On radar detection of ultra-high energy extensive air showers

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JPL Tracking Systems & Applications Section 335

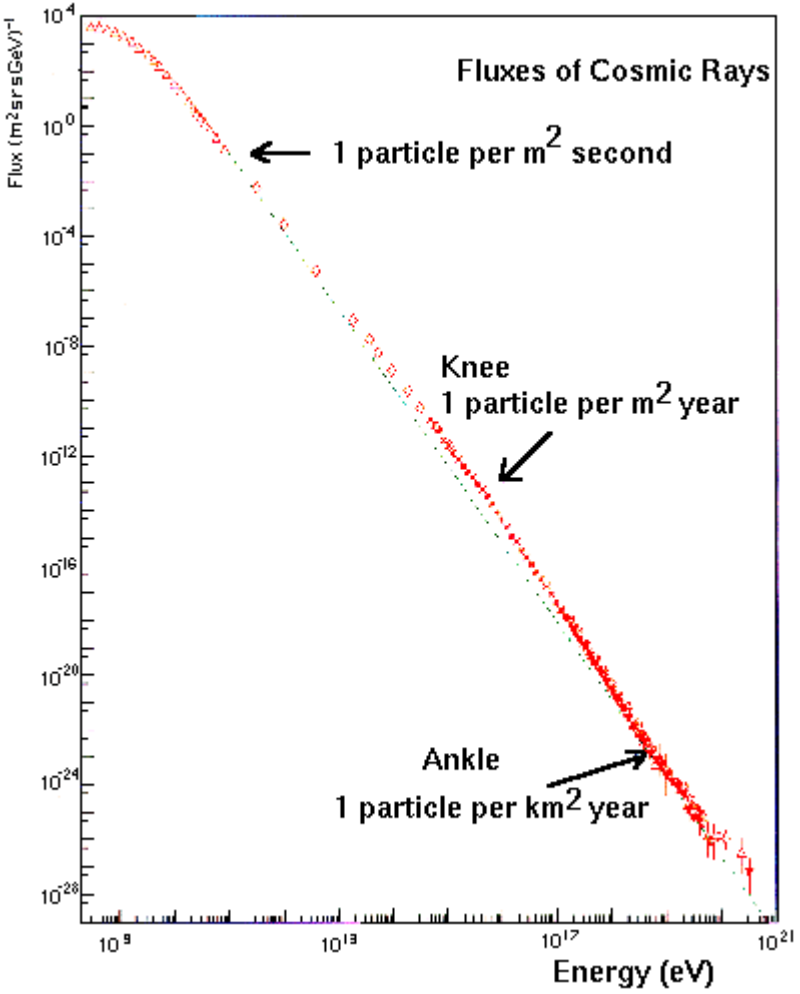
RADHEP 2000

Highest Energy Cosmic Rays & Detectors

Volcano ranch, US

Fly's Eye, Utah

Yakutsk, Russia



AGASA array, Japan

- EHECR >1e18 eV seen since 60's
- No energy cutoff seen, events to > 3e20 eV
- Sources almost certainly extragalactic, but ***how do they evade photopion production on 3K photons??***

Pre-WWII “radar”: did it detect air showers?

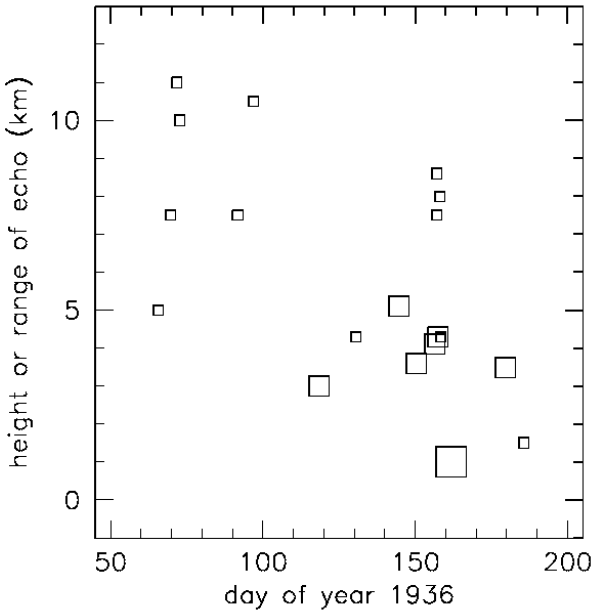
• Colwell & Friend (1937), Appleton & Piddington (1936) & many others saw sporadic transient echoes from 1-10 MHz pulsed “radar”

• Blackett & Lovell (1940) proposed that this *could be due to very large air showers* that had recently been shown to exist by P. Auger

• B& L cosmic ray flux estimates & radar cross section were remarkably good--but did anyone ever test this proposal?

• K. Suga (1962) & T. Matano et al (1968) revisited the problem, but with flawed analysis, and no results ever reported.

• No further reports or results to the present...



Data from Colwell & Friend (1937) showing dates when “strong” “very strong” or “extra strong” echoes were seen at the plotted altitudes.

• Frequency was 1.6 MHz, with a 3 microsec pulse, 200 W peak.

• By modern analysis, they should have had Ethr ~ 10^17 eV,

• the observed rate is consistent with a ~1% efficiency.

Meteor ionization reflections

Basic reflection geometry

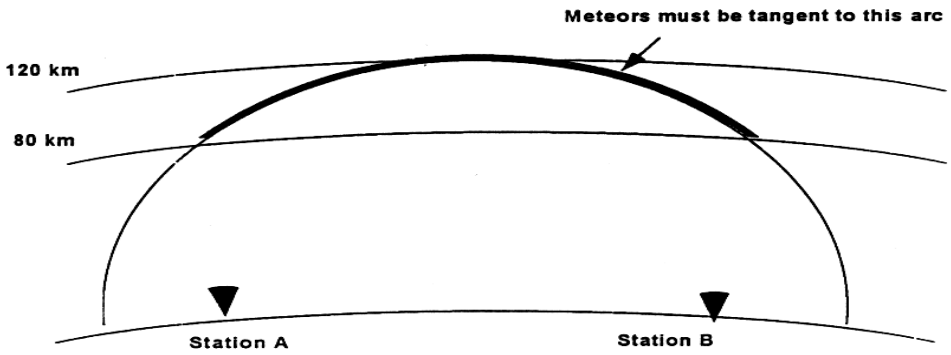
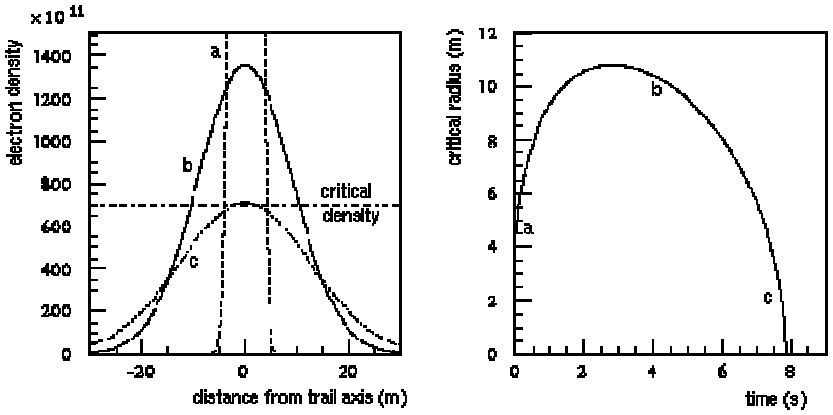
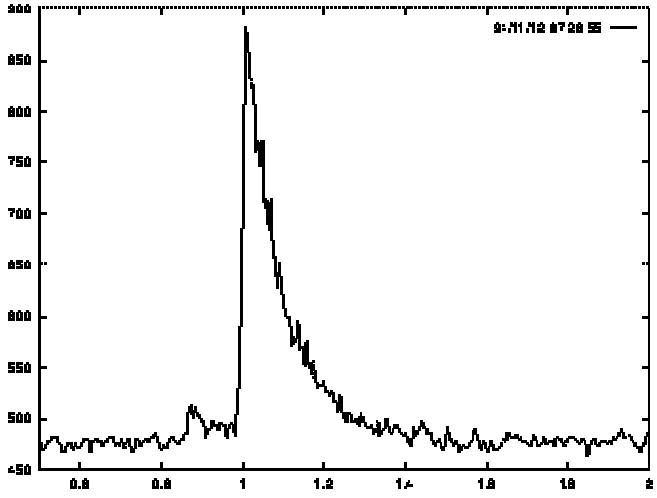


Figure 2 Constraint of Meteor Trails

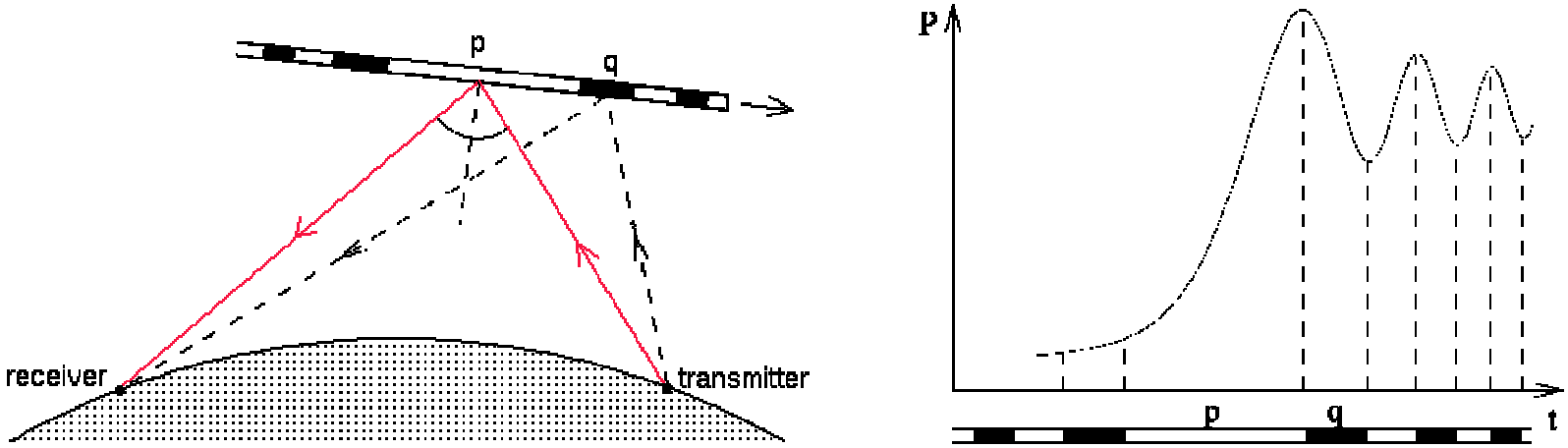


Ionization density & plasma frequency determine over- vs under-dense regime. Diffusion eventually dissipates the column.

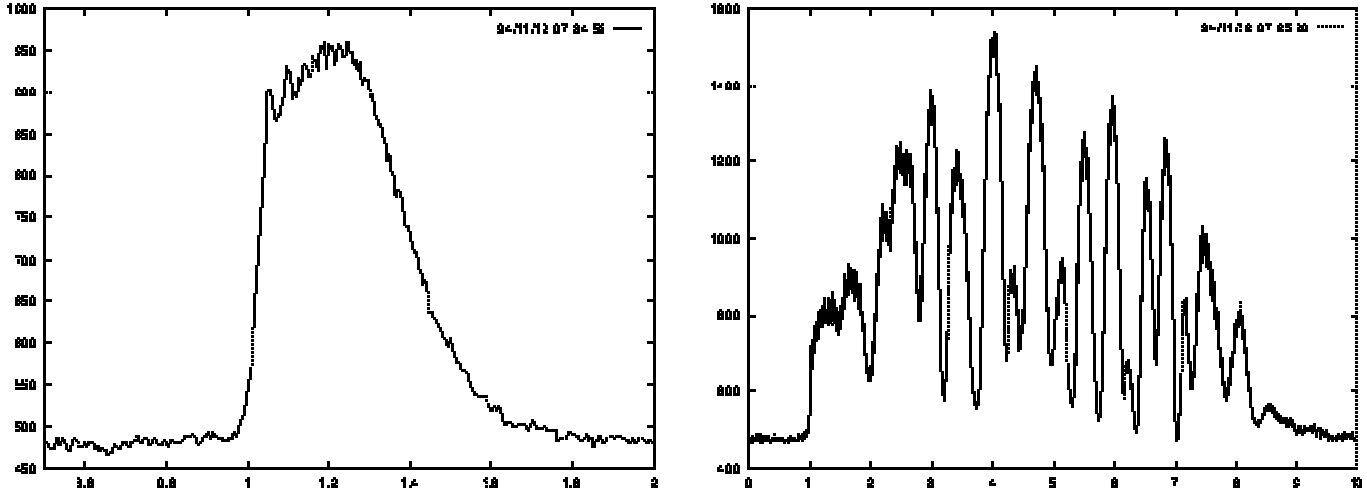


A typical reflection from an underdense meteor trail

Interference effects in meteor reflections



Multipath effects in scattering geometry



Overdense reflections showing varying degrees of interference

Recipe for determining EAS radar echo detectability

1. Determine ionization density vs shower energy & altitude

2. Determine lifetime of free electrons in the air column
   - gives the maximum time scale for radar interrogation

3. Determine the total radar cross section of the electrons
   - depends on plasma characteristics, radar wavelength

4. Specify the radar power & pulse characteristics

5. Estimate echo SNR from the radar equation
   - will depend on assumed background: thermal, RFI?

Extensive Air Shower ionization profile

Giant EAS can be parameterized by primary particle energy & shower depth (Kamata & Nishima '58, Greisen '65), giving number of HE electrons:

$$N_e \;=\; \frac{0.31\exp[(d/X_0)(1-1.5\ln s)]}{\sqrt{\ln(E/E_{crit})}}$$

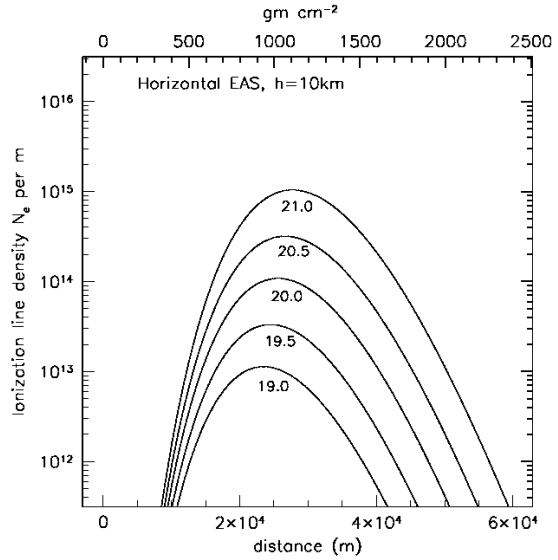
Where *s* is the *age parameter* relative to the shower maximum. Tranverse distribution is a power law:

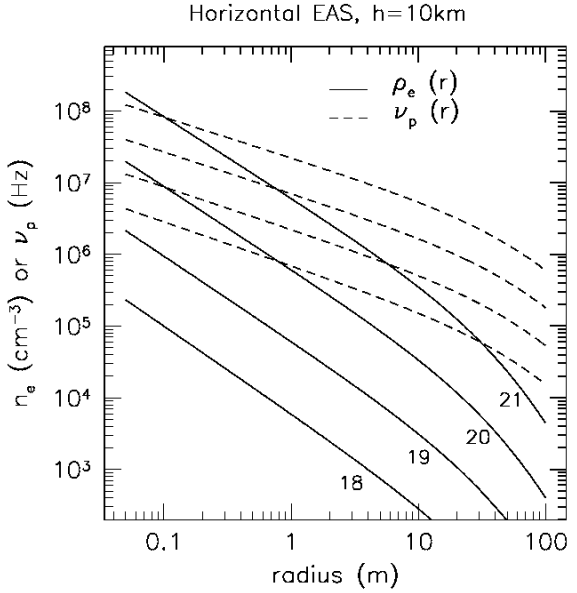
$$\xi_e \;=\; K_N\,\left(\frac{r}{r_m s_m}\right)^{s-2}\left(1+\frac{r}{r_m s_m}\right)^{s-4.5}$$

Where r_m is the Moliere radius ~ 70m at sea level.

Shower electron energy goes mostly into ionization with a yield of about 1 ion pair per 34 eV energy. Top figure shows electron line density for various EAS energies. Once the density profile is known (bottom fig), the plasma frequency can also be estimated:

$$\nu_p = \sqrt{(n_e e^2/\pi m_e)} \simeq 8.98\times 10^3\sqrt{n_e}\ \mathrm{Hz}$$





Electron attachment issues

• **Process: e + O2 => O- + O**

• Early work estimated attachment rate based on eletron swarm data from 20's & 30's, predicted 1-10 microsec free electron lifetimes

• But: air samples were not CO2 free, not always dry--strong effects!

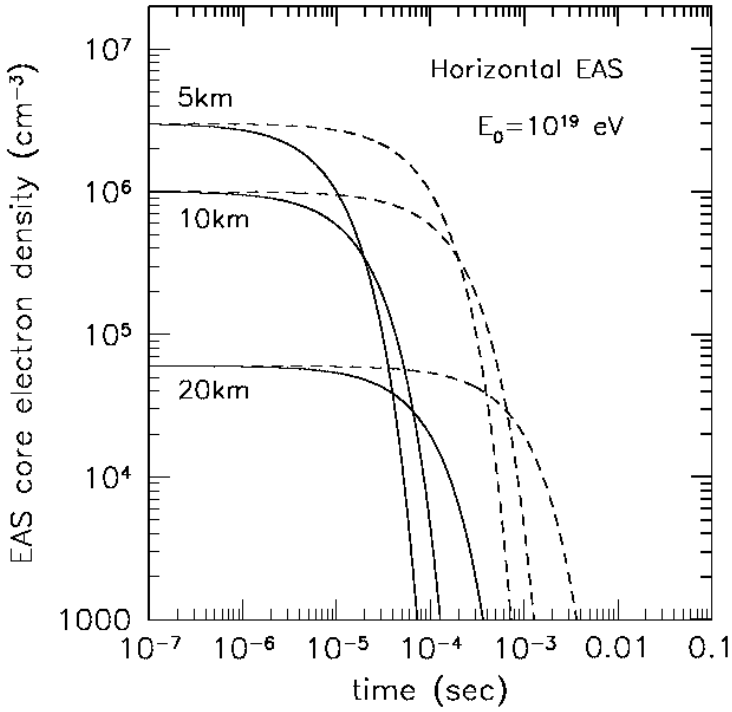
• Moruzzi & Price (1974) found *no attachment* in pure air at limits <2% of early measurements:

cross section< 3e-20 cm^2

• Their work suggests that N2 may mediate rapid detachment in pure air:

Process: O- + N2 => products + e

• If detachment cross section is large, lifetime could be 1-10 ms or more



Plot of free electron number evolution for three horizontal shower altitudes, and two values of attachment coefficient: M&P limit (solid line) and 10% of M&P limit.

Radar cross section (RCS)

•Defined as the equivalent area of perfect reflector that would produce the same return power if uniformly scattered

•RCS can be much smaller or much larger than physical cross section, depending on geometry of scattering surfaces, materials, resonance effects

Object	RCS (m^2)	Xsection (m^2)
Pickup truck	200	10
Commercial jet	100	1000
Large fighter aircraft	6	100
Bird	0.01	~0.01
Stealth fighter	0.000001	70

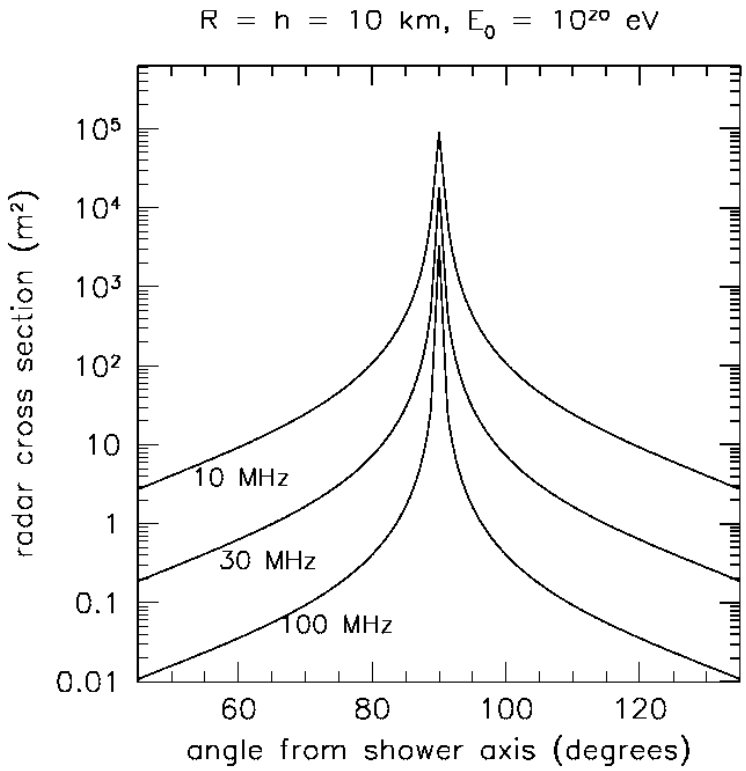
Overdense Case: EAS ionization column looks like a long, thin wire

• Radar scatters from plasma surface at critical density => like a metal cylinder

• Details depend on polarization & angle, “traveling wave” resonances are also present

• Thin wire approximation gives a first order estimate for EAS:

$$\sigma_b^{od}(\theta) \simeq \frac{\lambda^2 \tan^2\theta \cos^4\phi}{16\pi\left[\left(\frac{\pi}{2}\right)^2 + \left(\ln[\lambda/(1.78\pi r_c \sin\theta)]\right)^2\right]}$$



Underdense case: volume scattering of electrons

• Electrons scatter independently with the Thomson cross section 6.7e-29 m^2

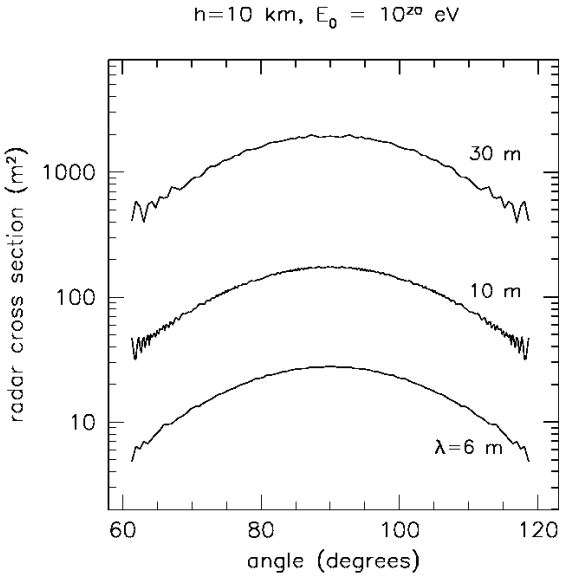
• Radar echo strength depends on the phase factors of the individual electrons:

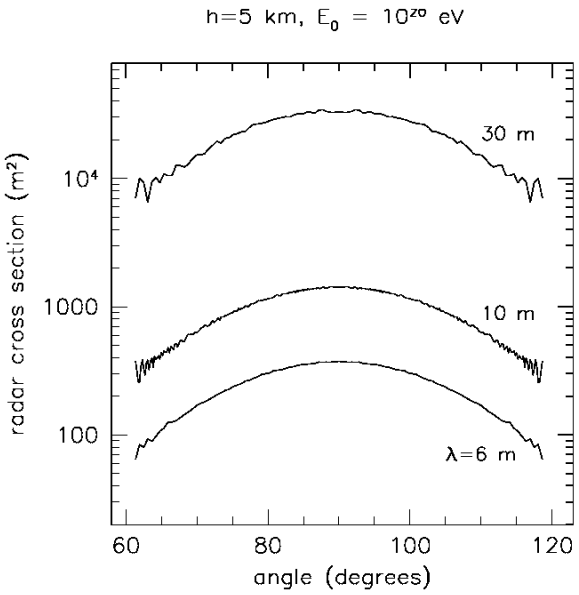
$$\sigma_b^{ud}(\mathbf{k}) = \left| \int n_e(\mathbf{r}) \sqrt{\sigma_T} e^{2i\mathbf{k}\cdot\mathbf{r}} d^3\mathbf{r} \right|^2$$

• The integral sums all of the e- scattering amplitudes using the two-way phase 2kr

• Equivalent to a 3-d Fourier transform of the electron density distribution

• => Radar echoes from EAS measure Fourier components of the electron density of the shower





Pulse reflection from diffuse ionization column

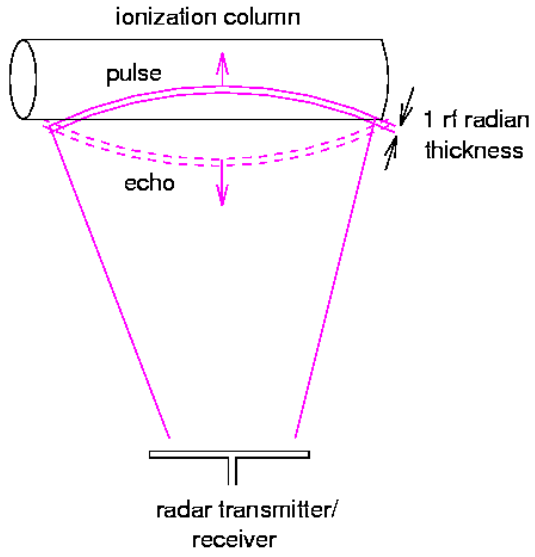
Pulse reflection from diffuse plasma target: a “Green’s function” analog approach:

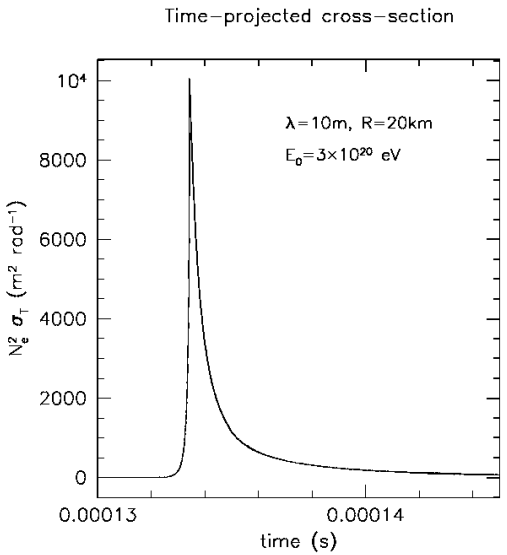
- All e- within a spherical shell of thickness << 1 wavelength produce an in-phase echo
- If we sum their scattering amplitude and project it on the time axis, we get a 1-dim Green’s function response:

=> “Time-projected cross section”:

$$Y(t)\Delta t \;=\; \sqrt{\sigma_T}\int_{r-t/4c}^{r+t/4c} n_e(\mathbf{r})d^3\mathbf{r}$$

Once this TPCS is estimated, pulse response is determined by convolving any pulse *amplitude* (not power) profile with the TPCS, and squaring it to get the actual RCS for the shower





Radar equation & radar echo SNR

The radar equation relates received power to RCS, transmitted power, antenna efficiency & gain, wavelength, and range

SNR is then estimated by comparing system noise, which depends only on bandwidth and system temperature:

$$\frac{P_r}{P_N} = \sigma_b P_t \eta \frac{G^2 \lambda^2}{(4\pi)^3 R^4} \frac{1}{k T_{sys} \Delta f}$$

Evaluating this for parameters appropriate to EAS detection gives:

$$\frac{S}{N} = 3.3 \left(\frac{\sigma_b}{1\ \mathrm{m}^2}\right) \left(\frac{P_t}{1\ \mathrm{kW}}\right) \left(\frac{\eta}{0.1}\right) \left(\frac{G}{10}\right)^2$$
$$\times \left(\frac{\lambda}{3\ \mathrm{m}}\right)^2 \left(\frac{R}{10^4\ \mathrm{m}}\right)^{-4} \left(\frac{T_{sys}}{10^3\ \mathrm{K}}\right)^{-1} \left(\frac{\Delta t}{10\ \mu\mathrm{s}}\right)$$

This assumes a pulse of width delta-t = 1/delta-f-- but this will depend on the type of *pulse compression*

Radar range resolution vs BW: pulse compression

• Noise proportional to bandwidth
=> to minimize noise use small BW

• But range resolution requires high BW => shortest possible pulses

• Solution: *chirped pulses*:
  • initial short, broadband pulse is dispersed with a ramped frequency => much longer pulse
  •received signal is inverse-filtered according to the chirp template
  • equivalent to cross-correlation of signal over long-pulse period => noise is reduced
  • full range resolution of initial BW is recovered
  • high immunity to interference

Top: a 2MHz BW pulse with a frequency ramped chirp, 10 microsec long. **Bottom**:
Fourier complex spectrum of the pulse, showing amplitude out to 2 MHz, and a linear phase gradient (the ramp). The BW corresponding to the pulse envelope is also shown.

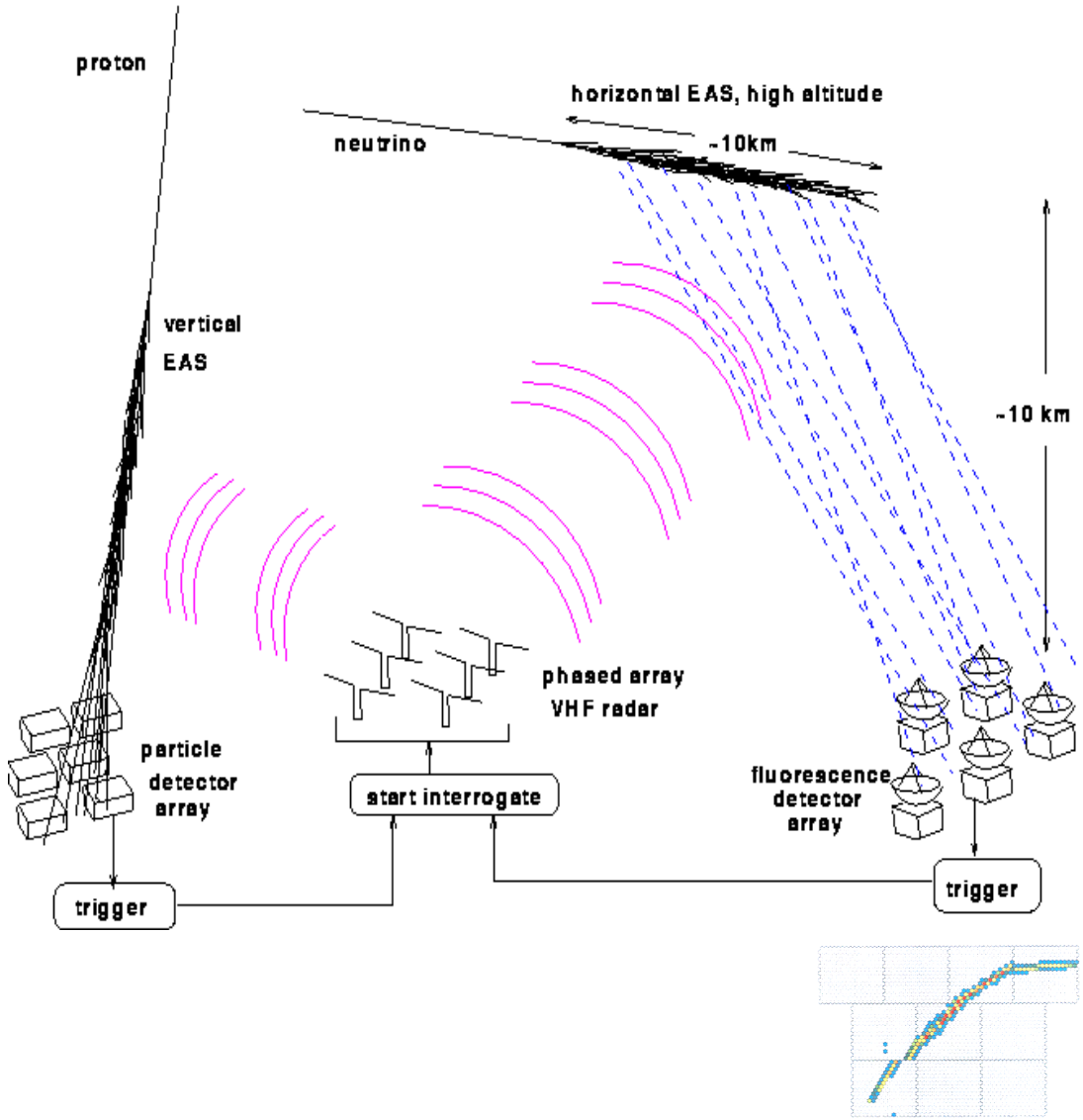
Radar complement to existing EAS detectors

Issues:

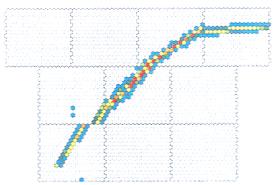
- free electron lifetime
- RF interference with existing experiments

Advantages:

- high precision ranges to EAS
- immune to atmospherics (?)
- good for high altitude, horizontal EAS => neutrinos



Would EAS radar work for the Auger observatory?



- Auger Observatory:
  - 1600 particle detectors, 1.5km spacing, ~100% duty cycle
  - 3000 km^2 array total area
  - Fluorescence array embedded with ~20-30 km spacing, 10% duty cycle
  - Operation by 2003 (?)

- Embedded radar array could:
  - operate at high duty cycle
  - estimate ranges and shower maxima for 10^19 eV EAS
  - complement fluorescence method

Parameter	value	±dBm
Received Power	$\sigma_b \eta P_t G^2 \lambda^2 \times (4\pi)^{-3} R^{-4}$	
Peak transmit power	60 kW	77.8
Pulse duration	10μs	...
chirp bandwidth	1 MHz	...
Number of repetitions	1	0.0
Antenna gain	50	34.0
wavelength	6 m	15.6
σ_b at $E = 10^{19}$ eV	2 m^2	3.0
range to EAS	22.4 km	-174.0
xmit/rcv efficiency	0.1	-10.0
$(4\pi)^{-3}$	5.04×10^{-4}	-33.0
Received power		-86.6 dBm
Noise power	$kT_{sys}\Delta f$	
Boltmann's constant	1.38×10^{-20} mWK^{-1}Hz^{-1}	-198.6
System temperature	2000 K	33.0
effective bandwidth	100 kHz	50.0
Noise power		-115.6 dBm
SNR	780	28.9 dB

Radar array as a standalone EAS detection system

EAS measurement requires at least 7 parameter estimation:

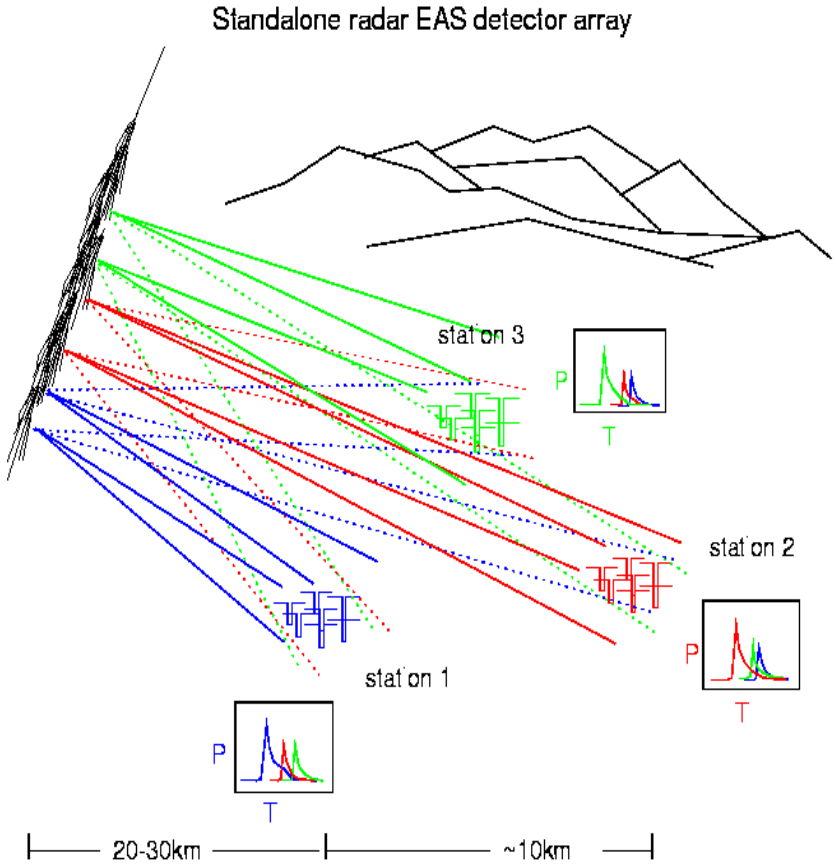
- Xm,Ym,Zm, theta, phi, Eo, dE/dx

A 3-station radar system, all with transmit/receive capability gives:

- Complex amplitude for each direct echo
- Each station gets two additional complex amplitudes from bistatic echoes
- Minimum of 18 measured quantities at high SNR
- ranges to ~10m on 10km baselines
  => mrad angles
- range, rates:
  - ~20 km @ 1e19 eV, 10 per day
  - ~60 km @ 1e20 eV, 2 per day
- Cost: ~$200K per station (?)

Issues:

- Complicated range-coding
- strong ground-echoes from other stations
- Ground clutter at large ranges



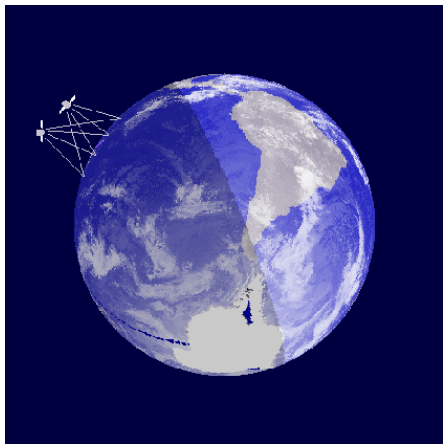
EAS radar from low earth orbit--OWL/AirWatch complement?

OWL/AirWatch:

• fluorescence detectors in LEO (probably on space station)

• Huge effective area--1sr of atmosphere from ~350km

• Potential problems: high bkg, hard to confirm EAS detections, range to EAS difficult



Parameter	value	±dBm
Received Power	$\sigma_b \eta P_t G^2 \lambda^2 \times (4\pi)^{-3} R^{-4}$	
Peak transmit power	60 kW	77.8
Pulse duration	50μs	...
chirp bandwidth	5 MHz	...
Number of repetitions	100	10.0
Antenna gain	50	34.0
wavelength	6 m	15.6
σ_b at $E = 3 \times 10^{20}$ eV	460 m^2	26.6
range to EAS	560 km	-230.0
xmit/rcv efficiency	0.1	-10.0
$(4\pi)^{-3}$	5.04×10^{-4}	-33.0
Received power		-109.0 dBm
Noise power	$kT_{sys}\Delta f$	
Boltmann's constant	1.38×10^{-20} mWK^{-1}Hz^{-1}	-198.6
System temperature	1500 K	31.8
effective bandwidth	20 kHz	43.0
Noise power		-123.8 dBm
SNR	30.8	14.9 dB

Radar Problems:

• free electron lifetime probably not adequate for triggered system => range-coded repetitive pulsing required

• Requires relatively high-powered system, high duty cycle (~10-20%)

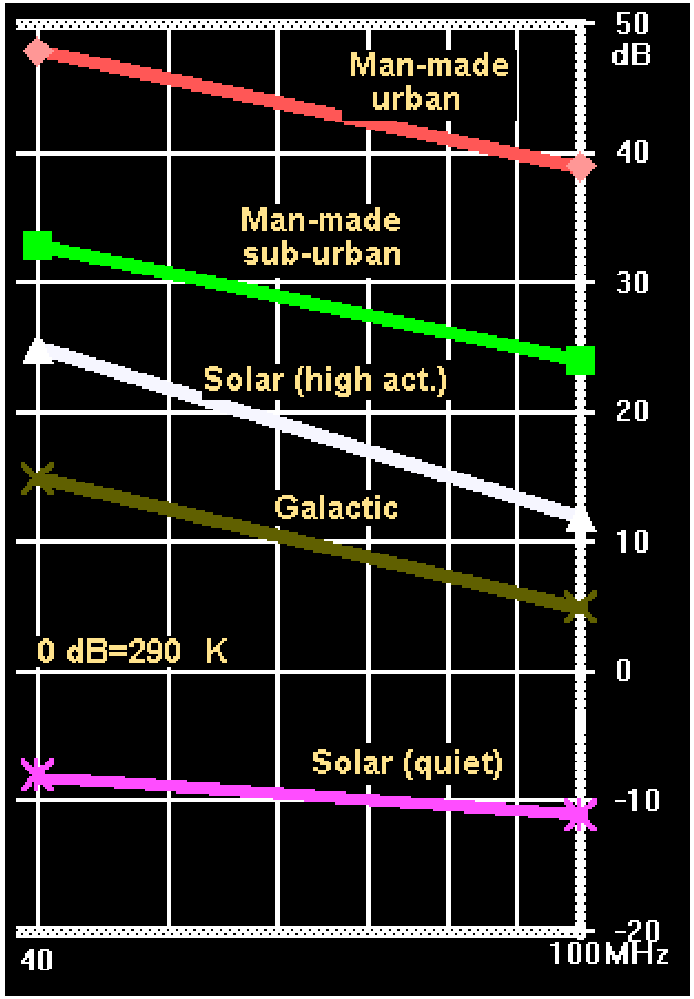
Radar Advantages:

• EAS confirmation, excellent range data

• meteor & ionospheric physics a byproduct

Thermal & nonthermal backgrounds

- SNR decreases with increasing Tsys
- Receiver noise <200K off-the-shelf, <100K at reasonable cost
- Galactic noise ~8000K at 40MHz, ~800K at 100MHz, galactic center 50% higher
- Solar maximum can give much higher daytime Tsys
- Rural operation is essential--cities are the noisiest of all!



Conclusions & plans

• Blackett & Lovell's prescient suggestion still looks viable, even more attractive with mature radar technology

• Implementation depends strongly on the electron attachment rates
    => need for better understanding & measurements of e- in air

• New technique => the devil is in the details
    • Air cherenkov (TeV gamma-ray detectors) ~15 year development required
    • Fluorescence technique ~8 yrs to initial detector, ~15 to HiRes
    • Maturity of radar methods will help

• Immediate plans: test it with commercial system (~$50K) next to an existing air shower array