DEP. OF SIGNAL THEORY AND COMMUNICATIONS

Chap.4. Elastic Lidar Systems

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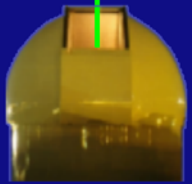


SUMMARY

MEASUREMENTS:

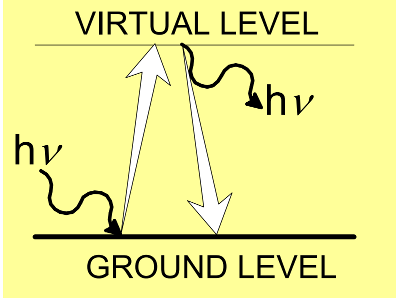
- Direct:
  Aerosol/molecular composed intensity returns
- Indirect:
  (Usually requires calibrating conditions/hypotheses)

  Optical parameters, pollution concentration and flux rate, wind

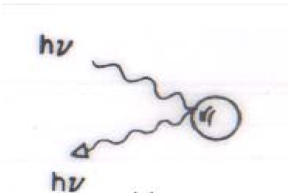
LASER TYPES:

- Ruby (λ = 694.3 nm, 347.2 nm)
- Nd:YAG (λ = 1064, 532 nm, 355 nm)
- Excimer (λ ~ 350 nm)

ELASTIC INTERACTION



(b)



(a)

Types of interaction:

1) *Rayleigh scattering (molecules, $r << \lambda$)*
2) *Mie scattering (aerosols, $r \approx \lambda$)*

Types of elastic lidar:

1) *Backscatter lidar*
2) *Doppler lidar*

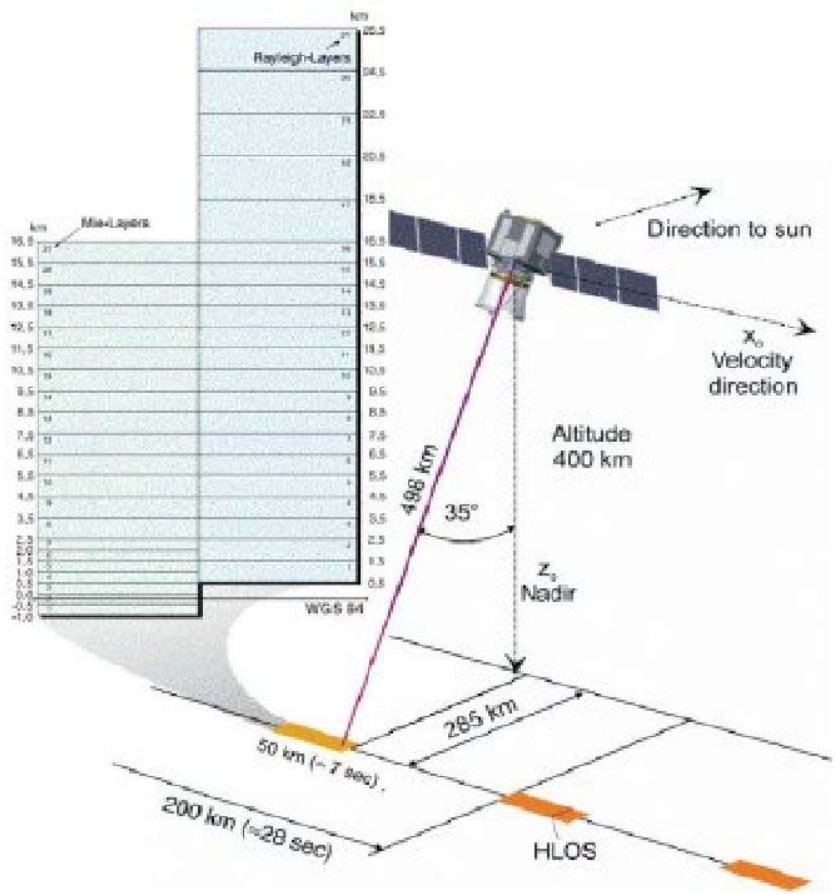
APPLICATIONS

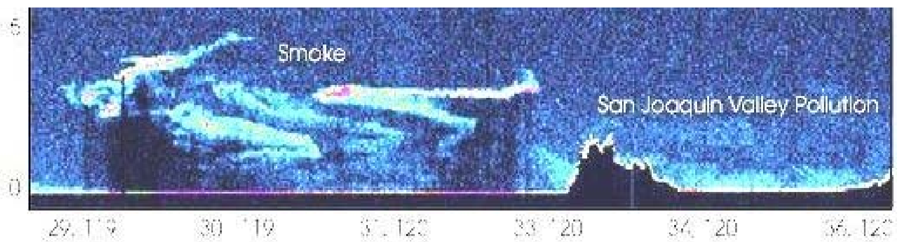
ENVIRONMENTAL

- *Pollution monitoring (source strength and location), Fires*
- *Transport models*
  - Air-quality regulations
  - Air-mass fluxes
- *Aerosols role*
  - Earth-atmosphere radiative budget
  - Photochemical effects
  - Air-mass tracers (e.g. wind tracers)

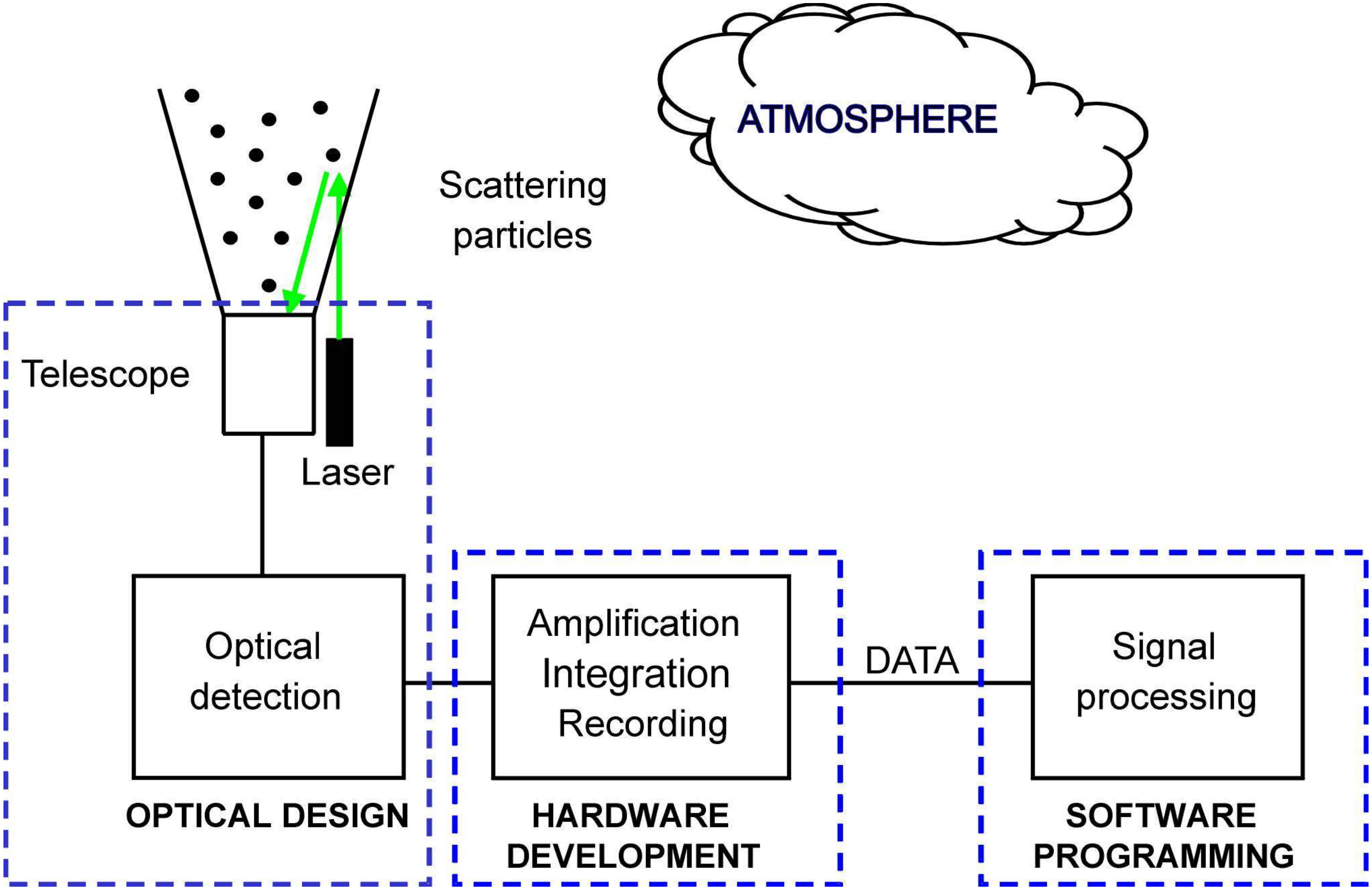
METEOROLOGICAL AND FSO COMMUNICATIONS

- *PBL (Planetary Boundary Layer)*
- *Cloud extent and monitoring*
- *Estimation of atmospheric attenuation (dB/km)*





ARCHITECTURE (I)



ARCHITECTURE (II)

RECEIVING OPTICAL SYSTEM

- *Telescope*
  - "optical antenna"
  - effective area, A_r

$$FOV = \frac{r_d}{f} \quad [rad]$$

- *Inteference filter*
  - limits background power

$$P_{back} = L_b(\lambda) A_r d\Omega d\lambda$$

- *O/E converter*
  - Photodiode, PMT
  - Conditioning chain

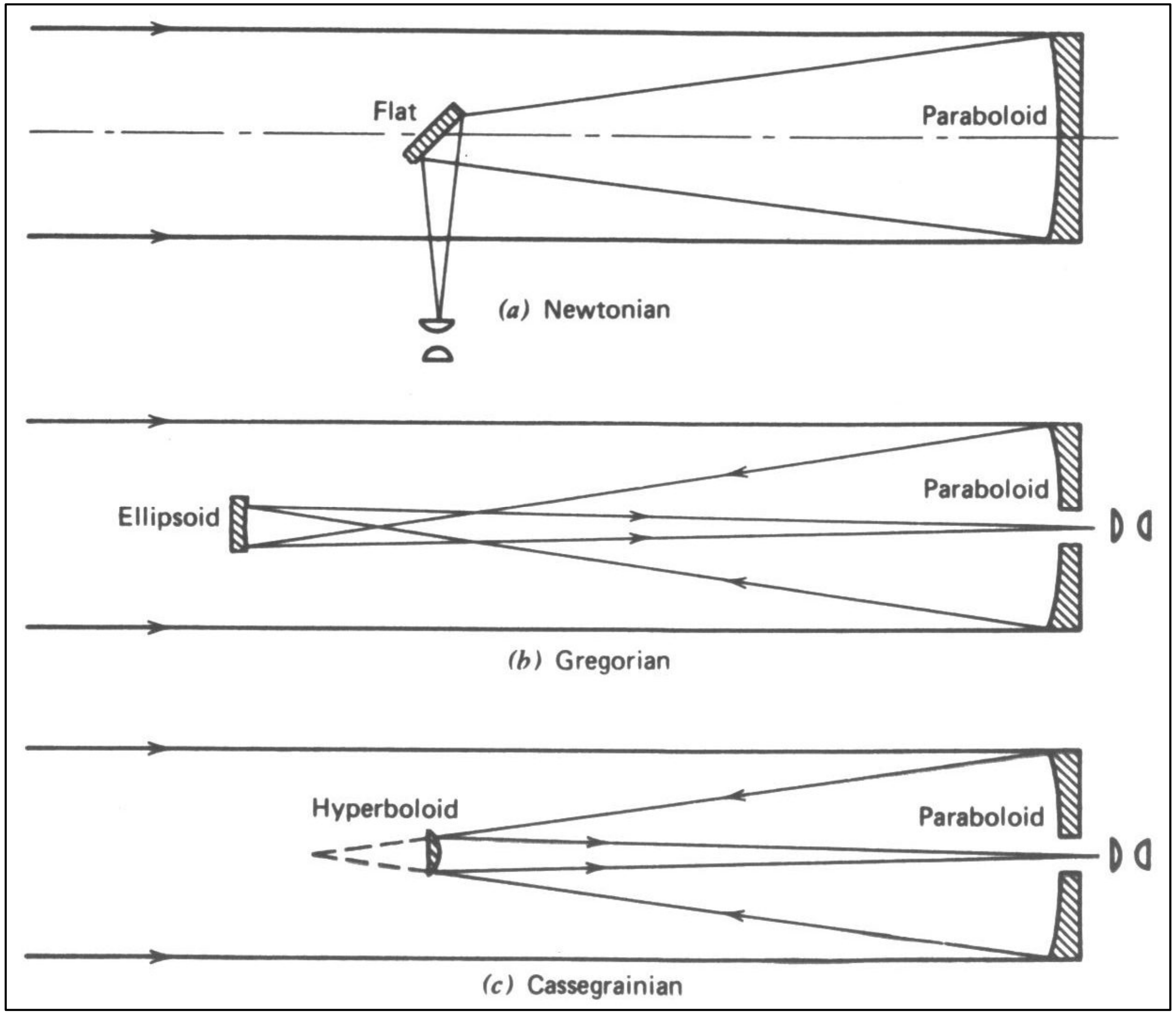
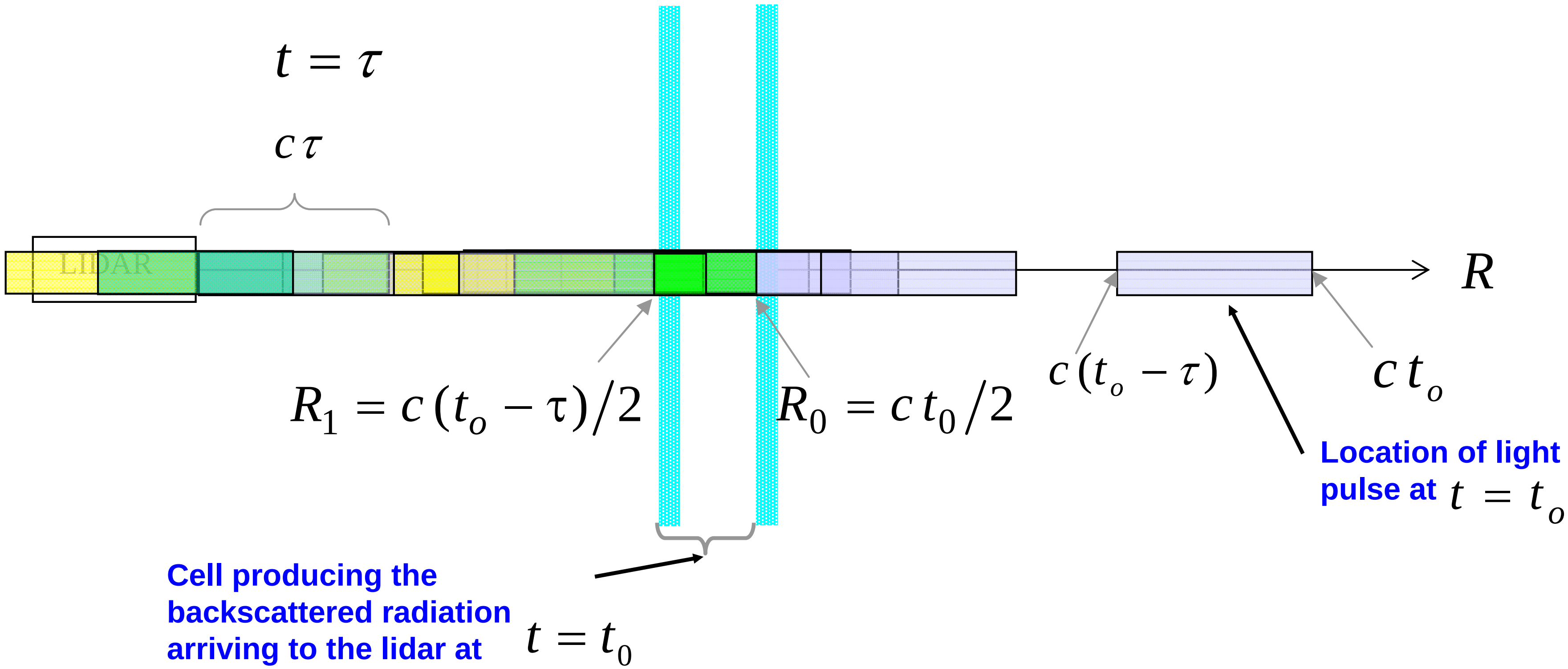


Fig. SOURCE: Measures (1992); R.M. Measures, "Laser Remote Sensing. Fundamentals and Applications". John Wiley & Sons, 1984. (Reprint de 1992, Krieger Publishing Company).

SPATIAL RESOLUTION (I)

INTERACION OF A LIGHT PULSE WITH THE ATMOSPHERE

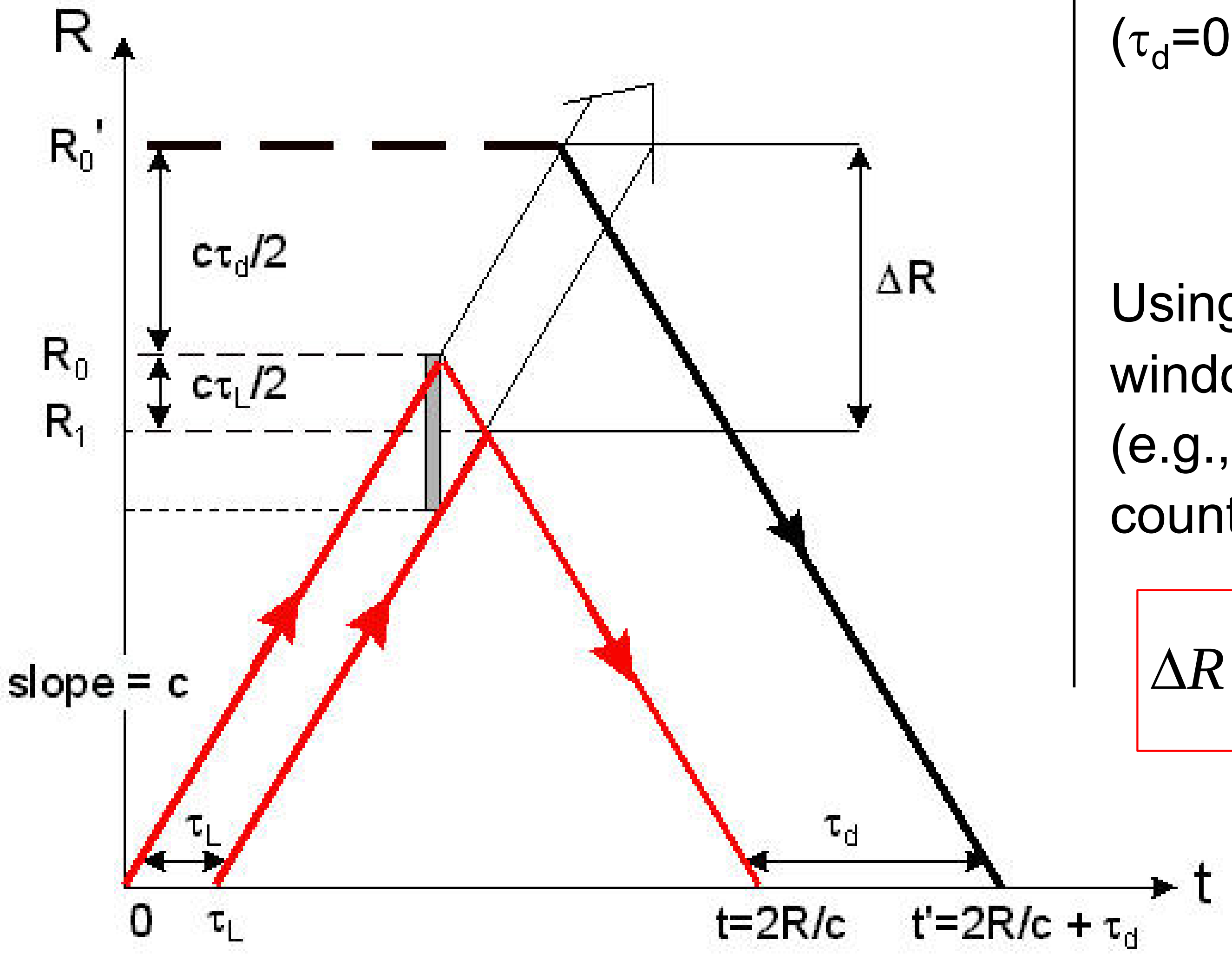


- *The max range from which energy is received at time t is R_0.*
- *At the same time t, additional energy is received from ranges illuminated by portions of the pulse transmitted after the leading edge, the min. range from which energy is received is R_1.*

SPATIAL RESOLUTION (II)

SPACE-TIME DIAGRAM

(rectangular-shaped laser pulse, τ_L)



Using analog recording (τ_d=0),

$$\Delta R_a = \frac{c\tau_L}{2}$$

Using a time detection window of length $\tau_d = 1/f_s$ (e.g., A/D sampling, photon counting),

$$\Delta R = \frac{c(\tau_L + \tau_d)}{2} \approx \frac{c\tau_d}{2}$$

THE (ELASTIC) LIDAR EQUATION (I)

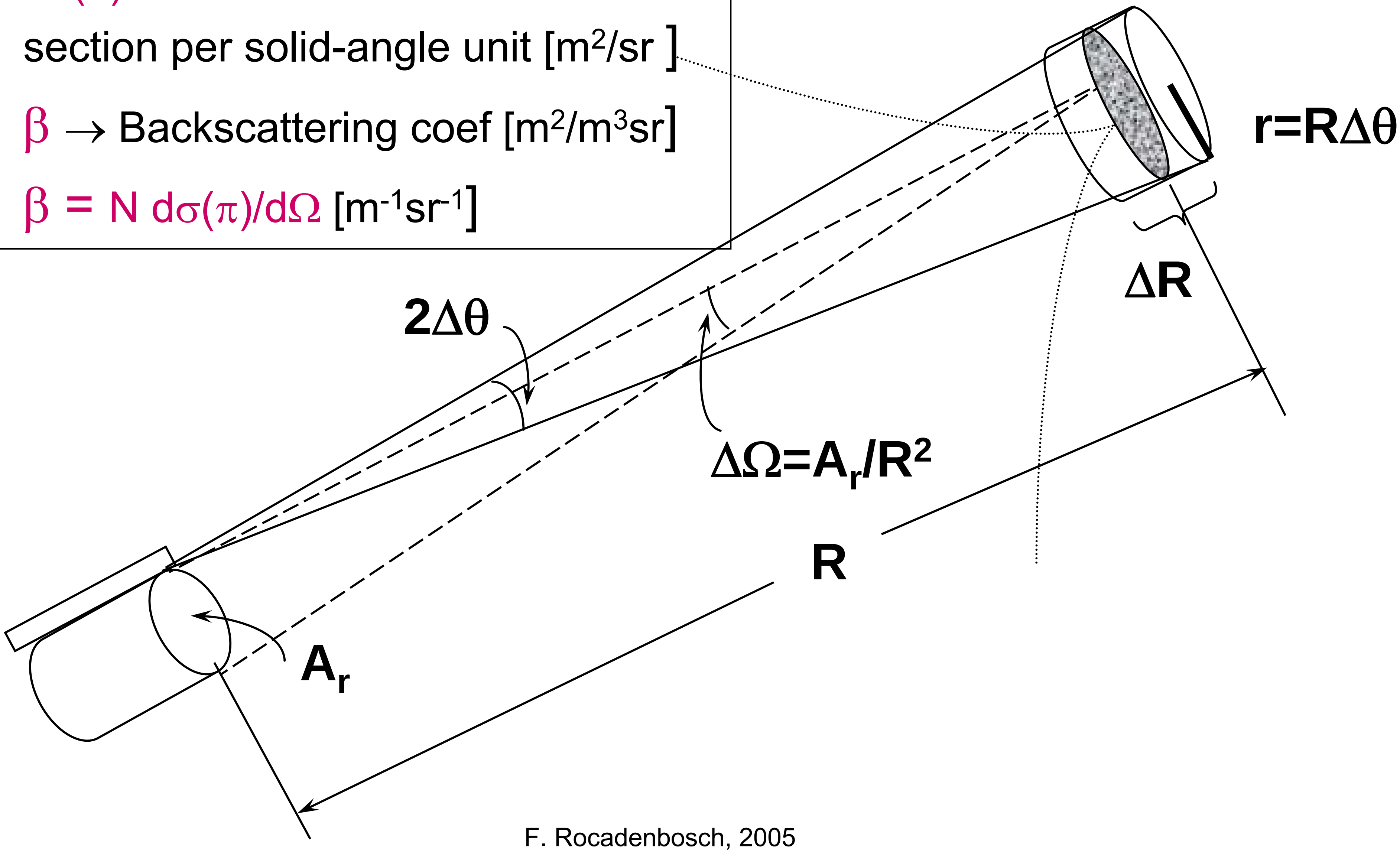
N → Particle concentration [part/m^3]

$d\sigma(\pi)/d\Omega$ → Backscatter cross-section per solid-angle unit [m^2/sr]

β → Backscattering coef [m^2/m^{3}sr]

$\beta = N\, d\sigma(\pi)/d\Omega$ [m^{-1}sr^{-1}]

WITHIN THE SCATTERING VOLUME:



THE (ELASTIC) LIDAR EQUATION (II)

BASIC INTERVENING MAGNITUDES

1) Laser emitted power per pulse (τ_L), P_0 [W]

$$P_0 = \frac{E}{\tau_L}$$

2) Incident power density on the atmospheric resolution cell, E_{in} [W/m^2]

$$E_{in}(R) = \frac{P_0}{\pi r^2} \exp\left[-\int_0^R \alpha(u)\,du\right], \quad r = R\Delta\theta$$

3) Cell-backscattered power per solid-angle unit, K_{sca} [W/sr]

$$K_{sca}(R) = \beta(R) E_{in}(R) V \quad \text{with} \quad \begin{cases} V = \pi r^2 \Delta R \\ \Delta R = c\tau_L/2 \end{cases}$$

4) Backscattered power collected by the telescope, P(R) [W]

$$P(R) = K_{sca}(R)\Delta\Omega \exp\left[-\int_0^R \alpha(x)\,dx\right], \quad \Delta\Omega = \frac{A_r}{R^2}$$

5) Finally,

$$P(R) = \frac{E\,\frac{c}{2}\,A_r}{R^2}\beta(R)\exp\left[-2\int_0^R \alpha(u)du\right]$$

THE (ELASTIC) LIDAR EQUATION (III)

Elastic LIDAR Equation (simple scattering)

$$P(\lambda,R)=\frac{K}{R^2}\beta(\lambda,R)\exp\left[-2\int_0^R\alpha(\lambda,r)dr\right]\xi(R)$$

where:

$\alpha(\lambda,R)$ atmospheric optical extinction coef. [m^{-1}]

$\beta(\lambda,R)$ atmospheric optical backscatter coef. [$m^{-1}sr^{-1}$]

– where $\beta(\lambda,R)=\overline{N}(R)\frac{d\overline{\sigma}(\pi)}{d\Omega}$,

– N is the average density of aerosols + molecules [m^2/m^3sr]

$\xi(R)$ overlap factor [ ], $0\leq\xi(R)\leq 1$

$P(R)$ optical return power [W]

K system constant [W m^3], $K=\frac{Ec}{2}A_r$

---

where:

E (peak) energy [J]

A_r effective telescope area [m^2]

THE LIDAR EQUATION (IV)

ATMOSPHERIC OPTICAL COEFFICIENTS

SOURCE: Measures (1992).

Concerning the lidar Eq., note that:

$$\alpha_\lambda(R) = \alpha_\lambda^{aer}(R) + \alpha_\lambda^{mol}(R) + \alpha_\lambda^{abs}(R)$$

$\alpha_\lambda^{abs}(R) \approx 0$

$$\beta_\lambda(R) = \beta_\lambda^{aer}(R) + \beta_\lambda^{mol}(R)$$

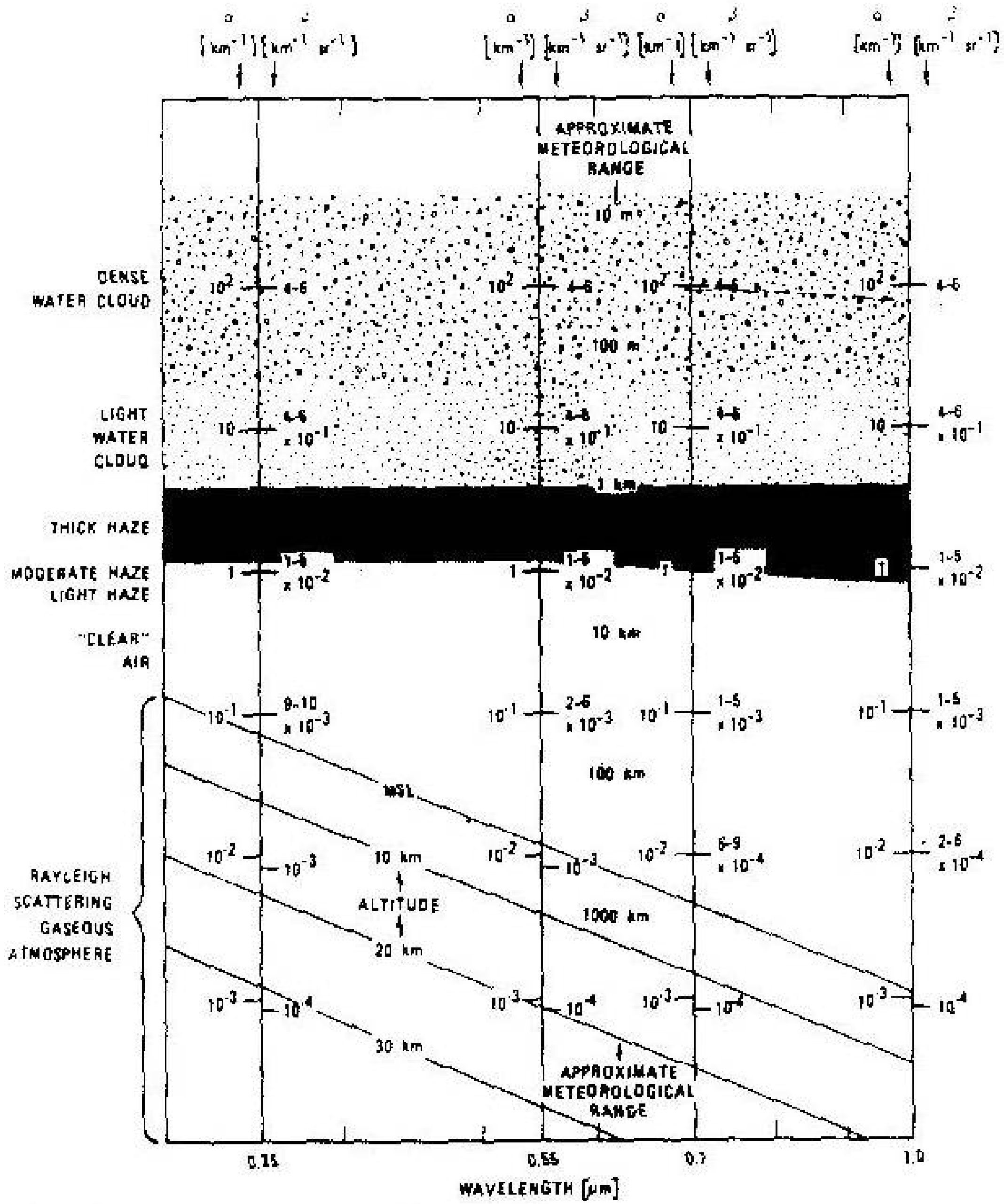


Fig. SOURCE: R.T.H. Collis and P.B. Russell, "Lidar Measurement of Particles and Gases by Elastic Backscattering and Differential Absorption," Chap.4 in *Laser Monitoring of the Atmosphere*, E.D. Hinkley, Ed., (Springer-Verlag, New York, 1976), pp.71-102.

THE LIDAR EQUATION (V)

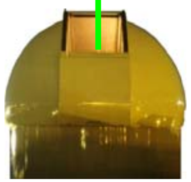
FURTHER COMMENTS:

1) Assuming a homogeneous atmosphere and ideality system conditions, the lidar equation takes its simplest form:

$$P(R) = \frac{K}{R^2} \underbrace{\beta}_{\text{backscatter}} \underbrace{\exp\left(-2\alpha R\right)}_{\text{transmittance}}$$

2) Note the *LIDAR optical thickness (COT) and related transmissivity!*

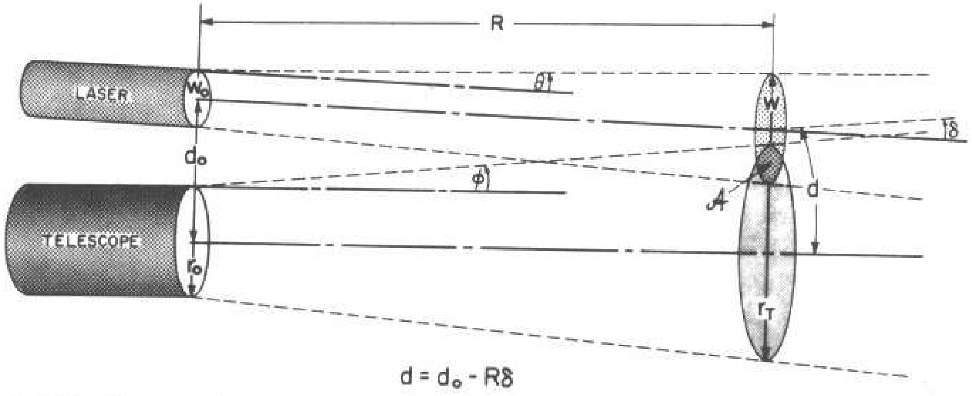
$$T(\lambda, R) = \exp\left[-2COT\left(R\right)\right]; \quad COT\left(R\right) = \int_0^R \alpha(\lambda, r)dr$$

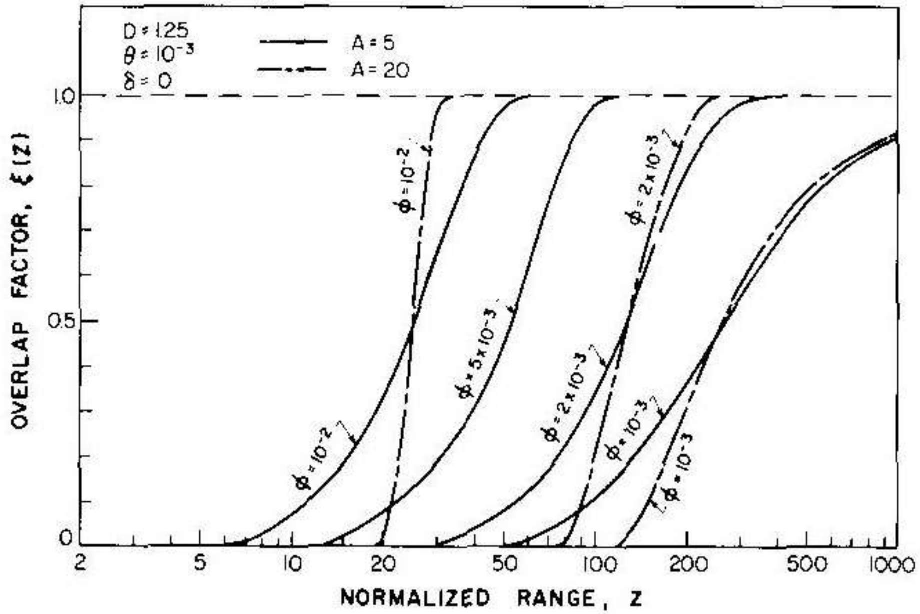


THE LIDAR EQUATION (VI)

OPTICAL OVERLAP FACTOR (OVF)

The telescope cannot “read” the full atmospheric cross-section illuminated by the laser beam (i.e., does not lie within its FOV)



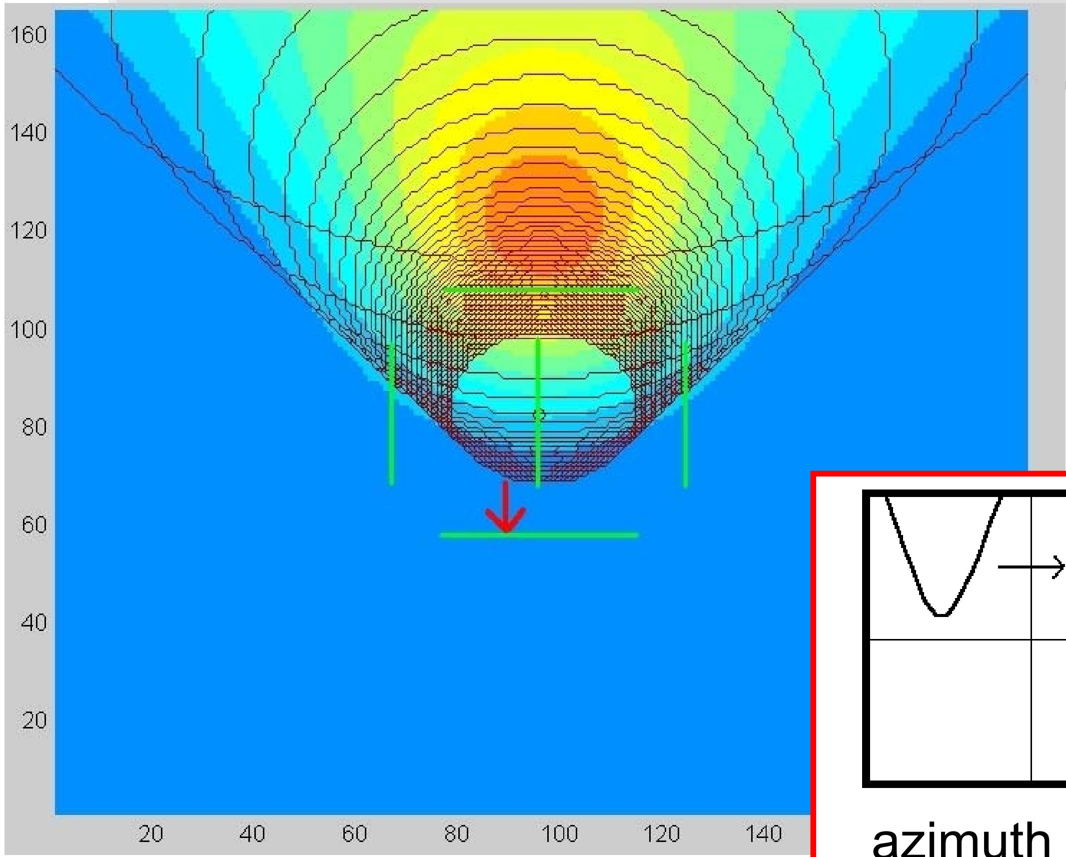


It is a function of many geometrical and optical parameters of both the laser and telescope.

Fig. SOURCE: Measures (1992).

THE LIDAR EQUATION (VII)

OVF OPTICAL ALIGNMENT

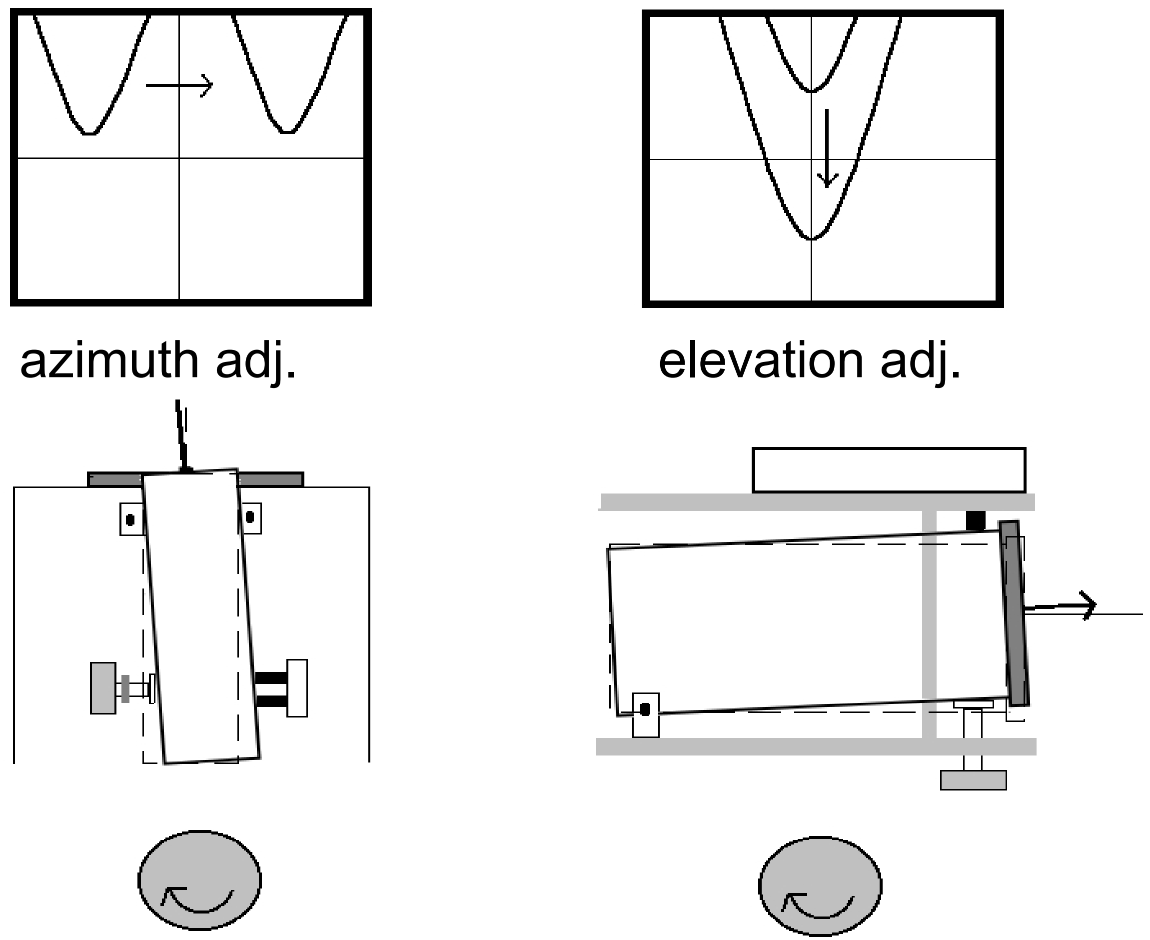


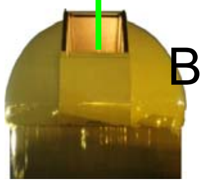
Atmospheric laser foot-print imaged is (telesc. far-field):

$$y_i = -\frac{f}{R}\left[\pm\sqrt{W_o^2+\theta^2 R^2}+d_o-\delta R\right]$$

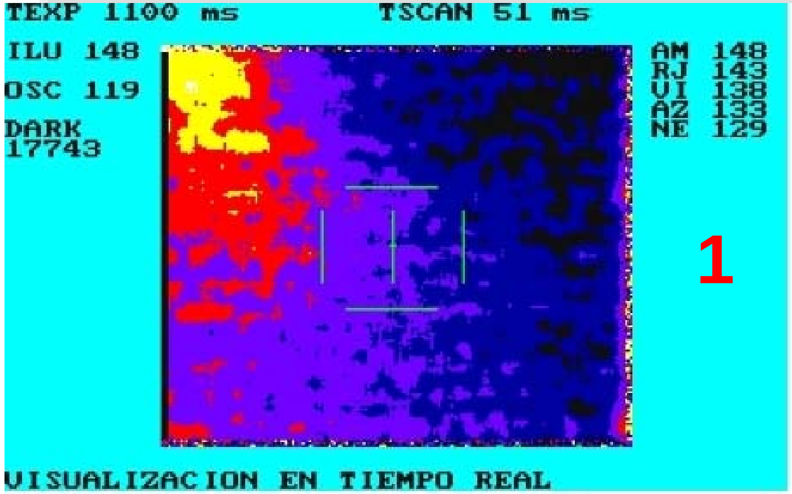
A) $$y_i = \underbrace{-f\left[\pm\theta\right]}_{size} - \underbrace{f\left[\Omega(R)-\delta\right]}_{y-position}$$

B) $$y_i = \underbrace{-\frac{f}{R}\left[\pm W_0\right]}_{size} - \underbrace{f\left[\Omega(R)-\delta\right]}_{y-position}$$

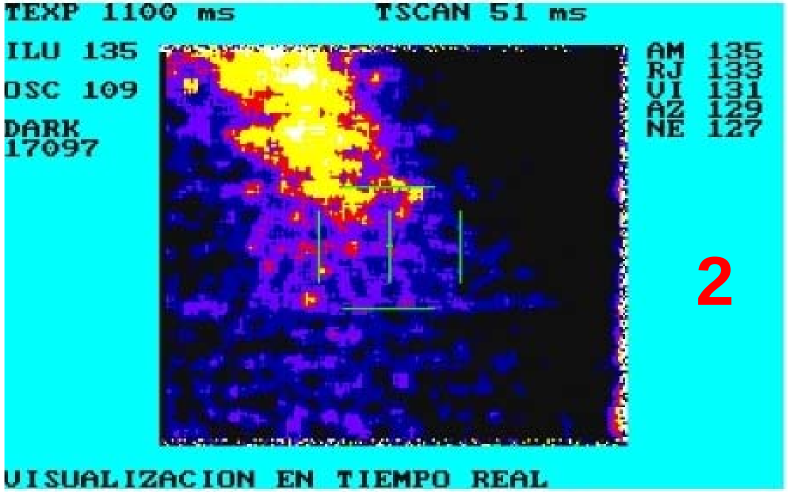




THE LIDAR EQUATION (VIII)



1



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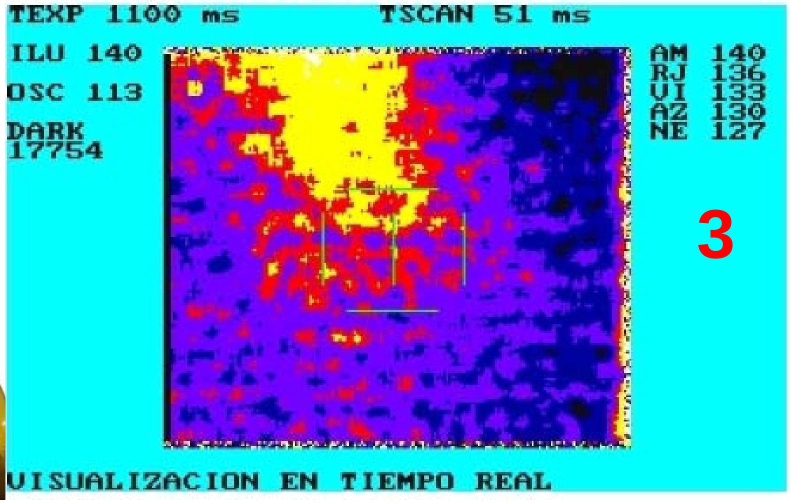

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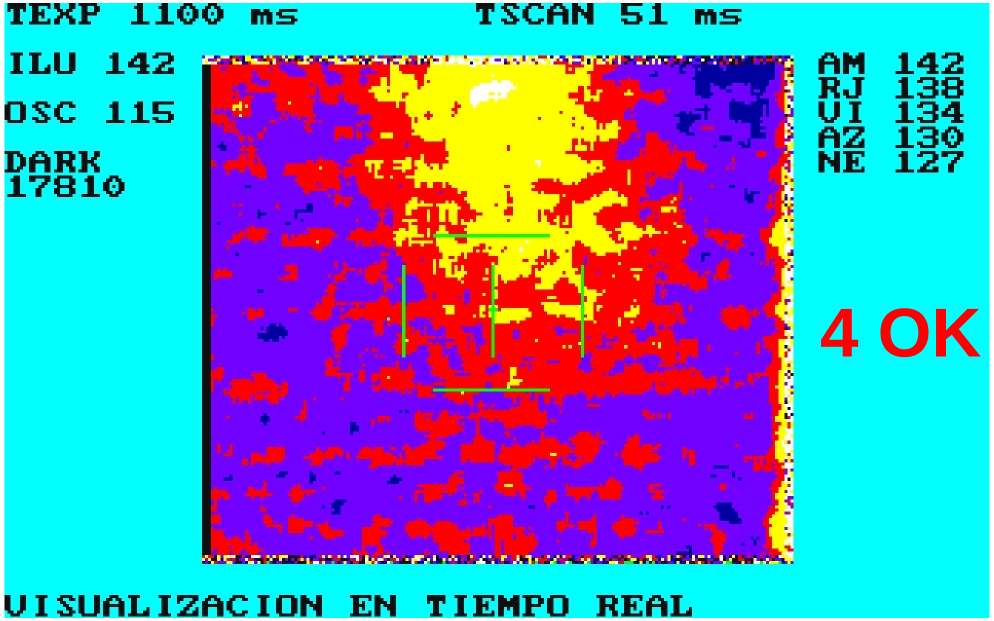
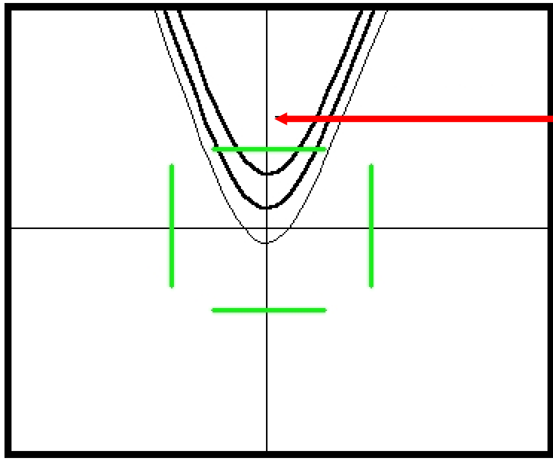


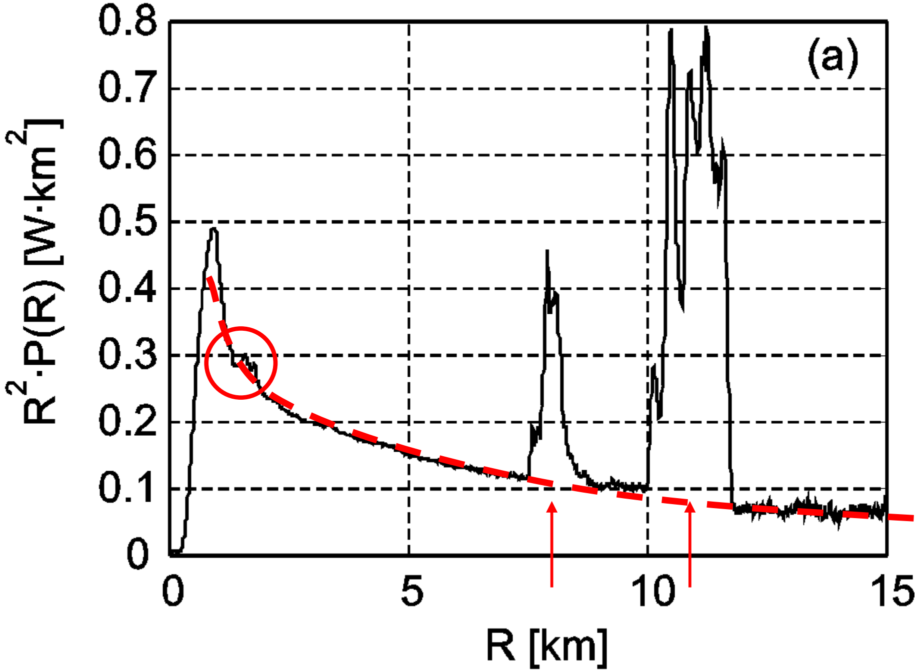
4 OK



brightest area

REF

THE LIDAR EQ. (IX): BASIC INVERSIONS



RANGE CORRECTION (R^2P):

Backscatter-transmittance plot

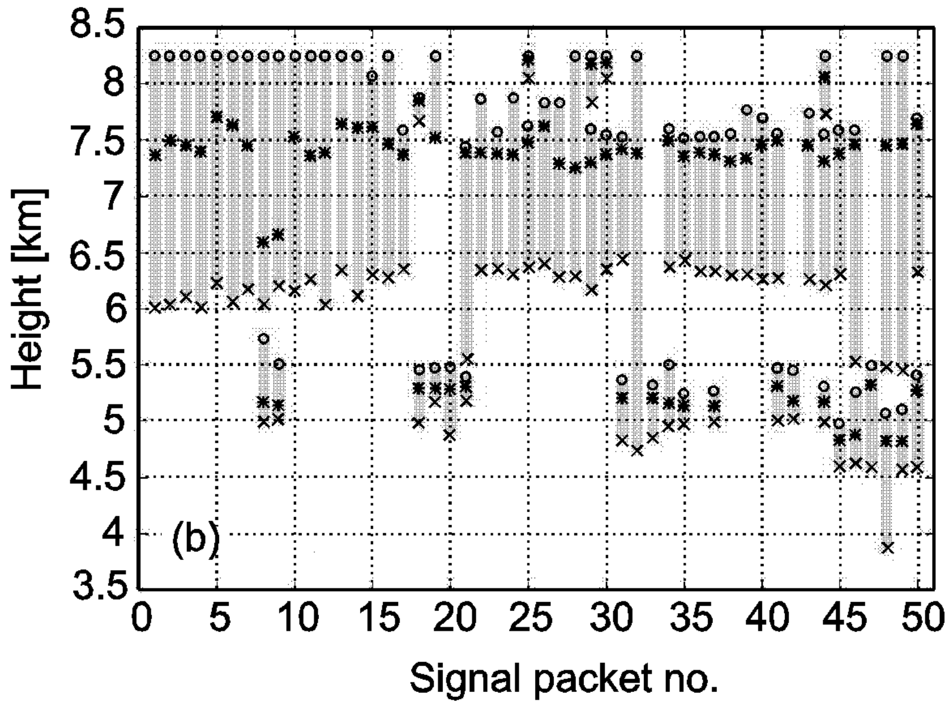
Reveals atmospheric structure

- *Mixing aerosol layer*
- *Cloud structure*

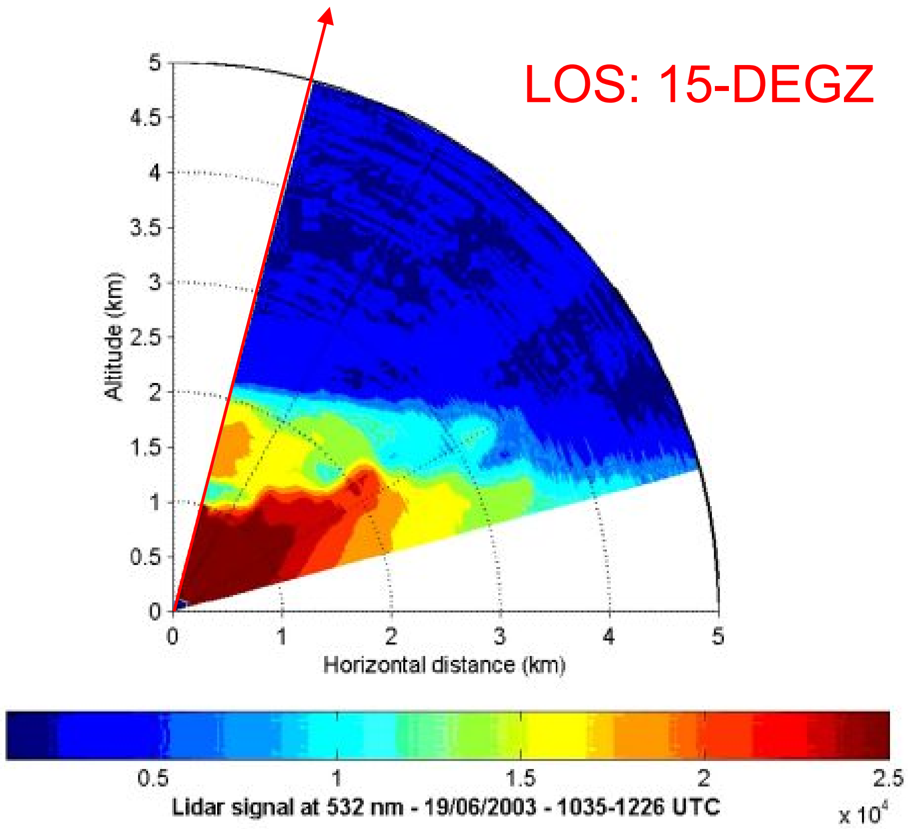
CEILOMETRY:

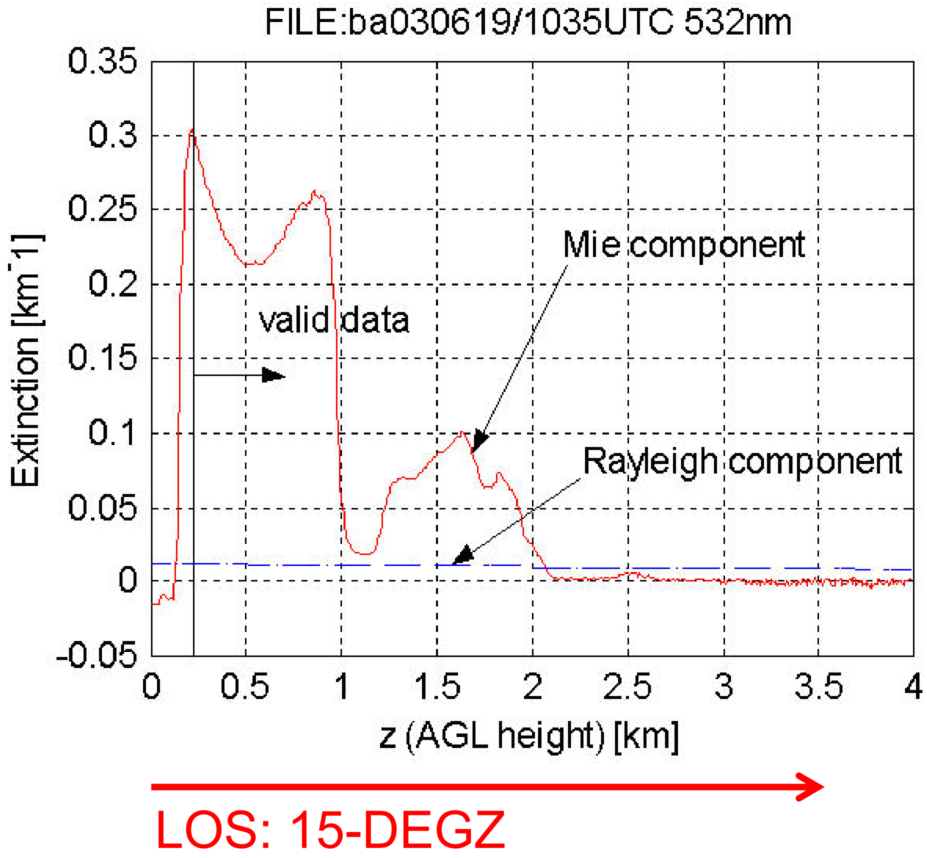
Cloud-height extent monitoring

- *Cloud base, peak, top*
- *No. of layers*



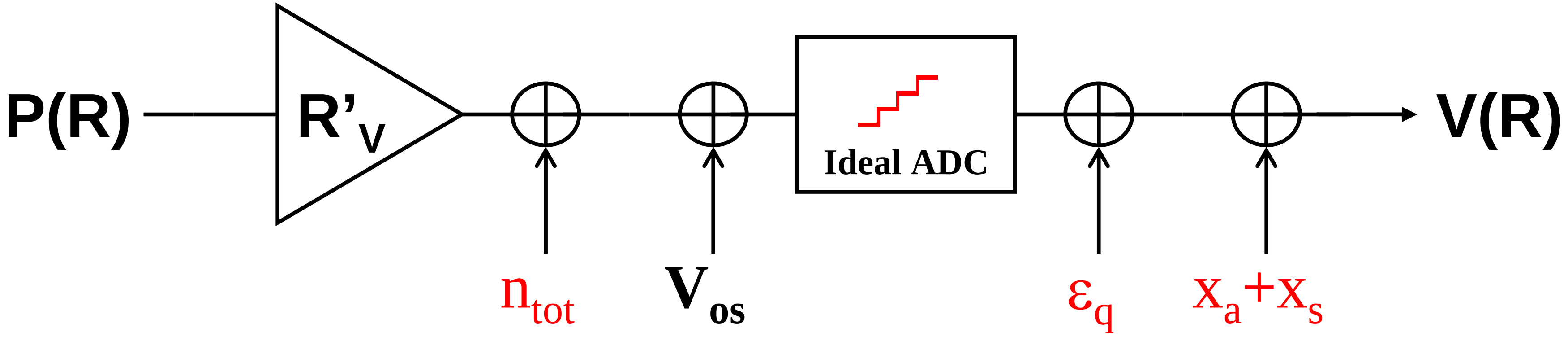
THE LIDAR EQ. (X): BASIC INVERSIONS





- *For optically "clear" atmospheres, the "range-corrected" (R^2P), "backscatter" and "extinction" representations* ***look very much alike.***

SIGNAL CONDITIONING (I): RECEIV. CHAIN



$$V(R) = R'_V L P(R) + V_{os} + n_{tot}(R) + \varepsilon_q + x_a(R) + x_s(R)$$

unwanted terms

R'_V: Net Voltage Responsivity (V/W)

V_{os}: Total system offset (user+drift+background)

n_{tot}: Total noise (photodetection + electronic)

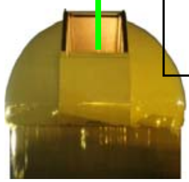
ε_q: Quantization noise

$x_{a,s}$: A/Synchronous interferences

$$V_{OS} = R'_V P_{Back} + V_{drift} + V_{user} + \sum \frac{dV_{drift}}{dt} \Delta t$$

Sampling at f_s, detection time $\tau_d = 1/f_s$, so that

$$\Delta R \approx \frac{c\tau_d}{2} = \frac{c}{2 f_s}$$



F. Rocadenbosch, 2005

SIGNAL CONDITIONING (II): KEYS

RECEIVER CHAIN

1) Mapping function

$$V(R) = R_i G P(R) + V_{OS}$$

2) Operational settings

a) Map B to -V_{max}

$$P(R \to \infty) = P_{back}$$

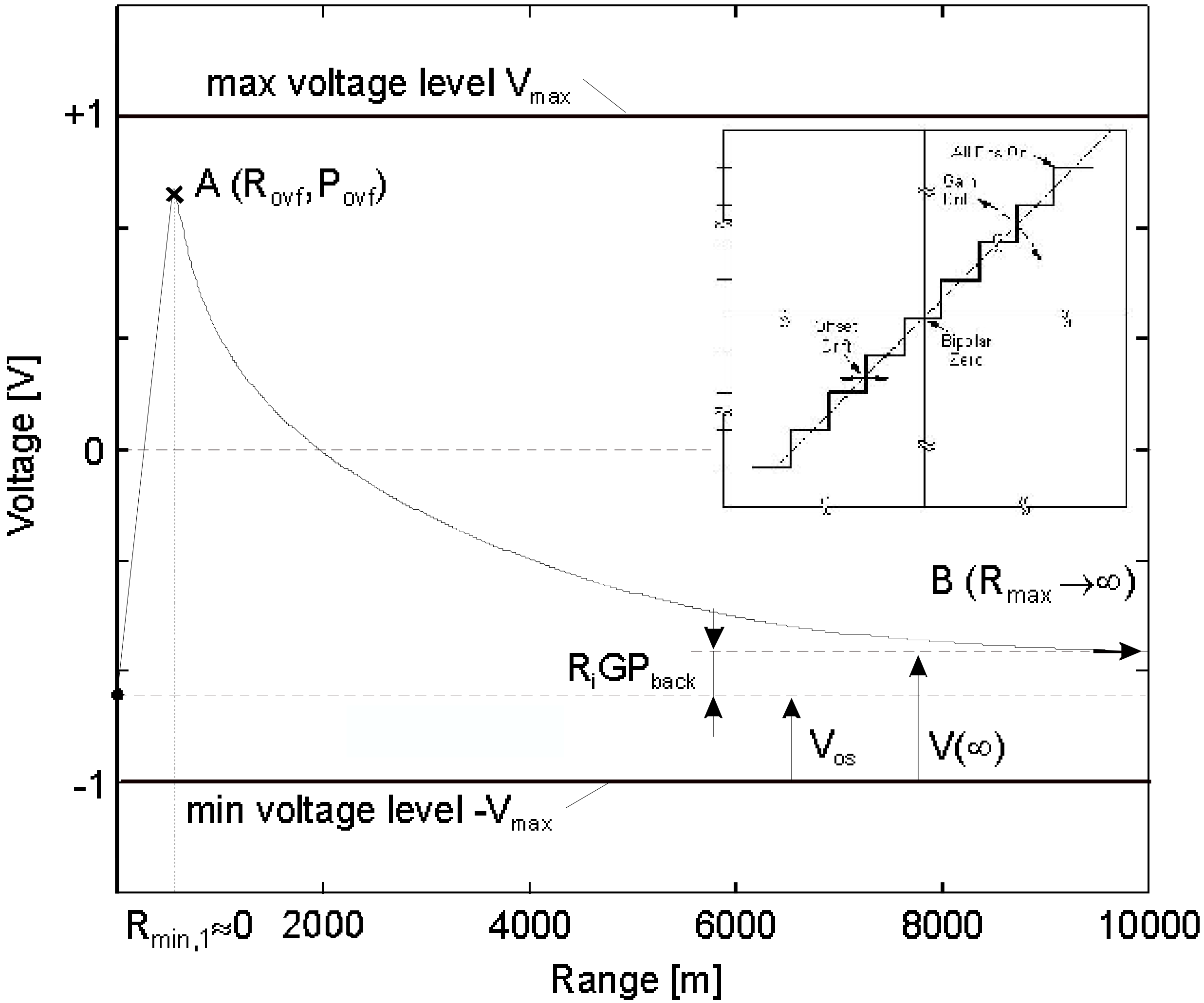
$$V_{OS} = -V_{max} - R_i G P_{back}$$

b) No ADC saturation

$$G = \frac{V_{max} - V_{OS}}{R_i P_{max}}$$

3) Intensity Display

$$V'(R) = V(R) - V(\infty)$$



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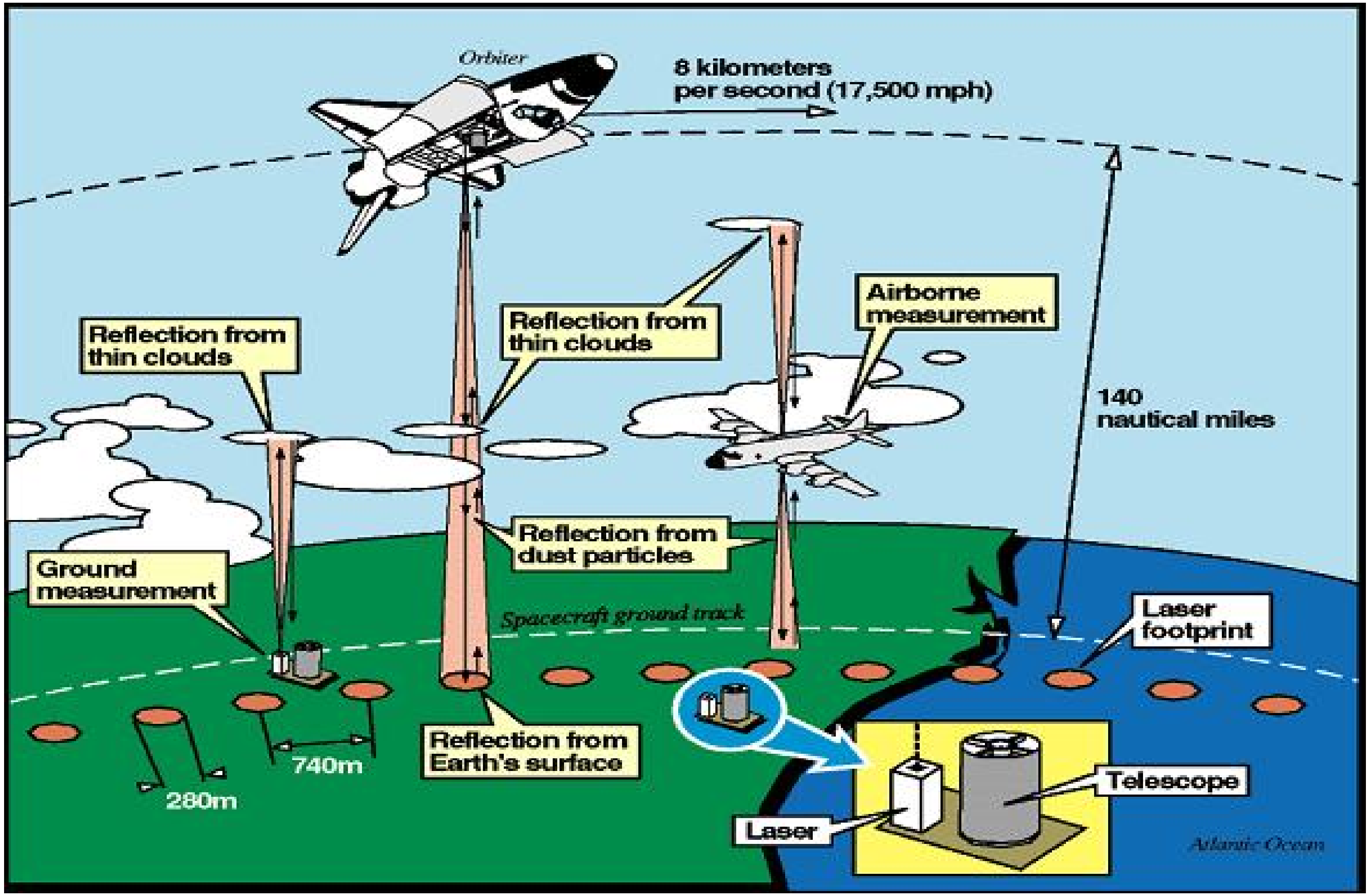
EXAMPLES OF REAL SYSTEMS: RSCH. AGENCIES

NASA, Lidar In-space Technology Experiment (LITE)

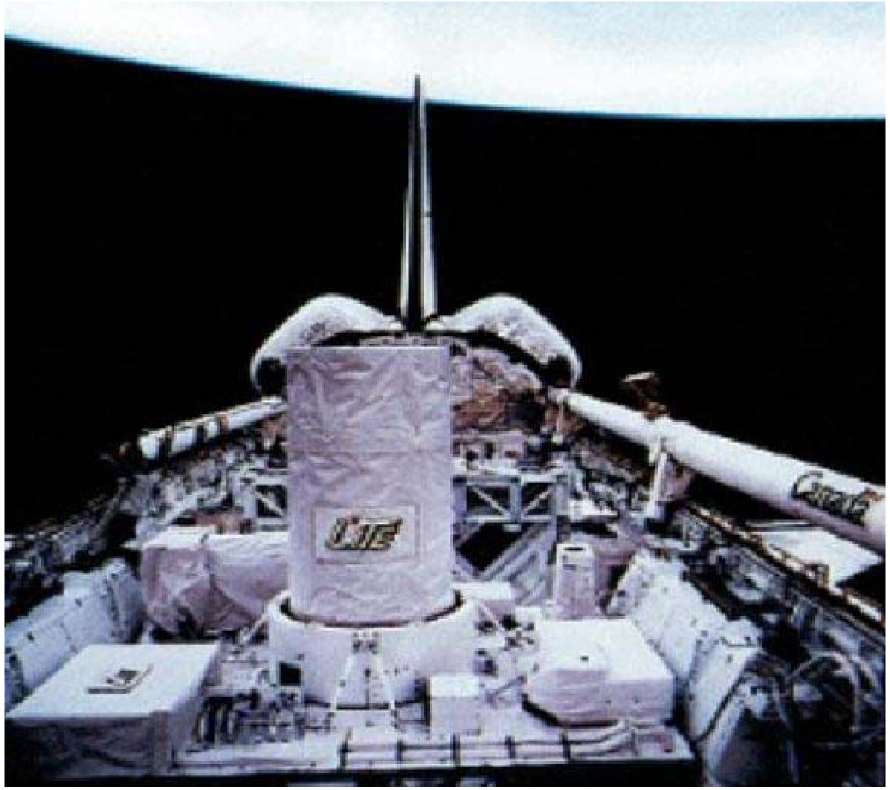


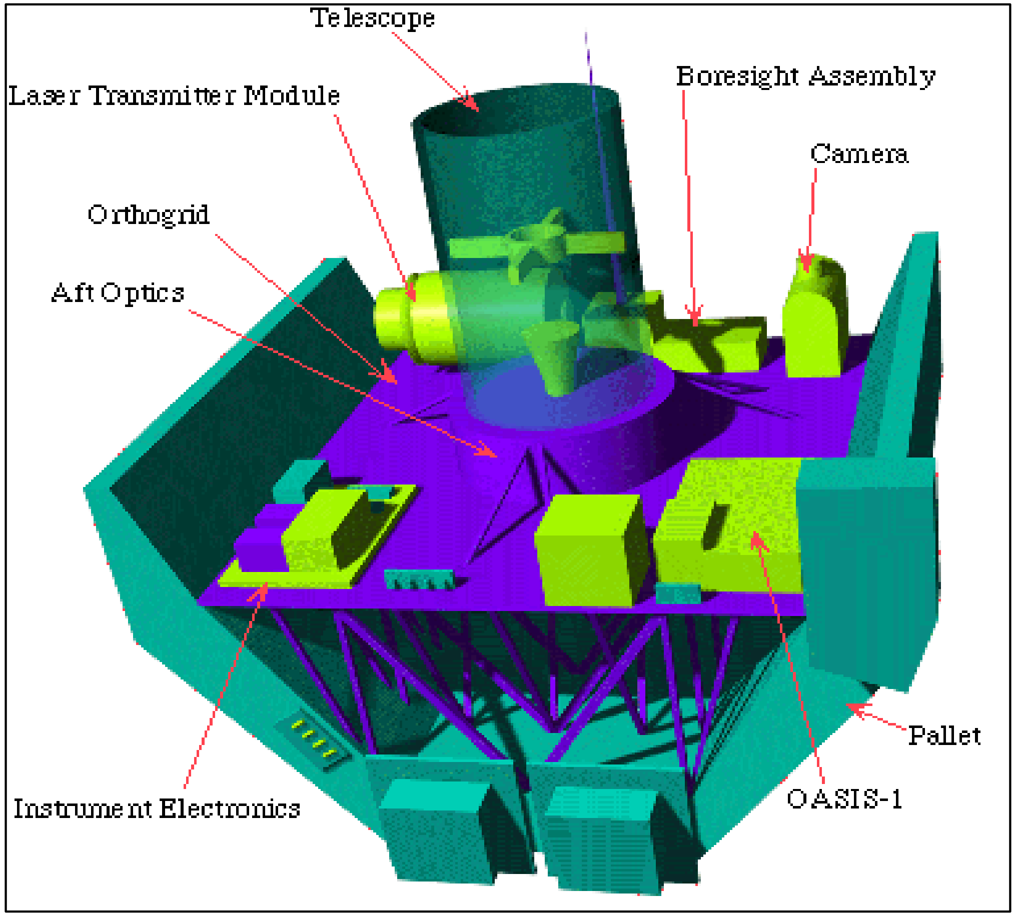
SPECS: Elastic lidar, Nd:YAG (1064, 532, 355 nm), Discovery 1994.

APLIC: Clouds & statosphere aerosol density, temperature

BACKSCATTER LIDAR & RESEARCH AGENCIES

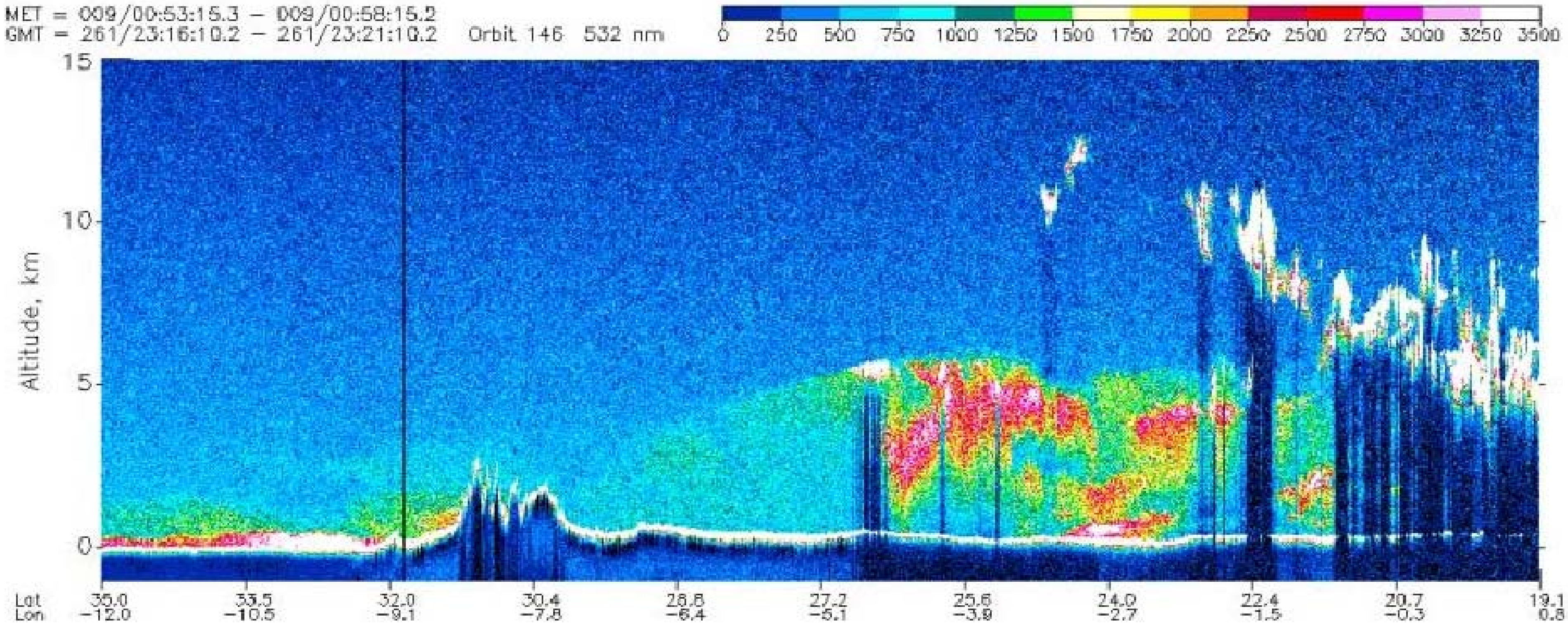
LITE (Lidar In-space Technology Experiment)





SOURCE:
http://www-lite.larc.nasa.gov/

BACKSCATTER LIDAR & RSCH AGENCIES



OTHER PROJECTS (ESA)

- *ATLID: similar to LITE (NASA)*
- *ALADIN: wind lidar space-borne sensor*

EXAMPLES: MICRO-LIDAR

CLOUD AND AEROSOL M-LIDAR

Transmitter	**Laser : Nd:YAG, SHG 532 nm**
Output wavelength	532 nm
Output energy per pulse	4 µJ
Repetition rate	5 kHz
Pulse duration	< 1 ns
Effective aperture	314 cm²
Field of view (full angle)	55 µrad
Filter bandwidth	0.5 nm
Detector	APD
Detection mode	Photon counting
Acquisition time	> 0.8 s
Vertical resolution	15 m
Size (diameter x height)	220 x 1000 mm
Weight	12.5 kg

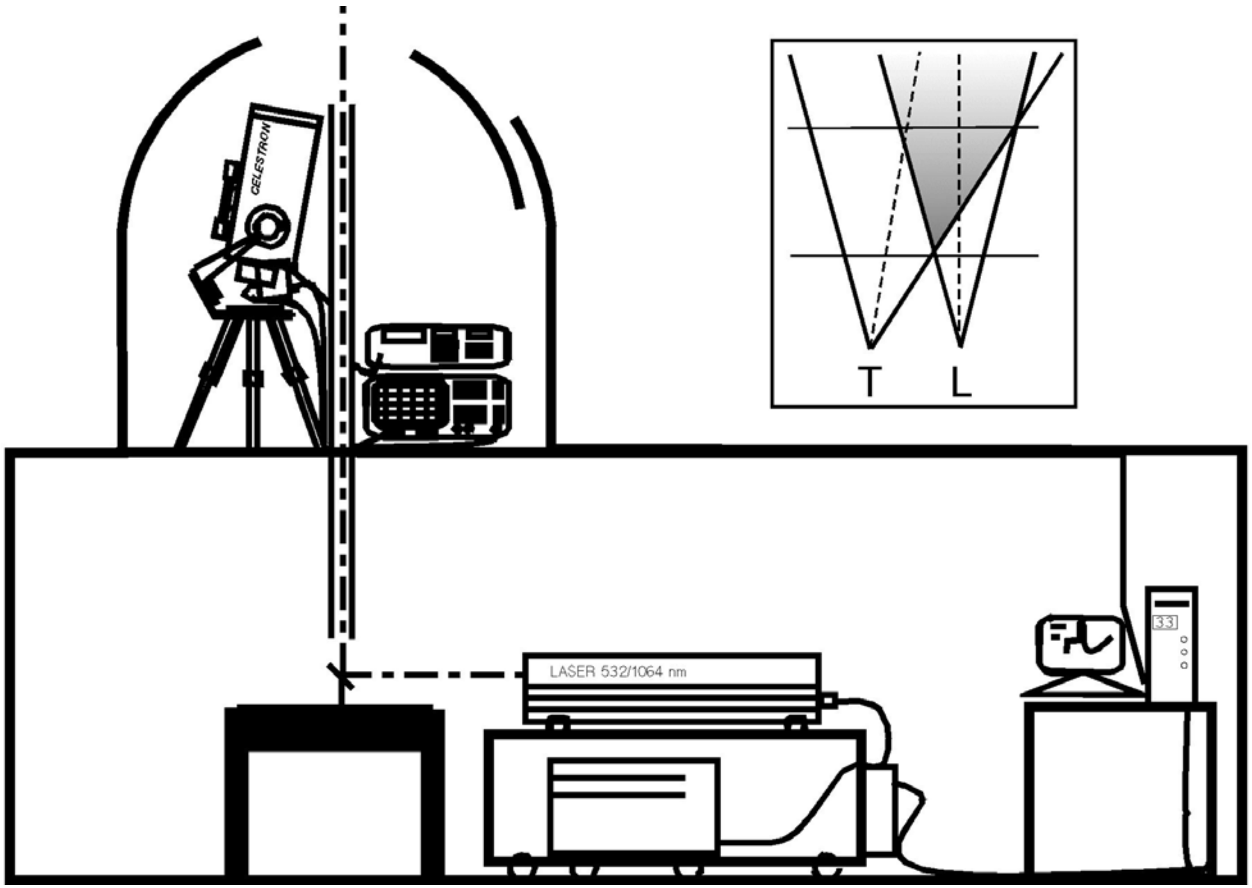
MAIN FEATURES:

- *Self-alignment of emission and reception axes*
- *Eye-safe*
- *Compact and portable*

SOURCE: CIMEL Electronique, http://www.cimel.fr (Mod. CE370-2)

EXAMPLES: BACKSCATTER LIDAR - UPC 1996

LASER		RECEIVER		SYSTEM SPECS	
Gain medium	Nd:YAG	**Focal length**	2 m	**Configuration**	Vertical biaxial
Energy	0.5 J/532 nm	**Aperture ∅**	20 cm	**System NEP**	70 fW·$Hz^{-1/2}$
Divergence	0.1mrad	**Detector**	APD (EGG C30954)	**Min. Det. Power**	< 5 nW
Pulse length	10 ns	**Net Responsivity**	6×10^{1}-3×10^{6} V/W	**Acquisition**	20 Msps/12bit
PRF	10 Hz	**Bandwidth**	10 MHz	**Spatial resolution**	7.5 m



DISTINCTIVE SPECS:

(as compared to µW RADARS)

ΔR = 7.5 m!

Δt = 1 min

BACKSCATTER LIDAR - UPC 1996

LASER		RECEIVER		SYSTEM SPECS	
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PRF	10 Hz	**Bandwidth**	10 MHz	**Spatial resolution**	7.5 m

ADVANCED CONFIGURATIONS: SRL - UPC 2004

Fig. 1

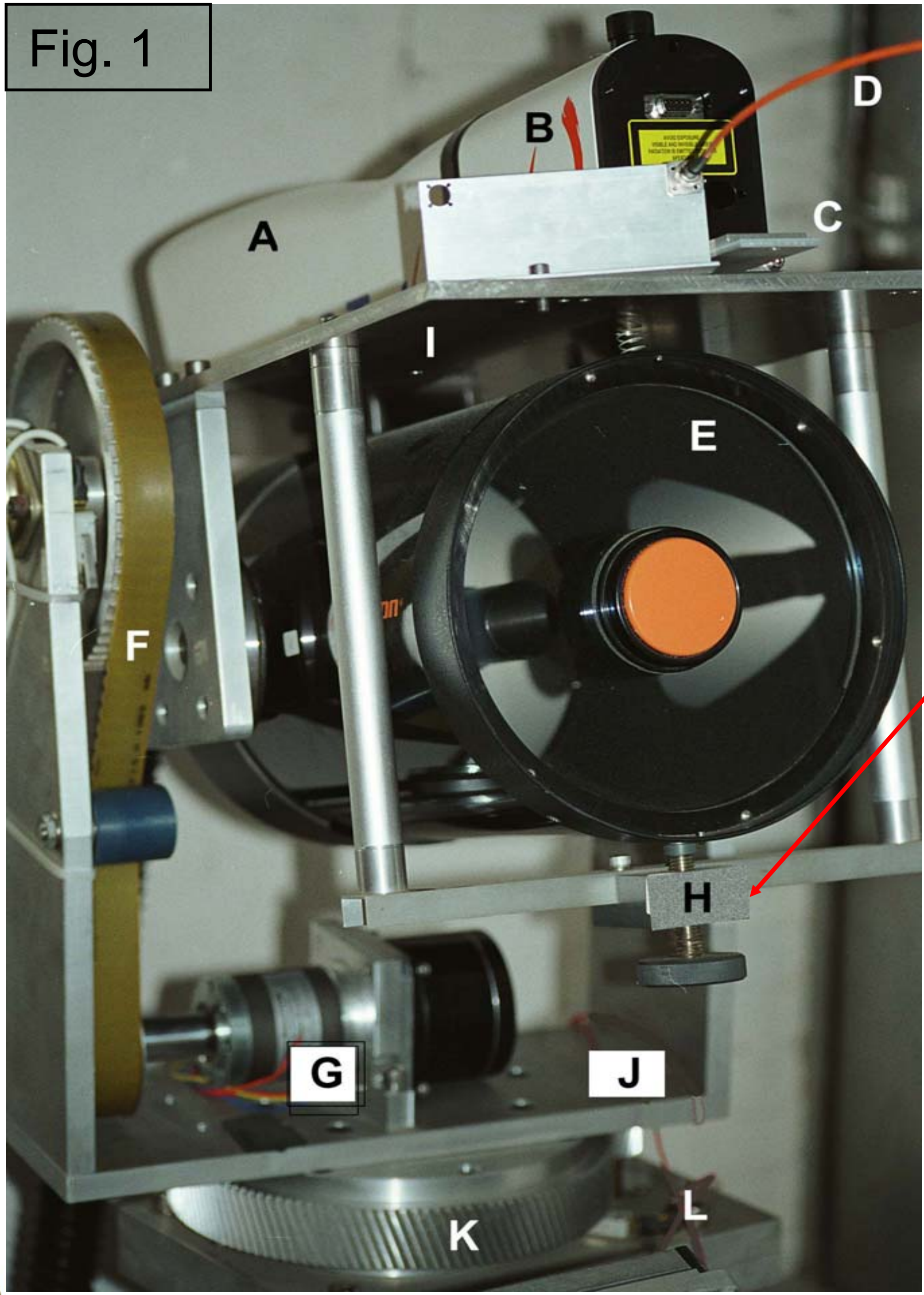
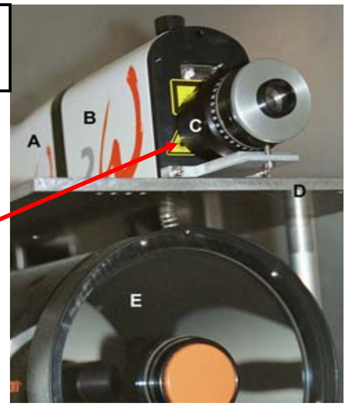


Fig. 2

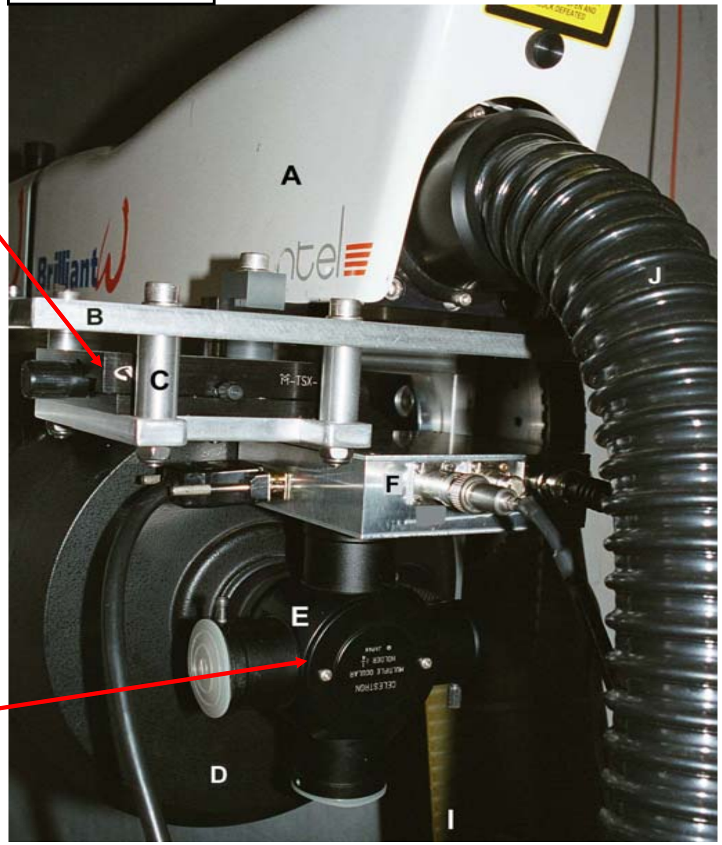


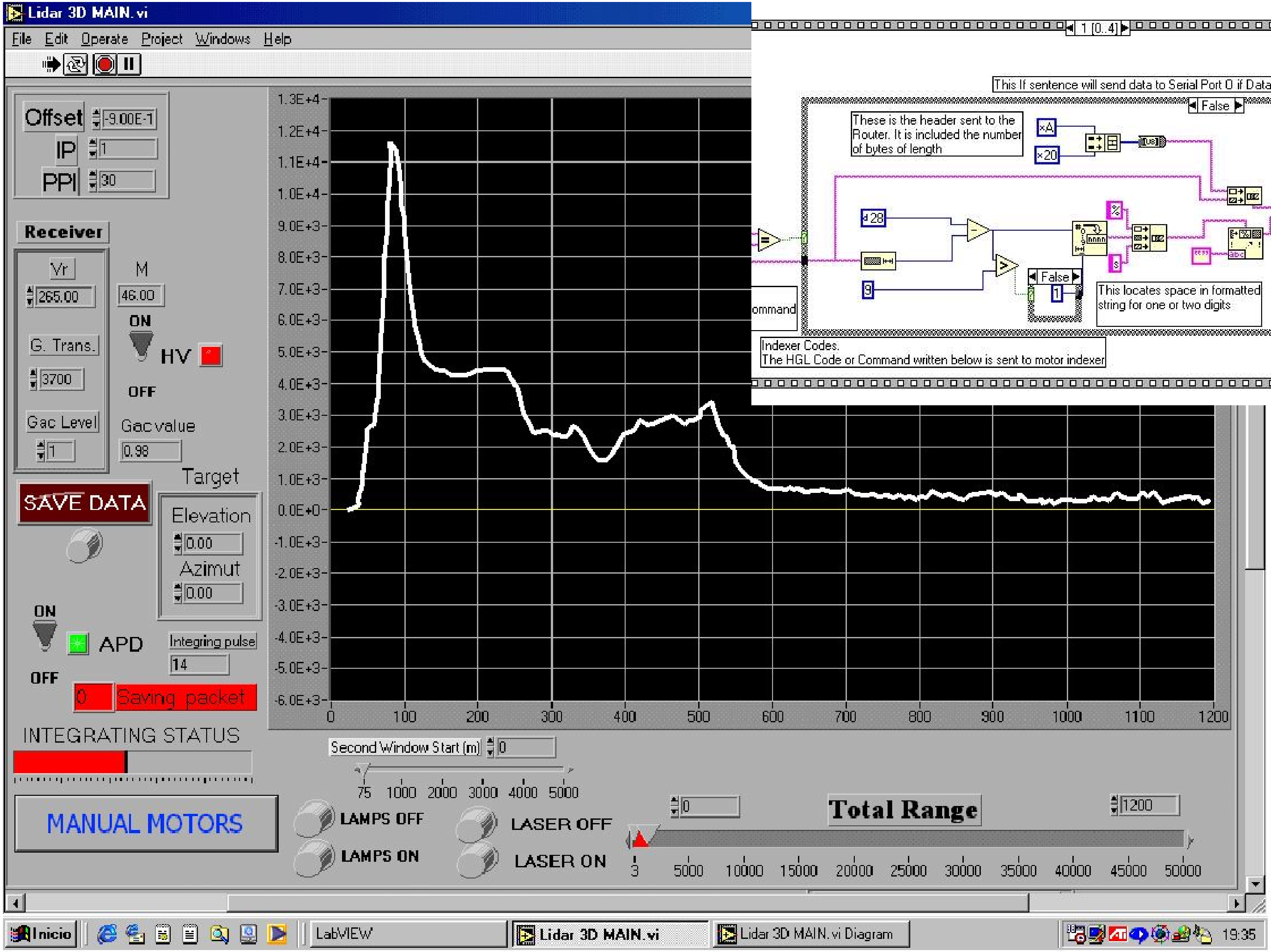
Polarim. Subs. (T)

Alignment

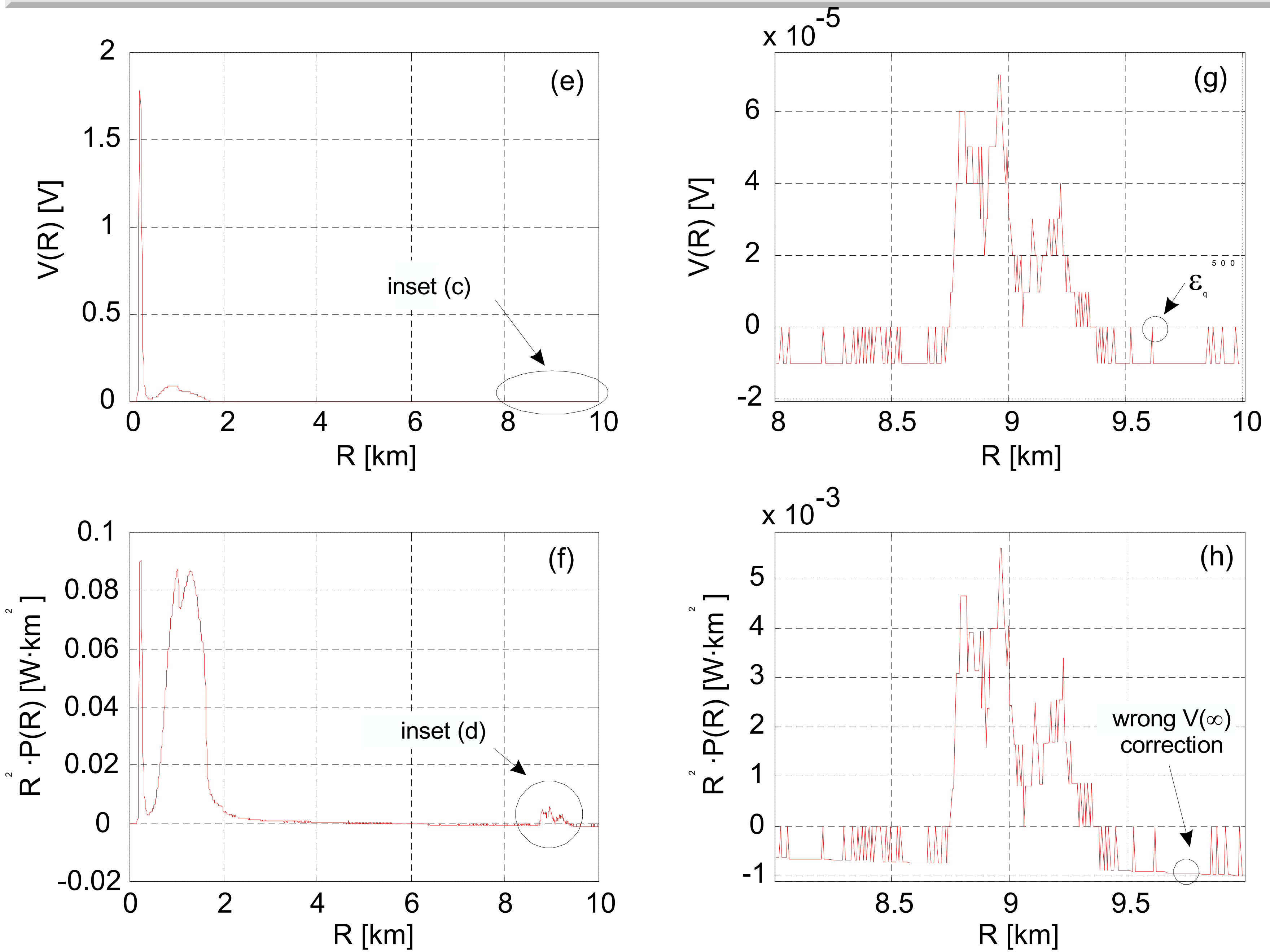
Polarim. Subs. (R)

Fig. 3




Lidar 3D MAIN.vi
File Edit Operate Project Windows Help
Offset -9.00E-1
IP 1
PPI 30
Receiver
Vr 265.00
M 46.00
ON
HV
OFF
G. Trans. 3700
Gac Level 1
Gac value 0.98
Target
SAVE DATA
Elevation 0.00
Azimut 0.00
ON
APD
OFF
Integring pulse 14
0 Saving packet
INTEGRATING STATUS
MANUAL MOTORS
Second Window Start (m) 0
LAMPS OFF
LAMPS ON
LASER OFF
LASER ON
Total Range
0
1200
This If sentence will send data to Serial Port 0 if Data
False
These is the header sent to the Router. It is included the number of bytes of length
This locates space in formatted string for one or two digits
Indexer Codes.
The HGL Code or Command written below is sent to motor indexer
LabVIEW
Lidar 3D MAIN.vi
Lidar 3D MAIN.vi Diagram
19:35

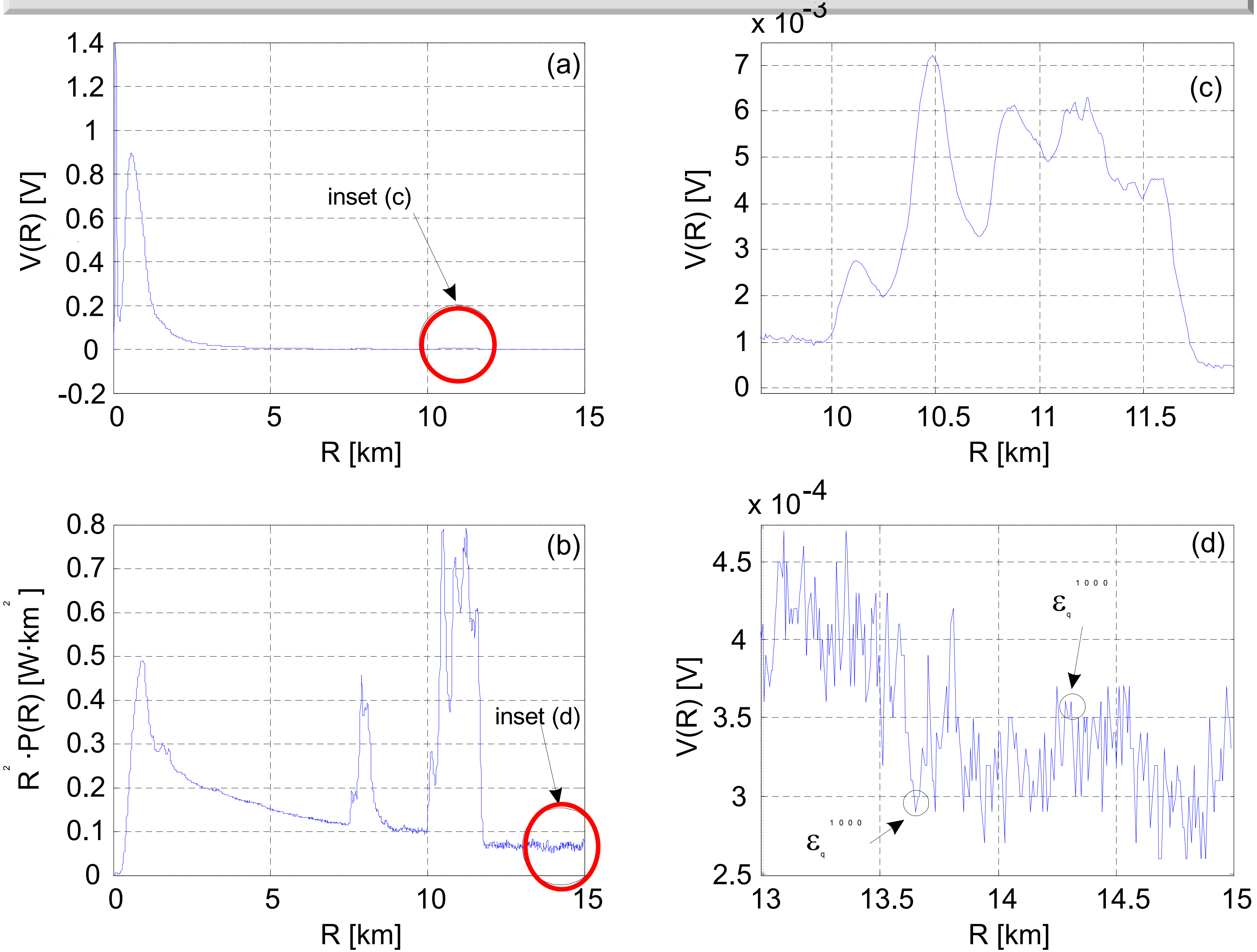
EXAMPLE OF BAD SIGNAL CONDITIONING

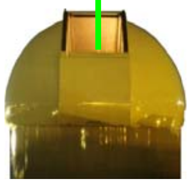


LIDAR (LASER RADAR)

DEP. OF SIGNAL THEORY AND COMMUNICATIONS

EXAMPLE OF GOOD SIGNAL CONDITIONING





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WINDOWED EXPLORATION (I)

CONCEPT

–We accommodate range A-B into the ADC at the odd pulses and C-D at the even ones.

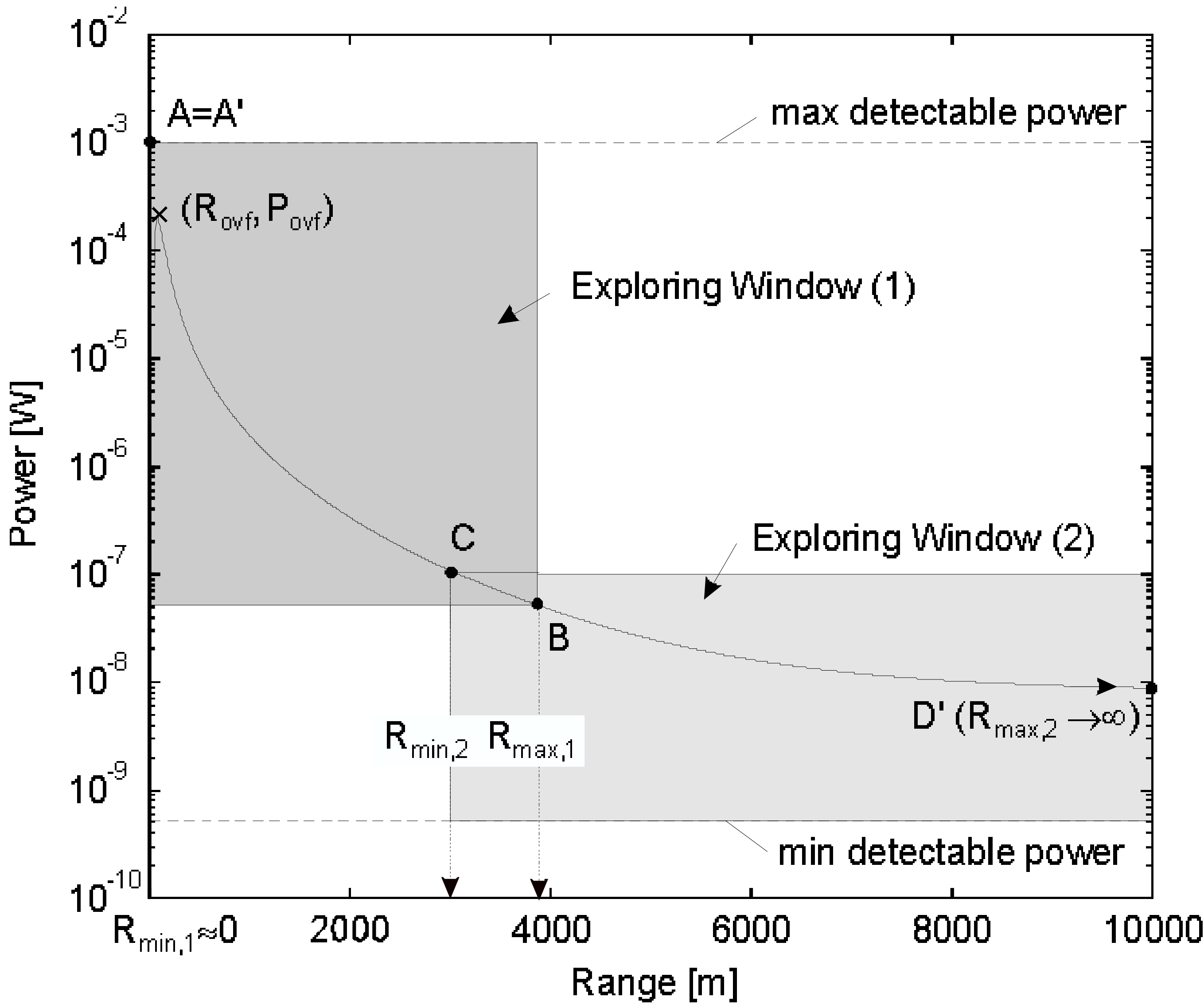
–Hence, ADC dyn. range doubles!

REQUIREMENTS

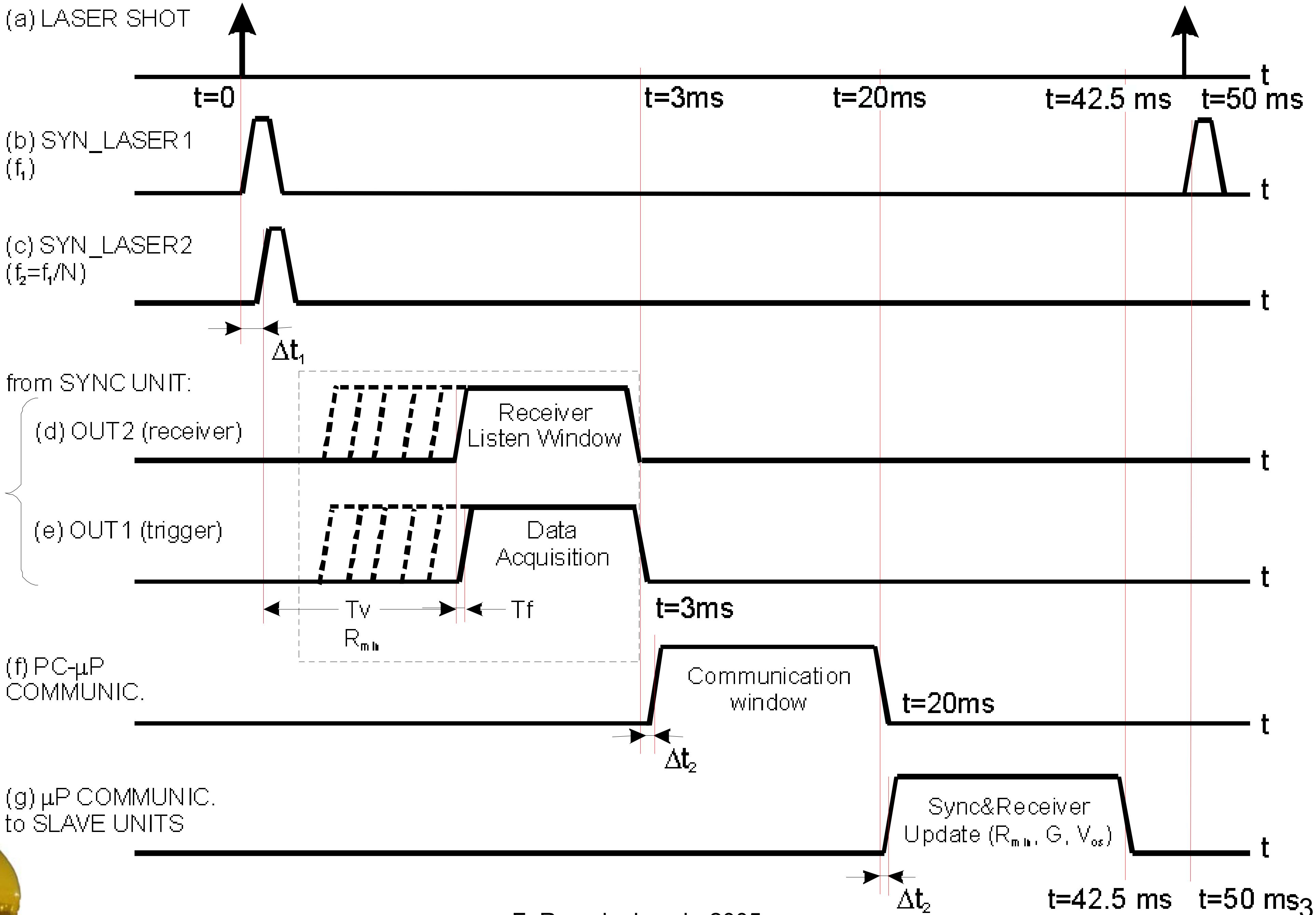
1) Each window is defined by a set

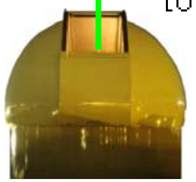
(G, V_{OS}, R_{min})

2) Synchronous G and V_{os} update

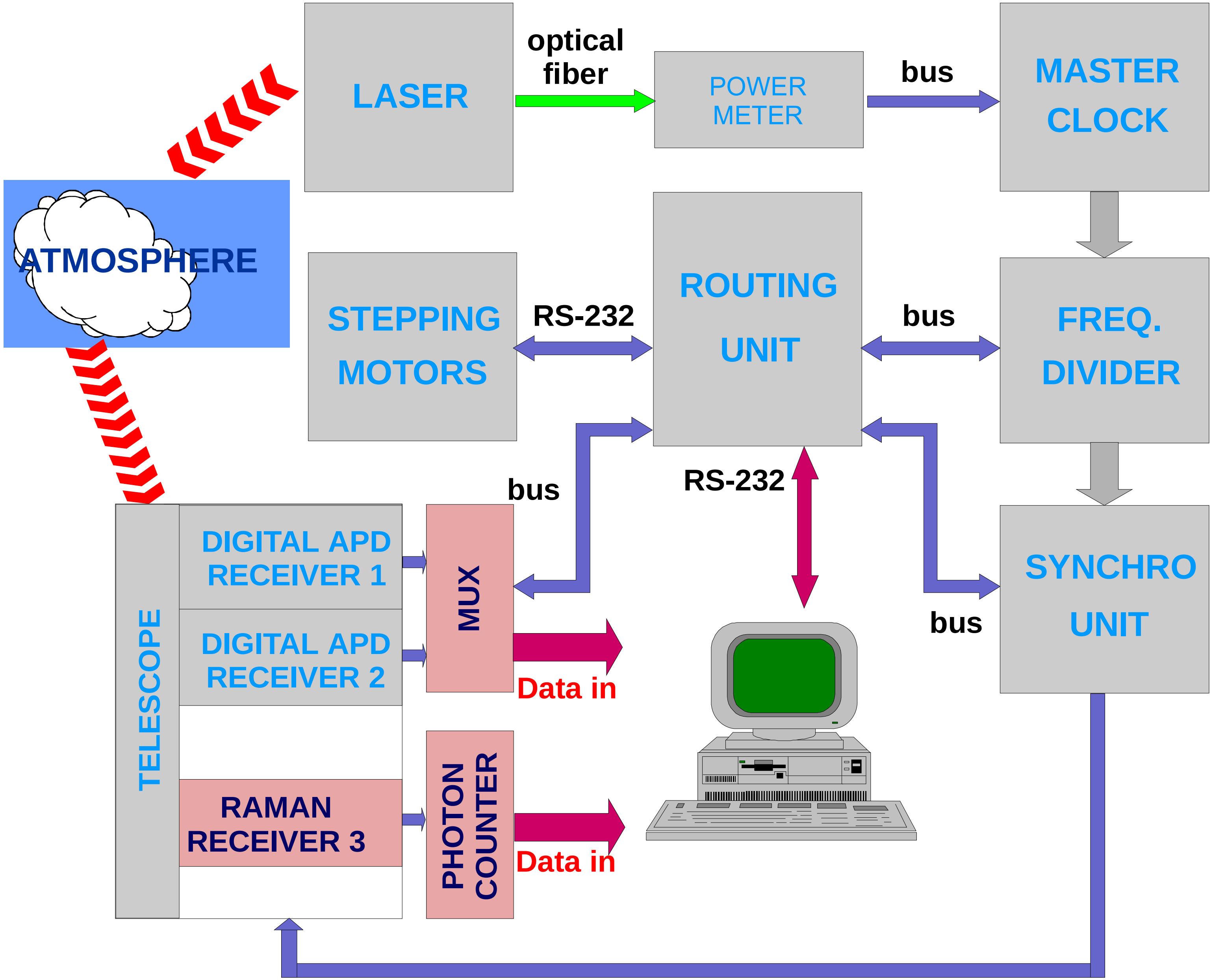


WINDOWED EXPLORATION (II)





SRL SYSTEM CONFIGURATION



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PSEUDO-RANDOM SYSTEMS

PN SEQUENCES (I)

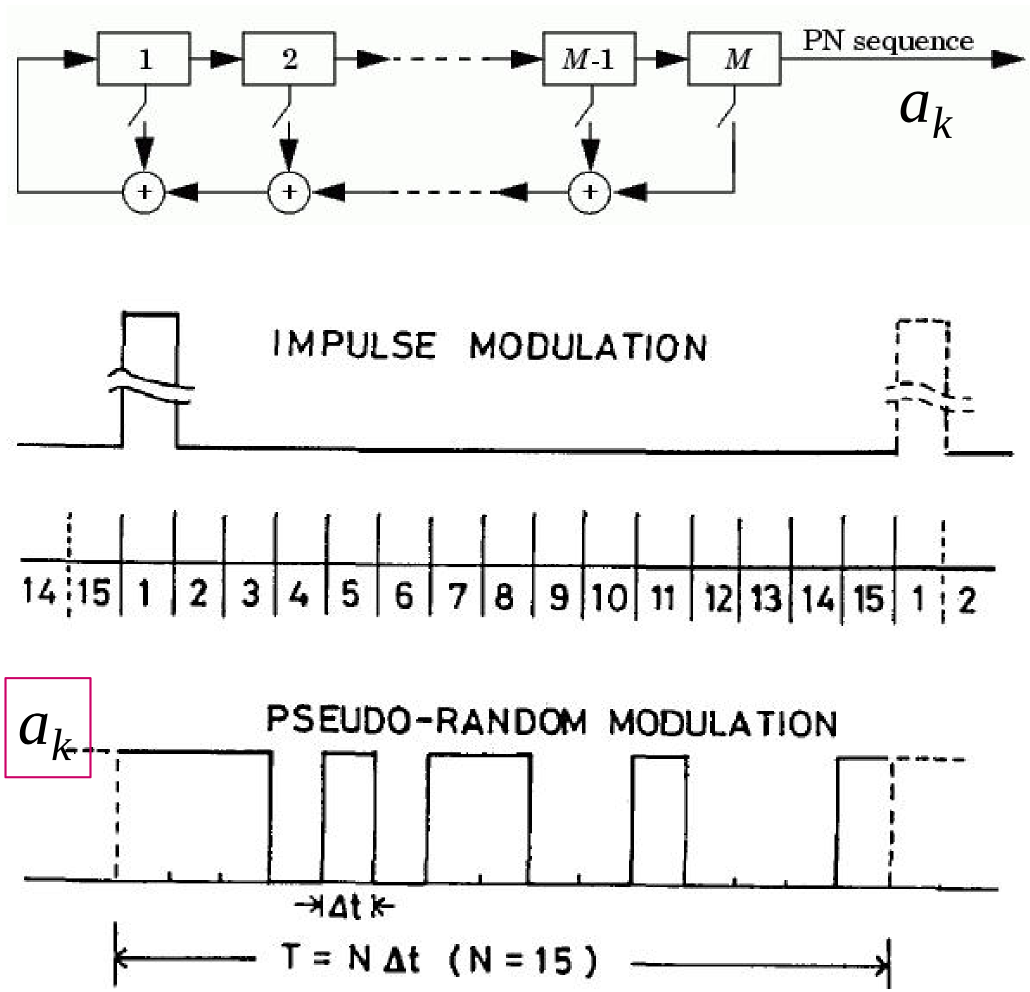


Fig. SOURCE: Takeuchi et al, "Random modulation CW lidar", Appl. Opt., 22(9), 1382-6 (1983).

KEYS:

1) A feedback n-stage shift register with non-zero initial state acts as a periodic seq. generator.

2) The PN (pseudo-noise) sequence length is

$$N = 2^n - 1$$

i.e., period = NT_b

3) Usually, the binary polar NRZ sequence is used,

$$a'_k = 2a_k - 1$$

$$a'(t) = \sum_k (2a_k - 1)\Pi\left(\frac{t - kT_b}{T_b}\right)$$

PSEUDO-RANDOM SYSTEMS

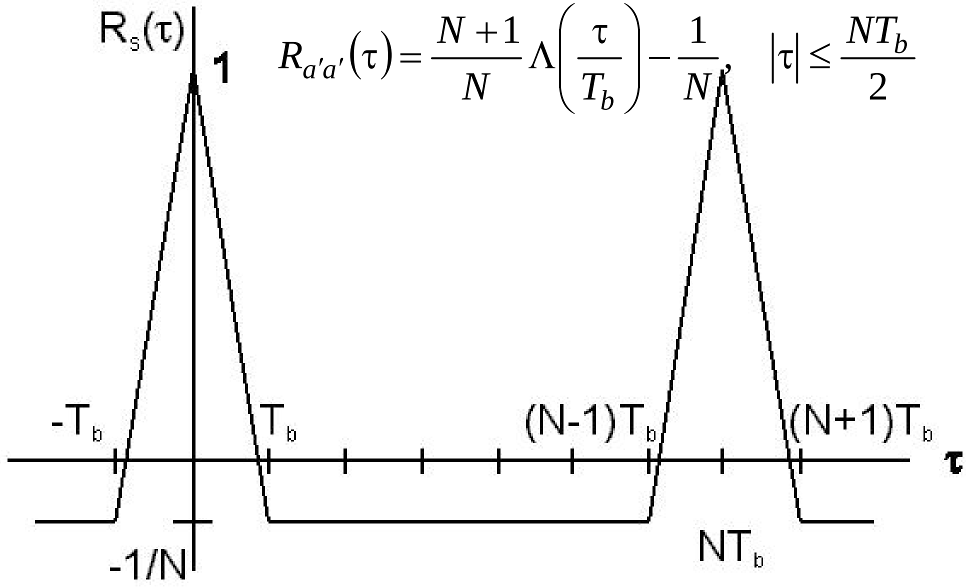
PN SEQUENCES (II)

4) Periodic Autocorrelation

$$\tilde{R}_{a'a'}(j) = \begin{cases} 1 & j = 0 \\ -\frac{1}{N} & j \neq 0 \end{cases}$$

$$\tilde{R}_{aa'}(n) = \begin{cases} \frac{N+1}{2N} = \frac{l}{N} & j = 0 \\ 0 & j \neq 0 \end{cases}$$

$$R_{a'a'}(\tau) = \frac{N+1}{N} \Lambda\left(\frac{\tau}{T_b}\right) - \frac{1}{N}, \quad |\tau| \leq \frac{NT_b}{2}$$



5) Reencounters the system (atmospheric) impulse response →

- *System identification*
- *Demodulation is substituted by correlation*

$$g(t) = \frac{c}{2} A_r \frac{1}{R^2} \beta(R) T(R)^2 \xi(\lambda) \xi(R)$$

$$\begin{cases} \tilde{x}(t) = Ea(t) = P_0' T_b a(t) \\ \tilde{y}(t) = \tilde{x}(t) * g(t) \end{cases}$$

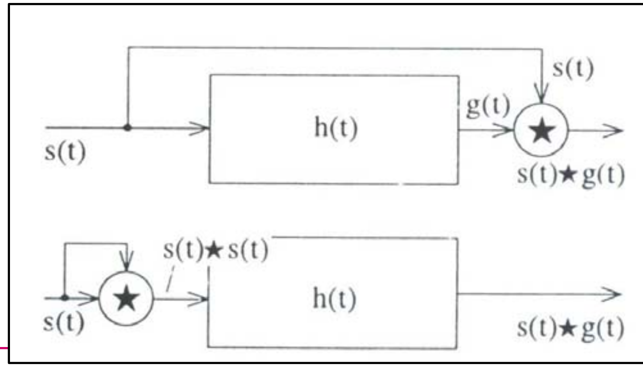
$$\tilde{\tilde{g}}(t) = \tilde{y}(t) * a'(t) \approx g(t)$$

PSEUDO-RANDOM SYSTEMS

THE ATMOSPHERIC ID. PROBLEM

- *The impulse excitation is substituted by*

$$\tilde{R}_{ss}(t) = l E_b \delta(t)$$



SYSTEM LAYOUT

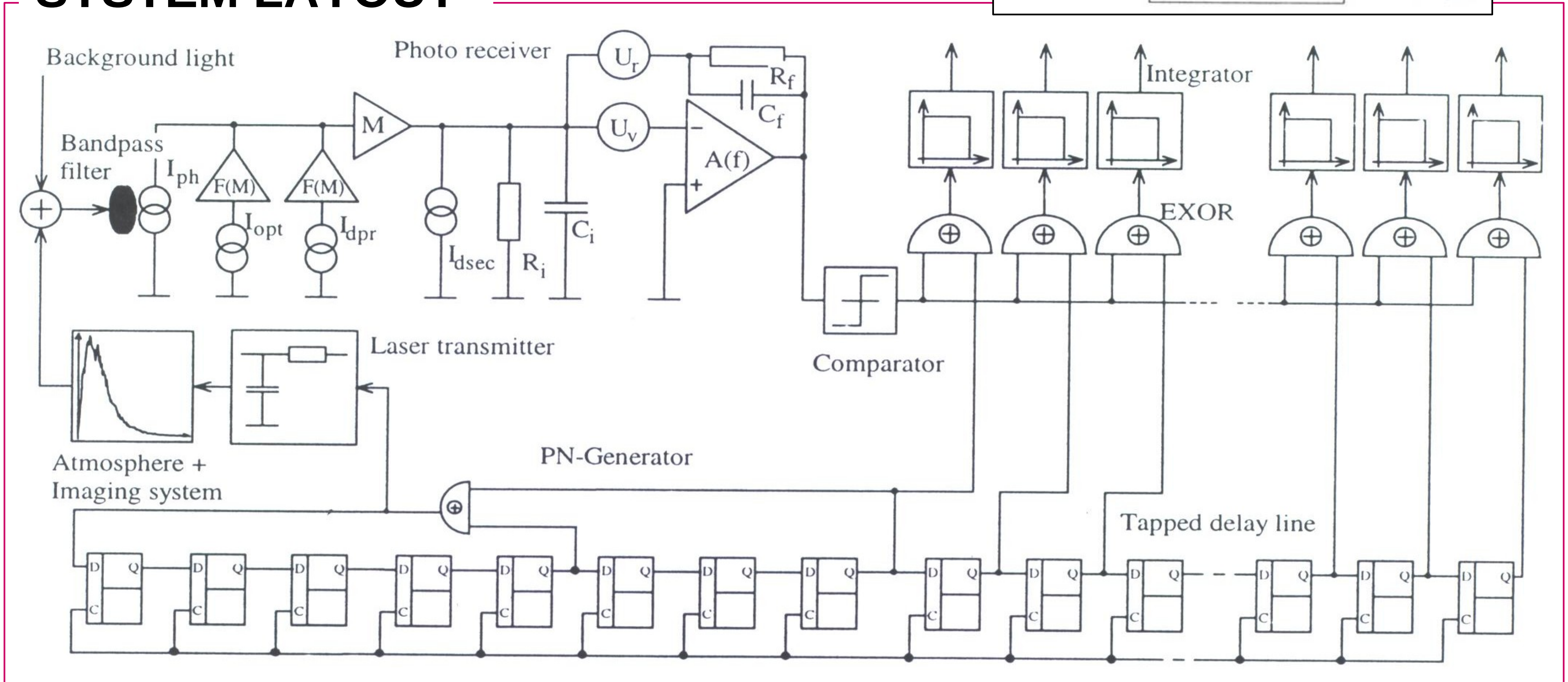
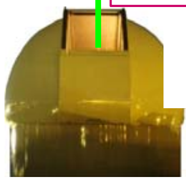
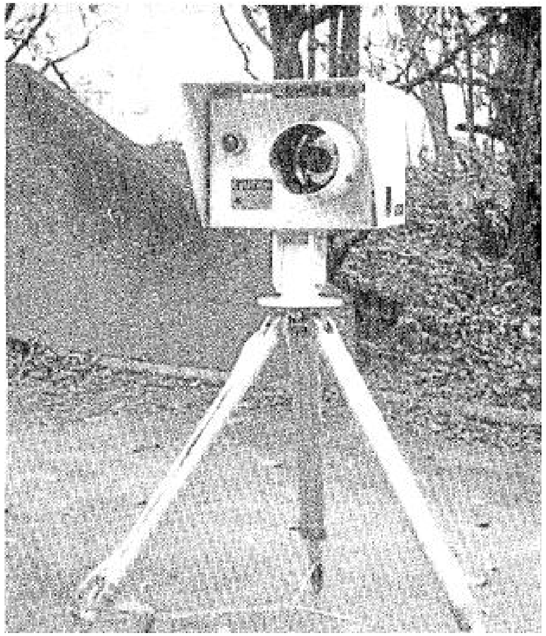


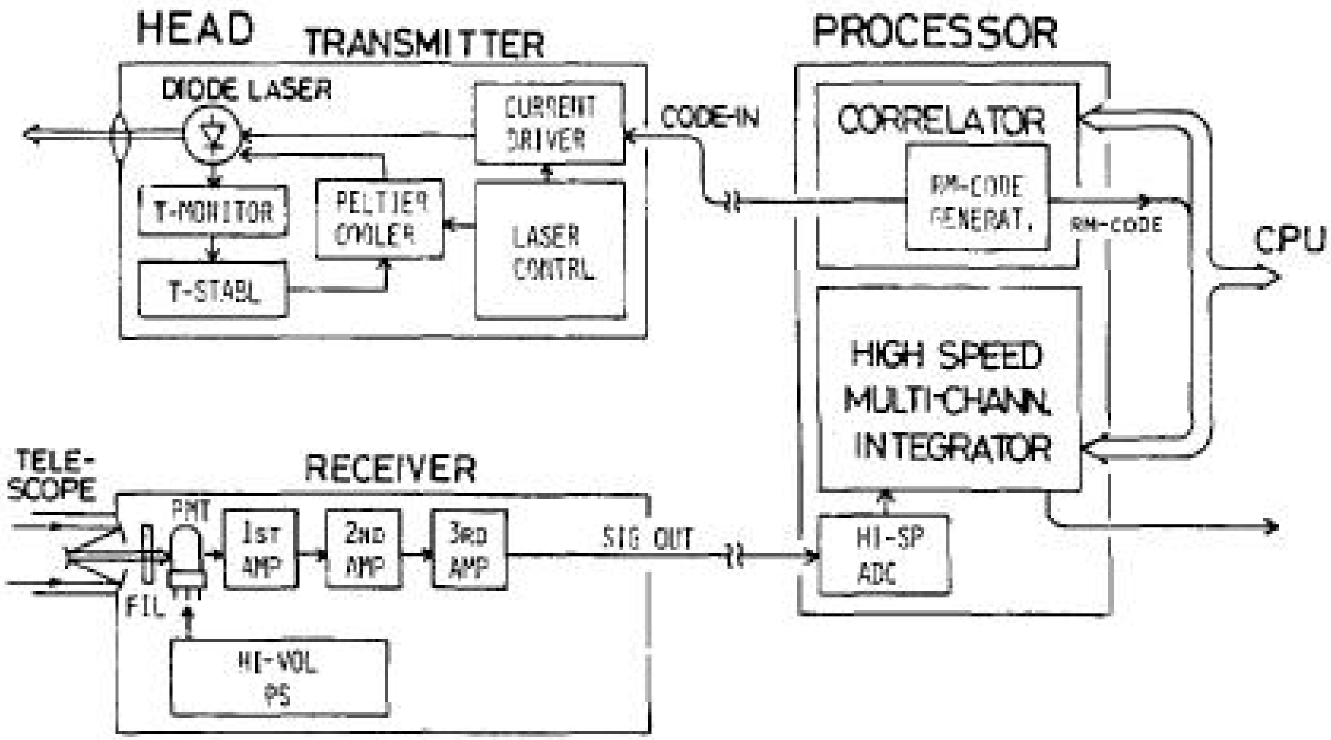
Fig. SOURCE: Bundschuh et al., "Feasibility study of a compact low cost correlation LIDAR using a pseudo-noise modulated diode laser and an APD in the current mode", IEEE (1996).



PSEUDO-RANDOM SYSTEMS

PROTOTYPE EXAMPLE





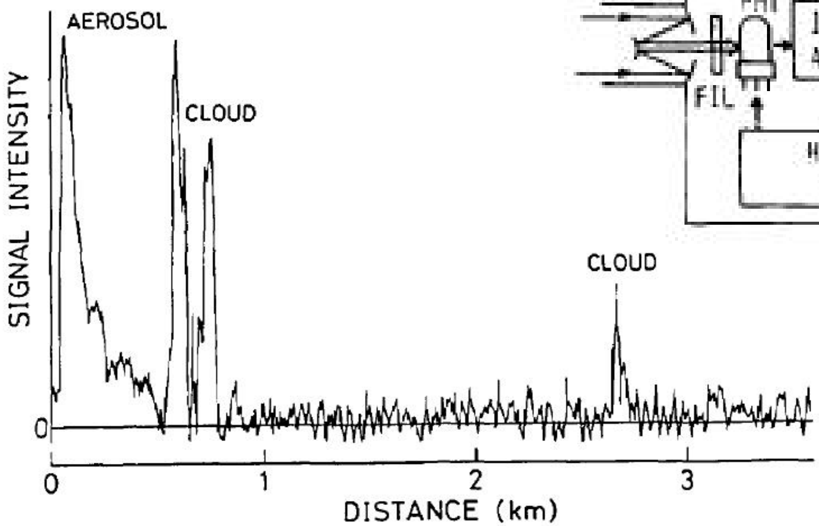


Fig. SOURCE: Takeuchi et al, "Diode-laser random-modulation CW lidar", Appl. Opt., 25(1), 63-7 (1986).