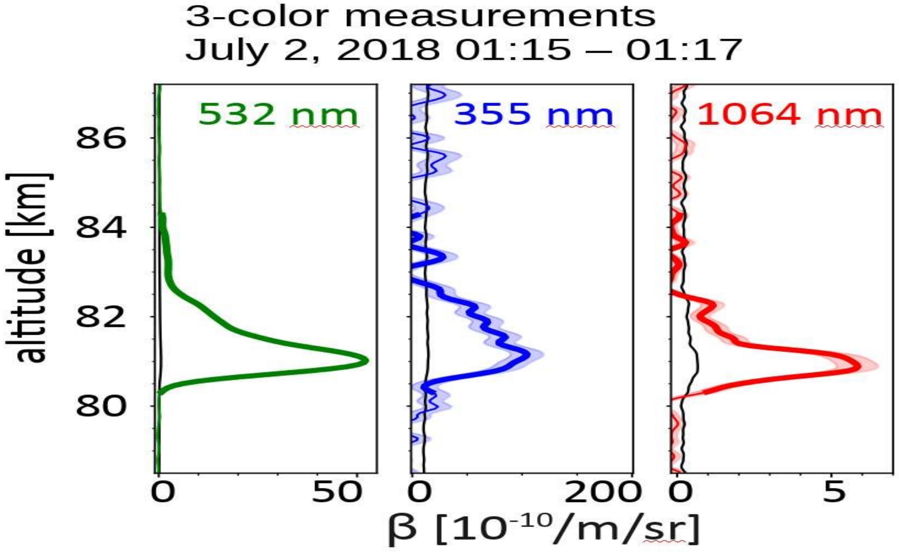
Nickel:

- large anthropogenic source expected in future scenario
- natural layer recently observed by lidar

Copper, Hafnium, Niobium, Germanium, …

- very low natural abundance, but is the anthropogenic injection large enough???
- not yet detected in mesopause region
- backscatter cross sections and chemical rates to be checked
- → *speculative*

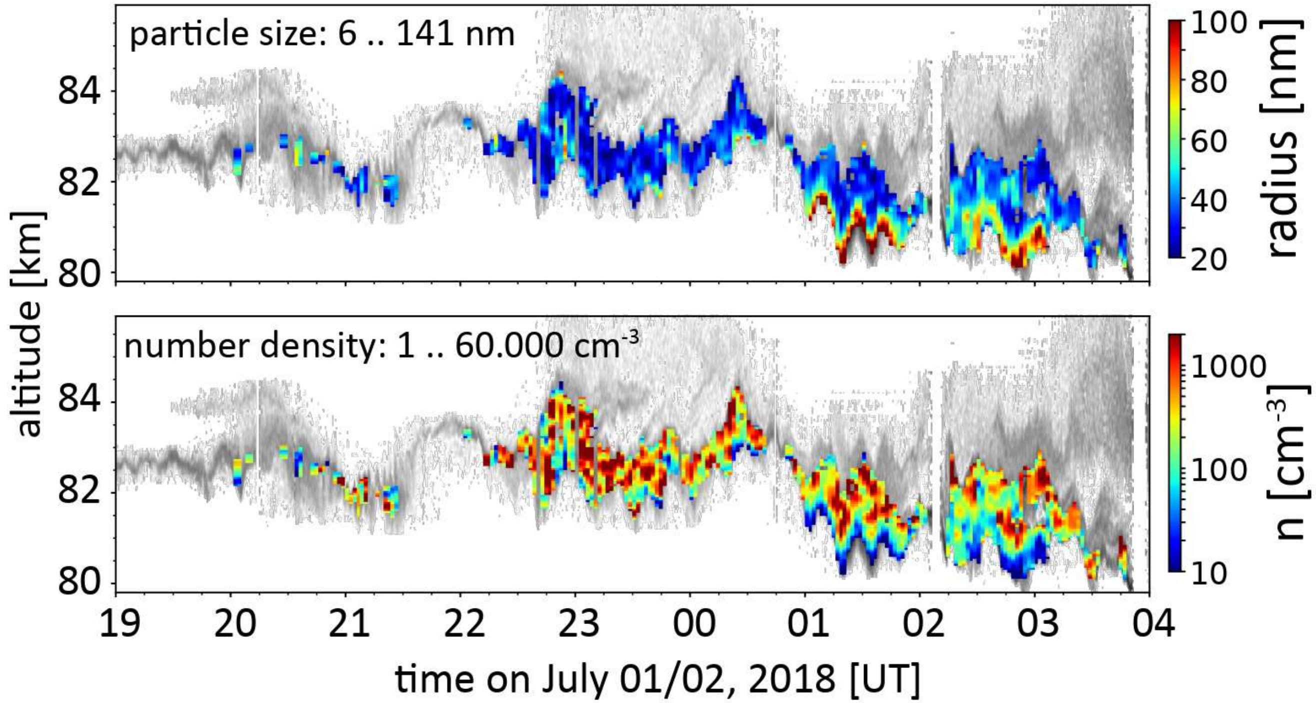
Aerosol particle size measurements by lidar



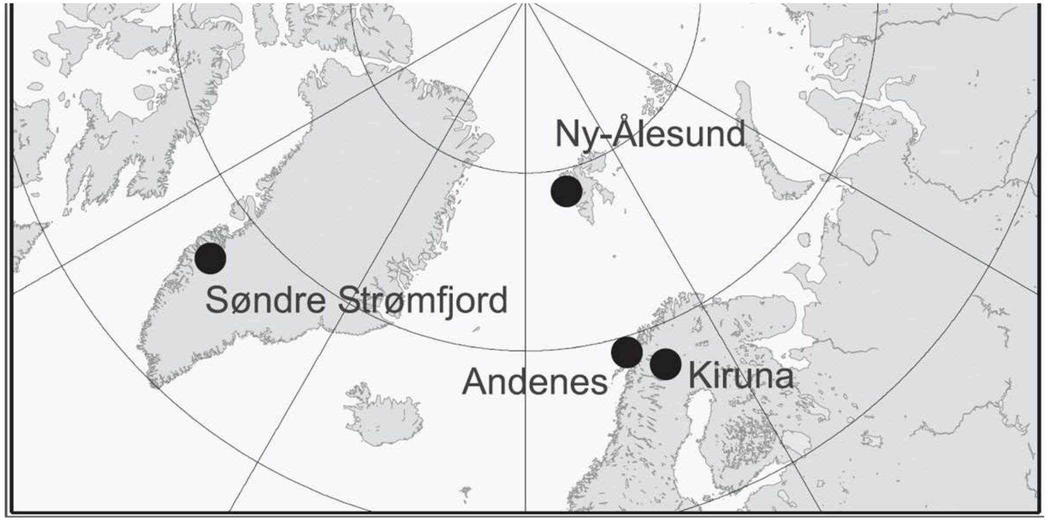
T-Matrix model for spheres, spheroids and cylinders

→ *mean size*
→ *width of the size distribution*
→ *number density*

With more parameters:
phase and refractive index



“Rocket aerosol layers” in the stratosphere?



Gerding et al., Ann. Geo., 2003

- Layer observed mid-November 2000 to mid-February 2001
- 3 wavelength + depolarization
- Solid particles (soot, Al_2O_3, SiO_2, Fe) of 30 - 50 nm radius
- Total cloud mass (lower limit): 200 - 2000 kg

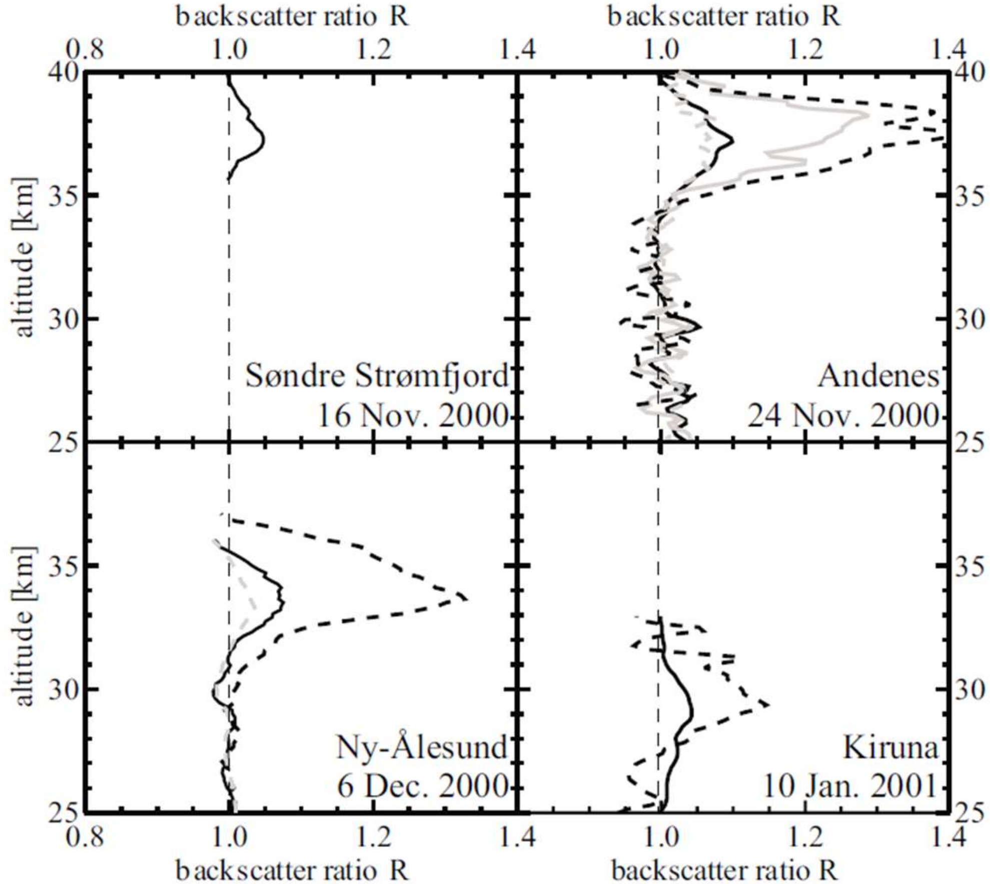
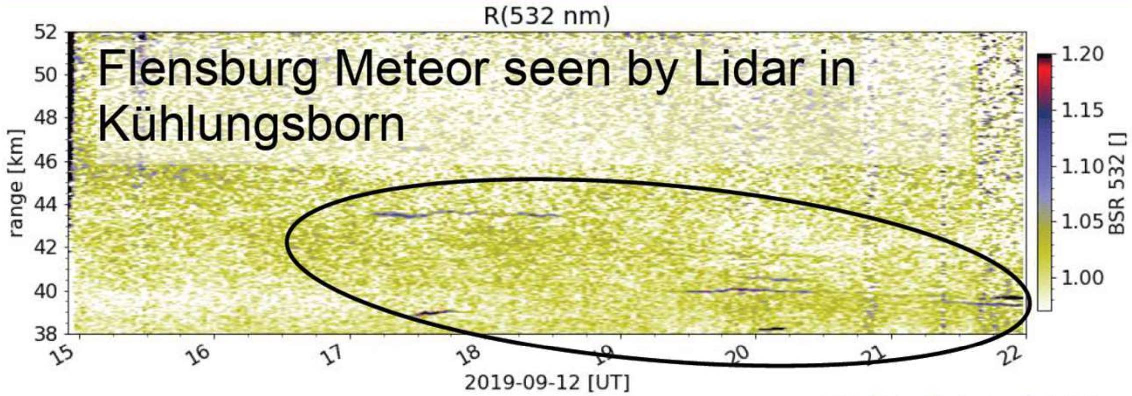


Fig. 2. Daily mean profiles of backscatter ratio for representative observations of the aerosol layer at each lidar station. Grey dashed: 355/353 nm (Andenes/Ny-Ålesund); solid black: 532 nm parallel polarised / non-polarised; black dashed: 532 nm perpendicular polarised; solid grey: 1064 nm.

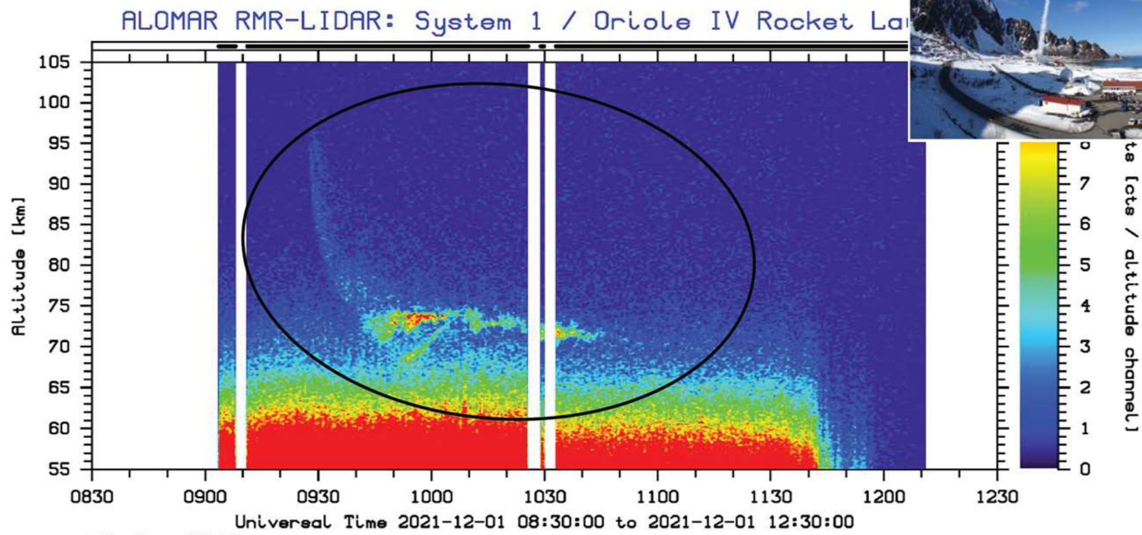
Middle atmosphere aerosol detections by lidar



- ➢ rare observations at Kühlungsborn and ALOMAR/Norway
- ➢ Specialized lidar for MSP currently under development

Kühlungsborn about 170 km away from trajectory

- NASA Oriole IV / Andoya Space 4 stage vehicle: Talos + Terrier Mk 70 + Oriole + Nihka.

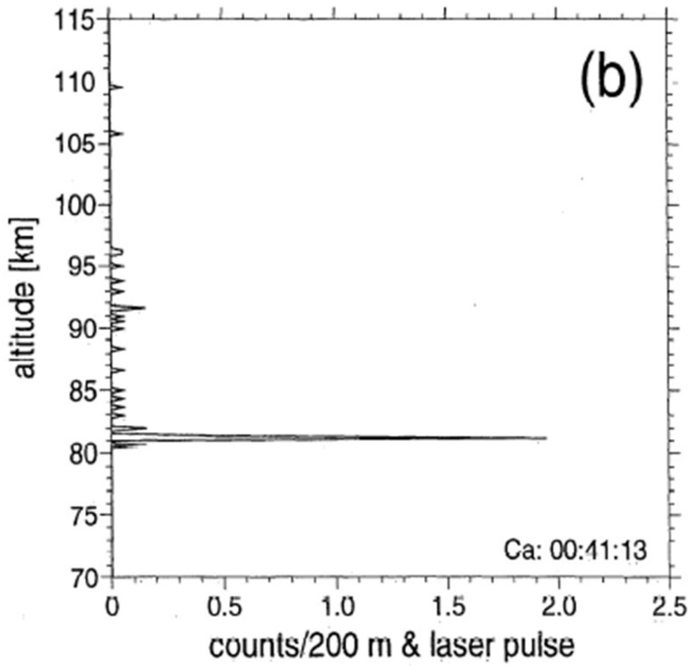


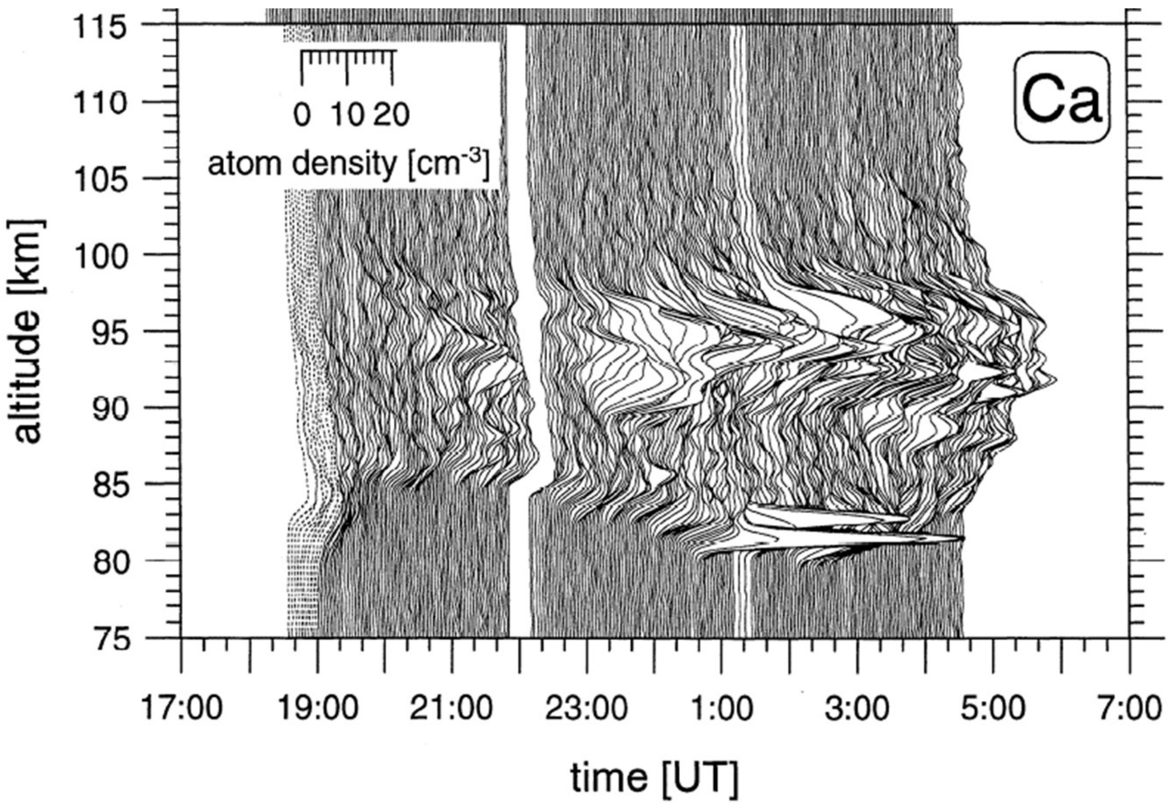
Fiedler, 2023

Observation of nearby ablation trails drifting through the lidar beam

Gerding et al., JGR, 1999

Kühlungsborn, March 6/7, 1997





Summary

- IAP has a long tradition of metal layer observations at different sites
- Satellite debris is expected to form an additional metal source, partly exceeding natural sources
- Metals in atomic state can be observed by lidar if density and backscatter cross section is sufficiently large
- State-of-the-art metal lidar with wavelength calibration needed
- Plans for repeating the 1980ies observations of Lithium (spring 2024)
- Depending on results and funding
  - further survey of different metals
  - setup of independent lidar for undisturbed layers
  - decide about location for long-term observations
- Ongoing observations of middle atmosphere aerosols

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