DEP. OF SIGNAL THEORY AND COMMUNICATIONS

LIDAR (laser radar)
Chap. 5A. Inversion Algorithms

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RAW-DATA PROCESSING

RAW-DATA RECORD

$$\left(V_{OS} = R'_V P_{back} + V_{drift} + V_{user}\right)$$

$$V_{raw}(R) = V(R) - V_{OS} = R'_V P(R) + n_{eq}(R) + \varepsilon_q + x_a(R) + x_s(R)$$

clean data term ($R'_V P(R)$)

$\varepsilon_q + x_a(R)$: $\ll n_{tot}(R)$

CALIBRATION RECORD

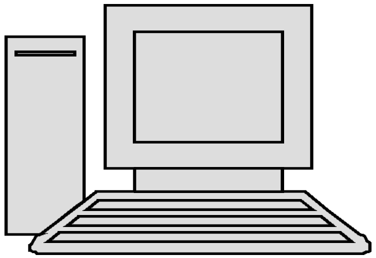
$$\left(V'_{OS} = V_{drift} + V_{user}\right)$$

$$V_{cal}(R) = V_{cover}(R) - V'_{OS} = n'_{eq}(R) + \varepsilon'_q + x'_a(R) + x_s(R)$$

raw

$V_{raw}(R)$

$V_{cal}(R)$

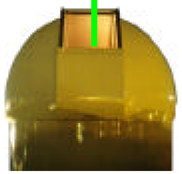


$$\hat{P}(R) \propto V_{raw}(R) - V_{cal}(R)$$

clean

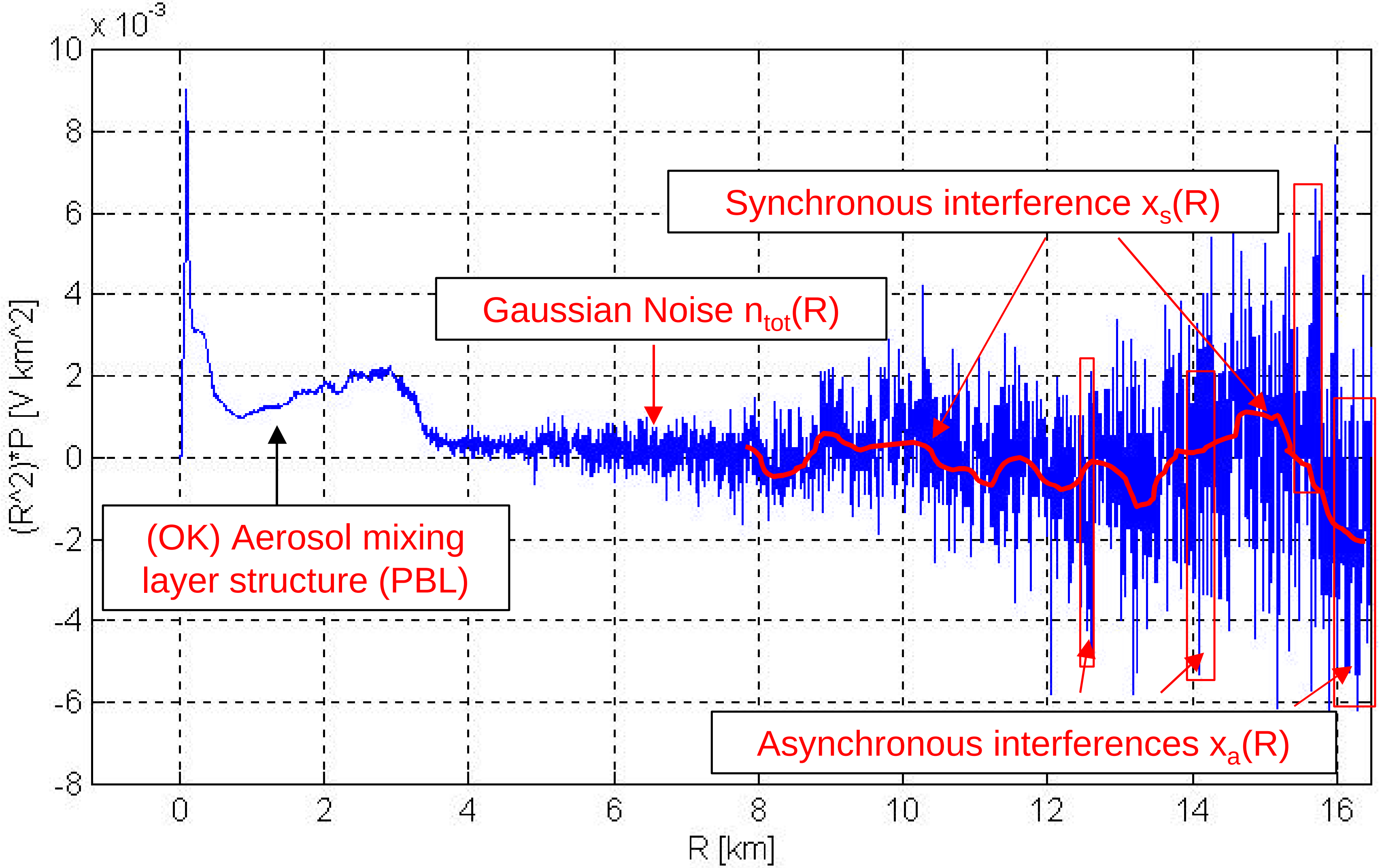
RAW DATA

Time/Spatial averaging	Calibration	Others
Noise reduction	Sync. interference cancellation	Range-interval selection, no clouds (stationarity),...

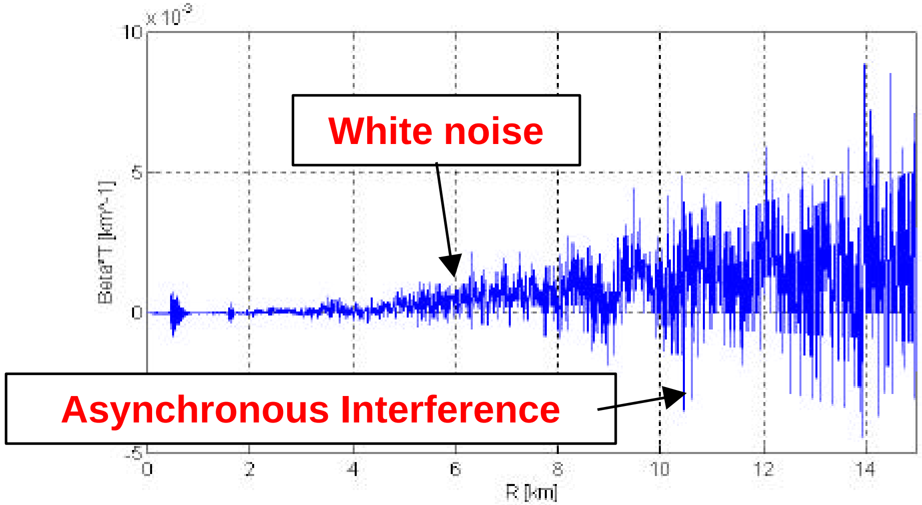


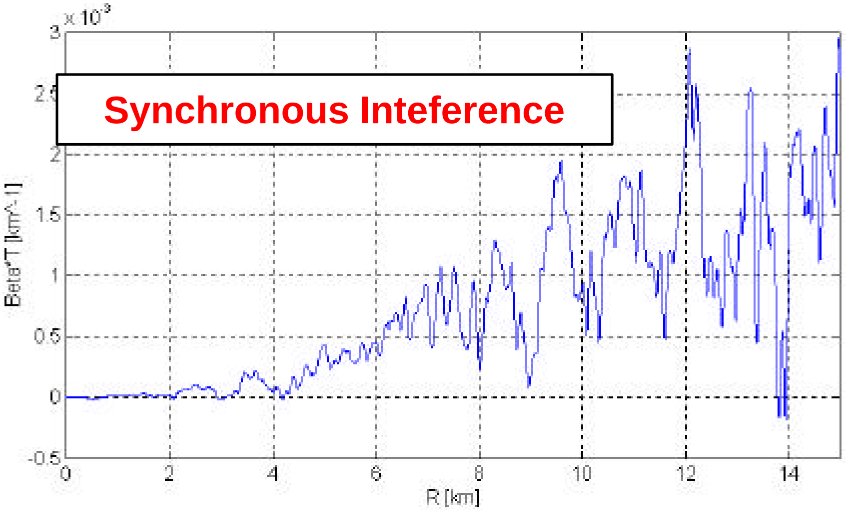
CORRUPTING NOISE SOURCES

Example of raw R^2P record



CALIBRATION PROCEDURE (I)





Time-avg raw signal

- *Record IP, PPI=N_1 pulses*

$$V_{raw,Ó}(R) = R'_V P(R) + n_{Ó_1}(R) + x_s(R)$$

Calibration signal

- *You cover the telescope aperture*
- *Record IP=1, PPI=N_2 pulses*

$$V_{cal}(R) = n'_{\Sigma_2}(R) + x_s(R)$$

CALIBRATION PROCEDURE

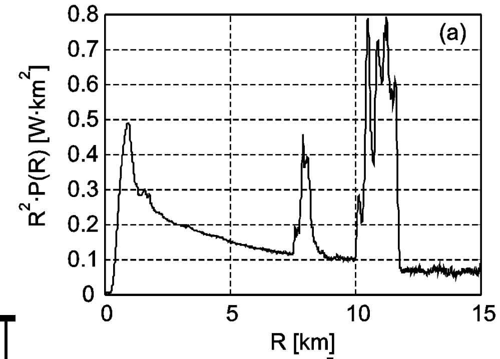
- ® $V(R) = V_{raw,\Sigma}(R) - V_{cal}(R)$
- *Synchronous interferences cancel out*

$$V(R) = R'_V P(R) + n_{Ó_1}(R) - n'_{Ó_2}(R)$$

CALIBRATION PROCEDURE (II)

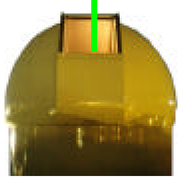
SNR PERFORMANCE

Noise variances during the calibration differential procedure ADD UP so...

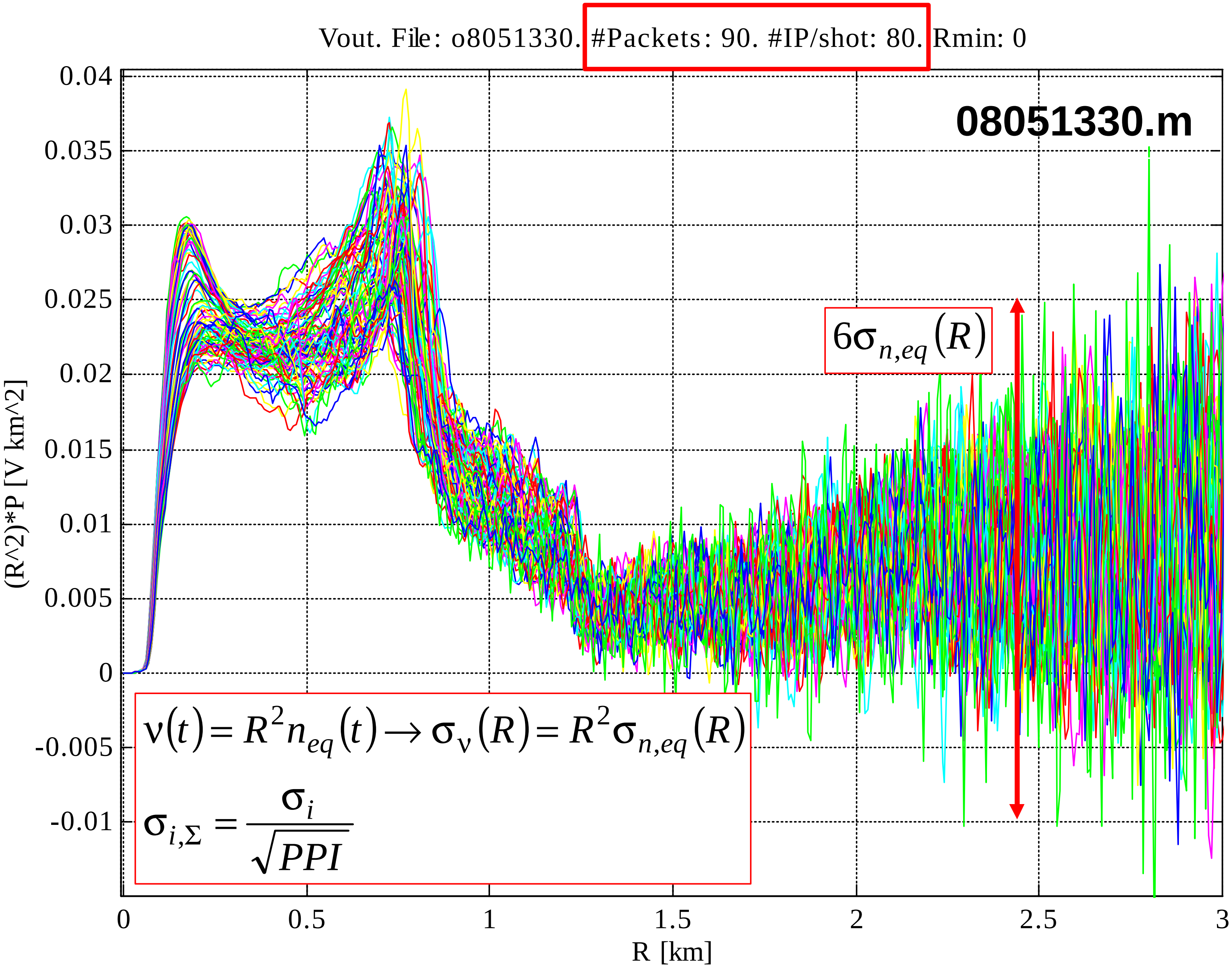


	SIGNAL RETURN	*NOISE SOURCES*	*STANDARD DEVIATION*	*COMMENT*
$V_{raw,\Sigma}$	$P(R) + P_{back}$	$n_{eq,\Sigma 1}$, x_s, (x_a)	$\frac{\sigma_{n,eq}}{\sqrt{N_1}}$	Meas. step PPI= N_1
V_{cal}	**0** (telescope covered)	$n_{eq,\Sigma 2}$, x_s, (x_a)	$\frac{\sigma_{n,eq}}{\sqrt{N_2}}$	Calibration PPI= N_2
V_{clean}	$P(R)$	$n_{eq,\Sigma}$, (x_a)	$\frac{\sigma_{n,eq}}{\sqrt{N_1}} + \frac{\sigma_{n,eq}}{\sqrt{N_2}}$	Sync.Interfer cancel out

$N_2 >> N_1$ is required to maintain measurement-step SNR !

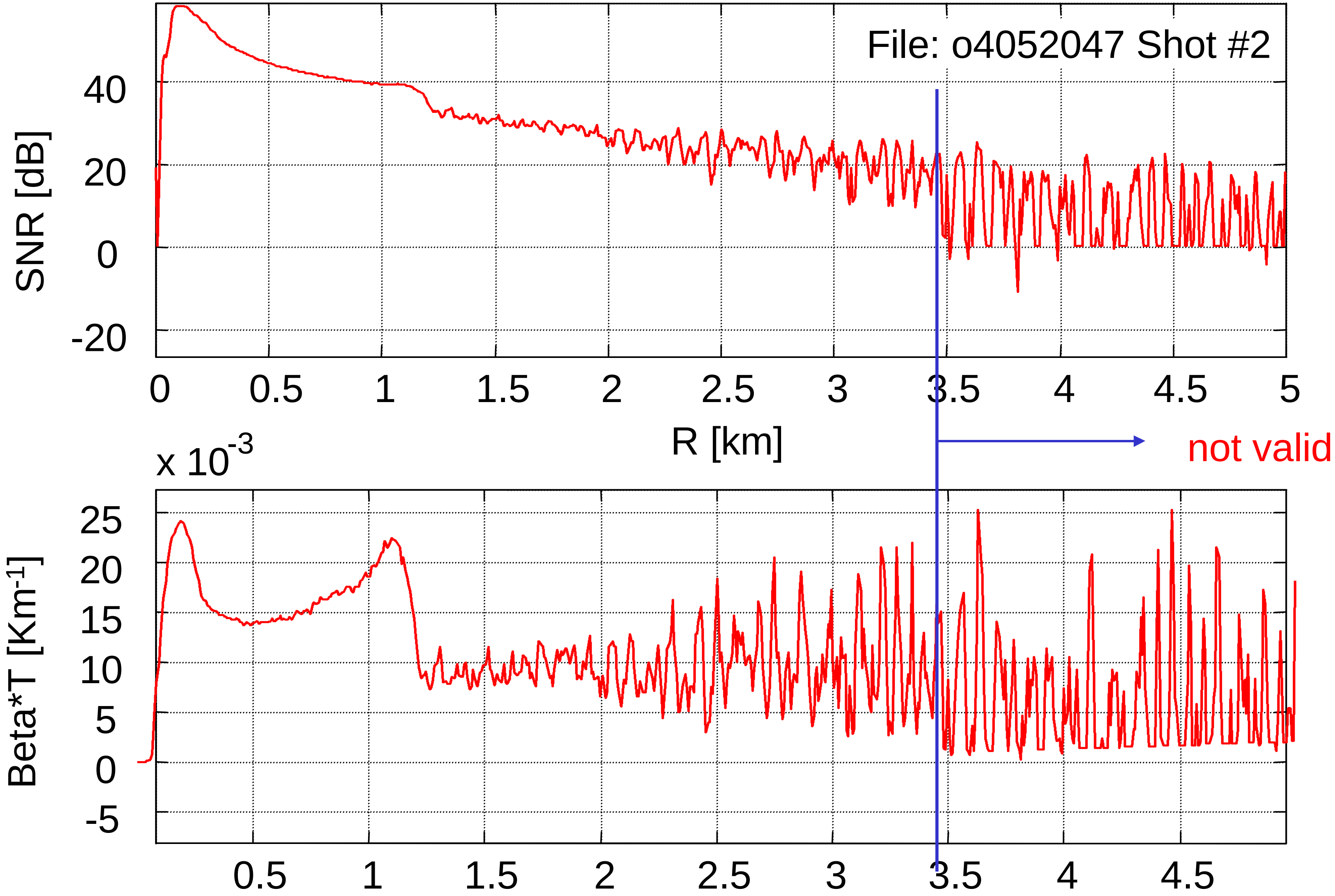


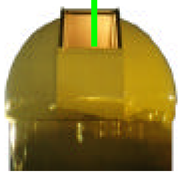
TEMPORAL AVERAGING (I)



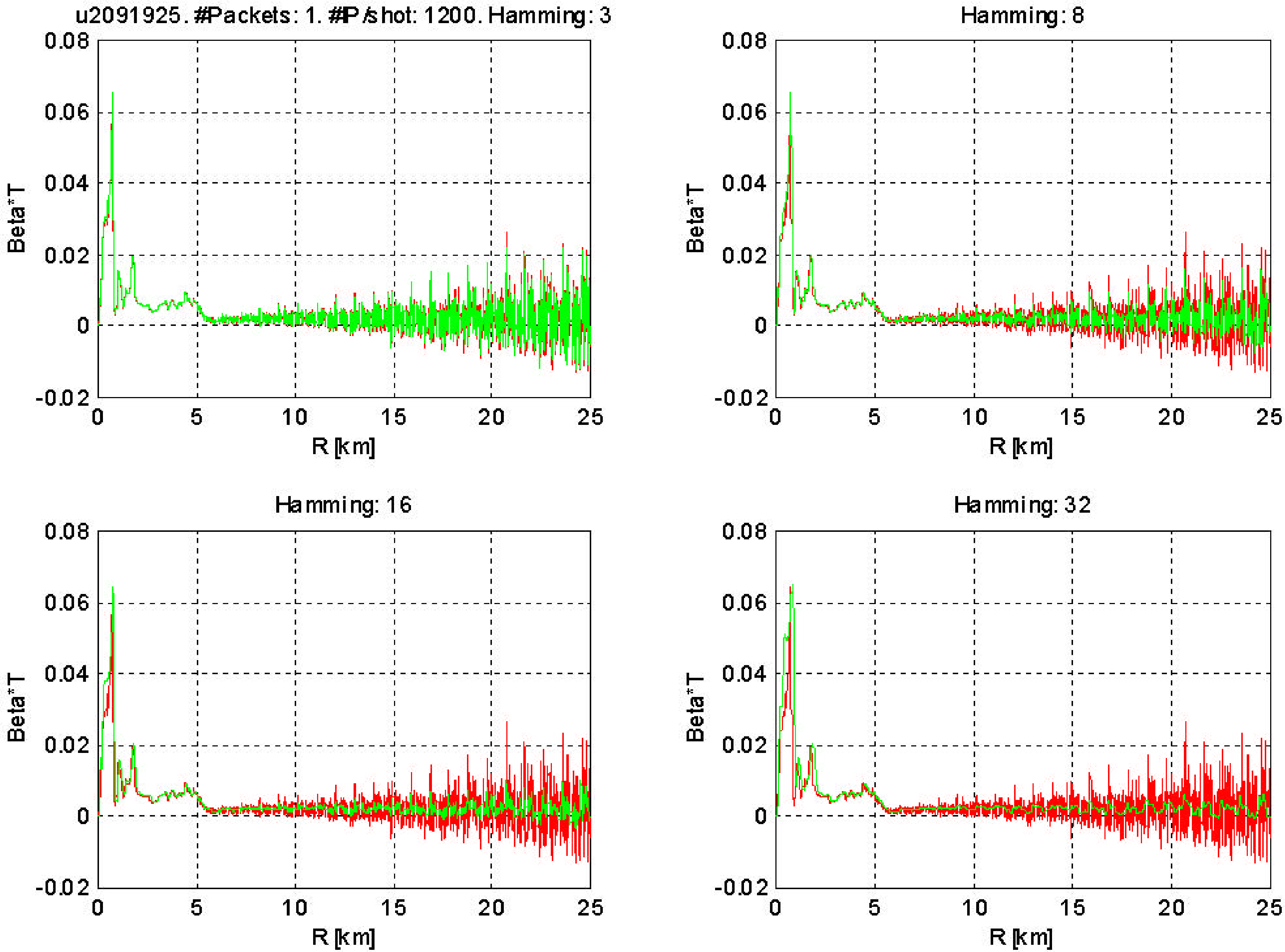
TEMPORAL AVERAGING (II)

SNR ESTIMATION

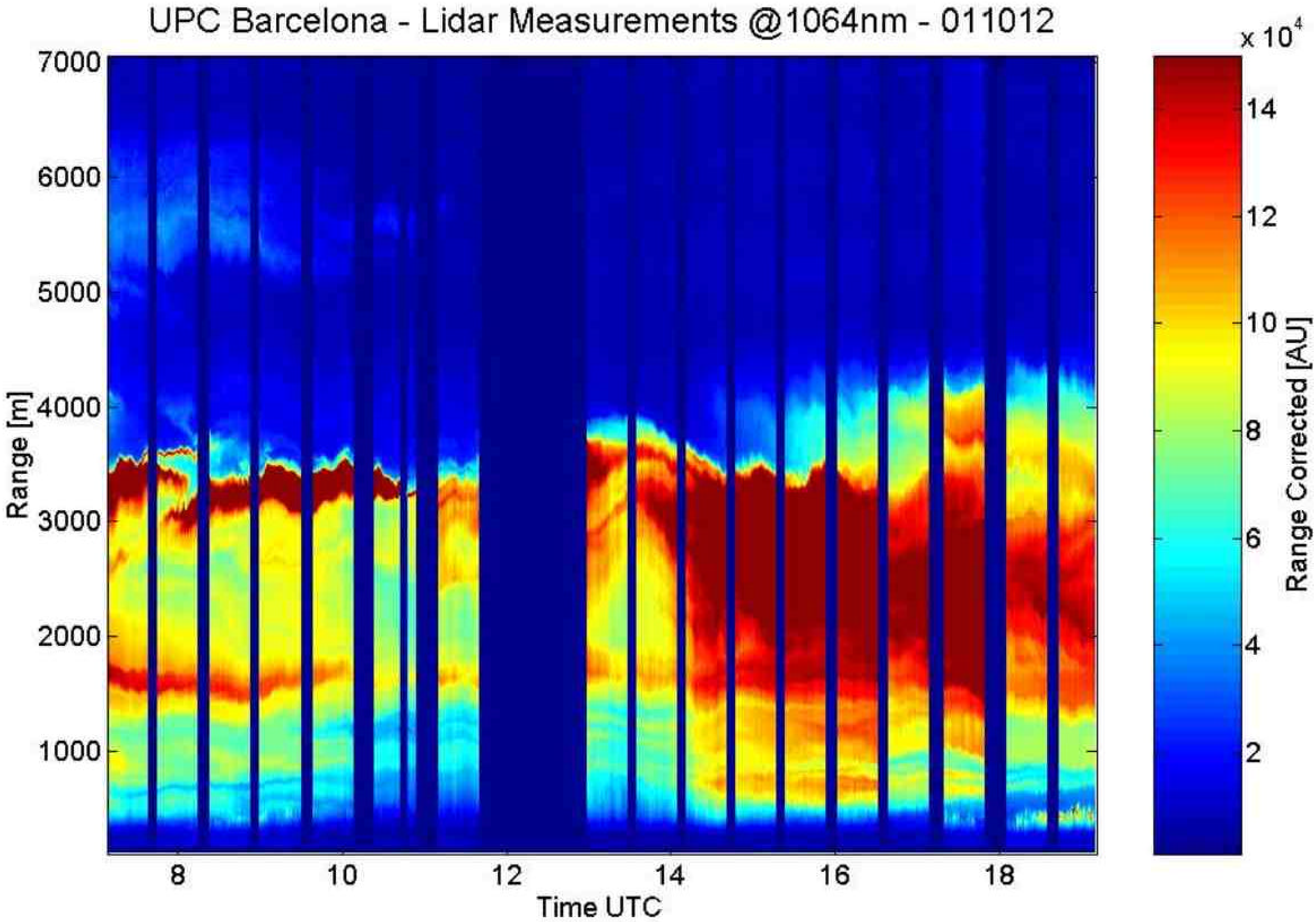




SPATIAL AVERAGING

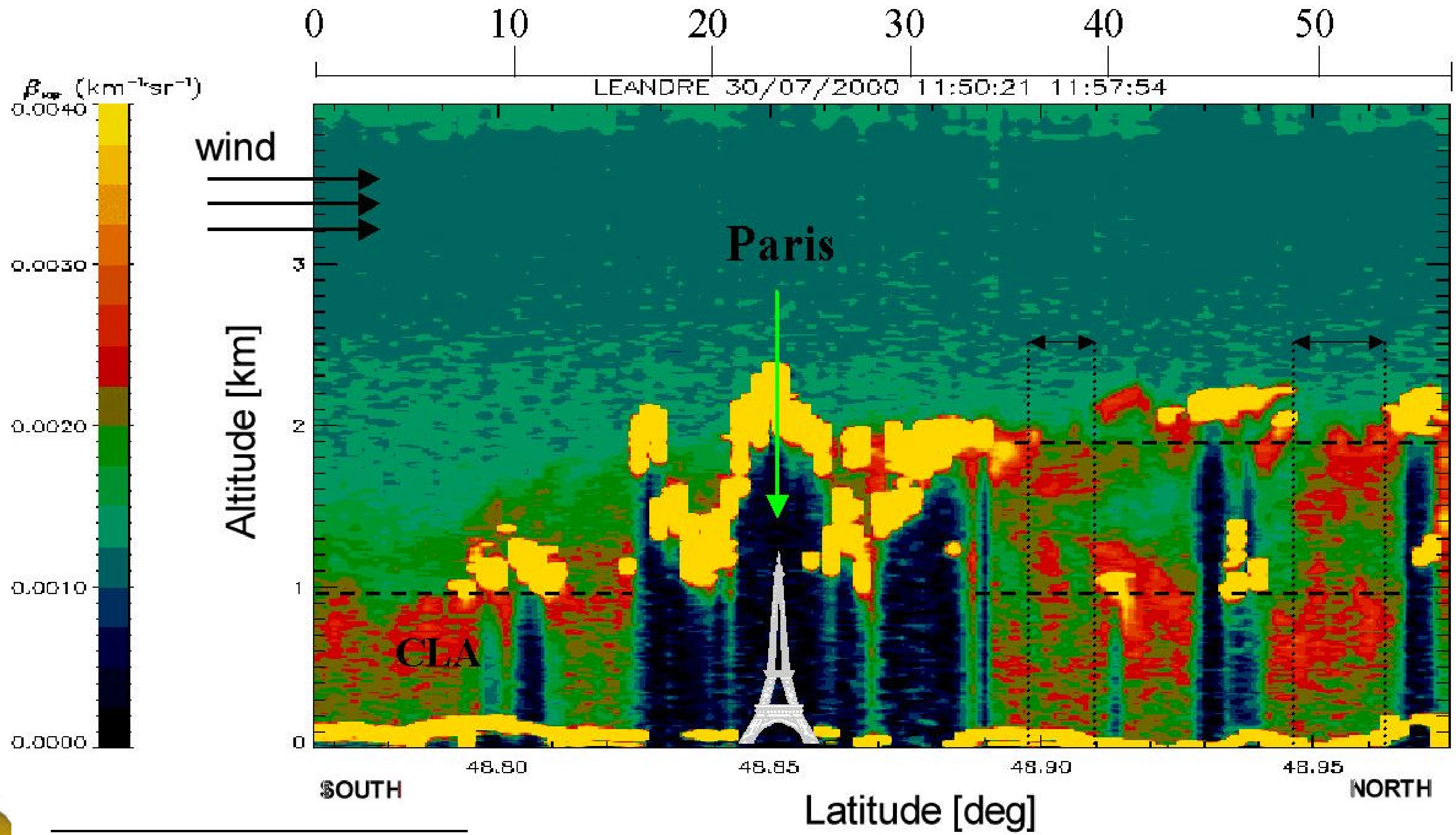


EXAMPLE (I): R²P TEMPORAL SERIES

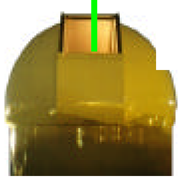


EXAMPLE (II): AIRBORNE R²P SPATIAL SERIES

Airborne 2D lidar profiles at 532 nm on a northbound axis over Paris on 30 July, 2000 - ESQUIF 2000



SOURCE FIG.: M. Sicard (internal correspondence).



1-D INVERSION OF OPTO-ATMOSPHERIC PARAMETERS

The elastic LIDAR single-scattering equation

$$P_{l_1}(R) = \frac{K_{l_1}}{R^2} b_{l_1}(R) \times \exp\left[-2\int_0^R a_{l_1}(r)dr\right] x(R)$$

$$b_{l_1}(R) = b_{l_1}^{aer}(R) + b_{l_1}^{mol}(R); \qquad a_{l_1}(R) = a_{l_1}^{aer}(R) + a_{l_1}^{mol}(R) + a_{l_1}^{abs}(R)$$

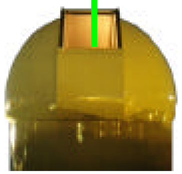
$a_{l_1}^{abs}(R) \approx 0$

where:

- $a_{l_1}(R)$ atmospheric optical extinction coefficient (Rayleigh+Mie) [km^{-1}]
- $b_{l_1}(R)$ atmospheric optical backscatter coefficient [km^{-1}sr^{-1}]
  - where $b(l, R) = \overline{N}(R)\frac{d\overline{s}(p)}{d\Omega}$,
  - and N is the avg. density of aerosol + molecular constituents [cm^2/cm^{3}sr]
- $x(R)$ optical overlap function (≈ 1 from 250 m onwards)
- $P(R)$ optical range-return power [W]

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

$$T(l, R) = \exp[-2COT(R)]; \quad COT(R) = \int_0^R a(l, r)dr$$



DIFFERENTIAL FORMULATION OF THE LIDAR EQ.

- *Let's depart from Bernouilli's form of lidar Eq.*

$$\frac{dS(R)}{dR} = \frac{1}{\beta(R)}\frac{d\beta(R)}{dR} - 2\alpha(R)$$

- *where*

$$S(R) = \ln\left[R^2 P(R)\right]$$

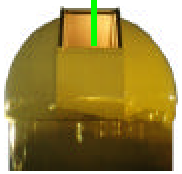
- *Under the assumption of a homogeneous atmosphere, the optical parameters are assumed to be constant over the entire lidar range*

$$a(R) \approx a \ ; \quad b(R) \approx b$$

- *This leads to the conjecture of low fractional gradients,*

$$\frac{1}{\beta(R)}\frac{d\beta(R)}{dR} << 2\alpha(R)$$

- *This is unjustified under the conditions prevailing in dense clouds, fog or where local inhomogeneities occur.*



1-D NON-MEMORY HOMOGENEOUS ALGORITHMS

SLOPE METHOD

- *Both methods assume a homogeneous atmosphere*

$$S(R)=\ln\left(R^2\left[P(R)+n(R)\right]\right)=\underbrace{mR+c}_{ideal\ line}+\underbrace{\ln\left(1+\frac{n(R)}{P(R)}\right)}_{noisy\ term}$$

$$\hat{S}(R)=\hat{m}R+\hat{c}\quad\rightarrow\hat{\alpha}=-\frac{\hat{m}}{2};\quad\hat{\beta}=\frac{\exp(c)}{K}$$

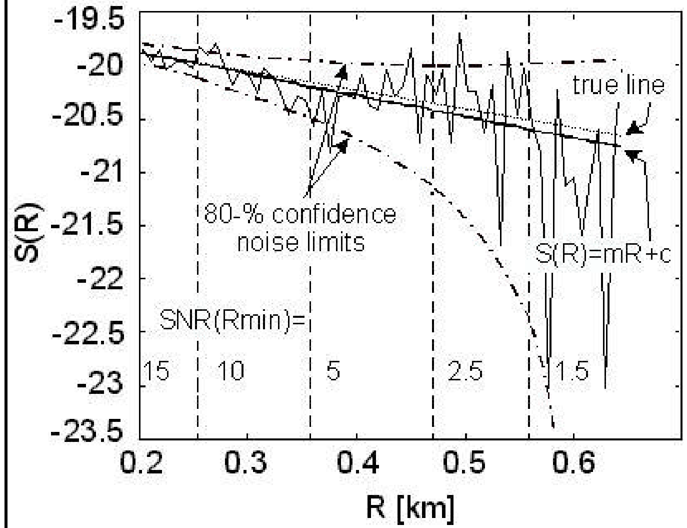
EXPONENTIAL FITTING

- *Best estimator in terms of extinction bias*

$$F(R)=R^2\left[P(R)+n(R)\right]=\underbrace{K\beta\exp(-2\alpha R)}_{ideal\ term}+\underbrace{R^2 n(R)}_{noisy\ term}$$

$$\hat{F}(R)=b\exp(-aR)\ \rightarrow\hat{\alpha}=-\frac{a}{2};\quad\hat{\beta}=\frac{b}{K}$$

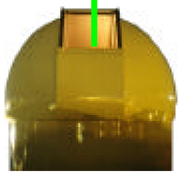
SOURCE FIG: F. Rocadenbosch et al., "Statistics Of The Slope-Method Estimator," Appl. Opt. 39(33), 6049-6057 (2000).



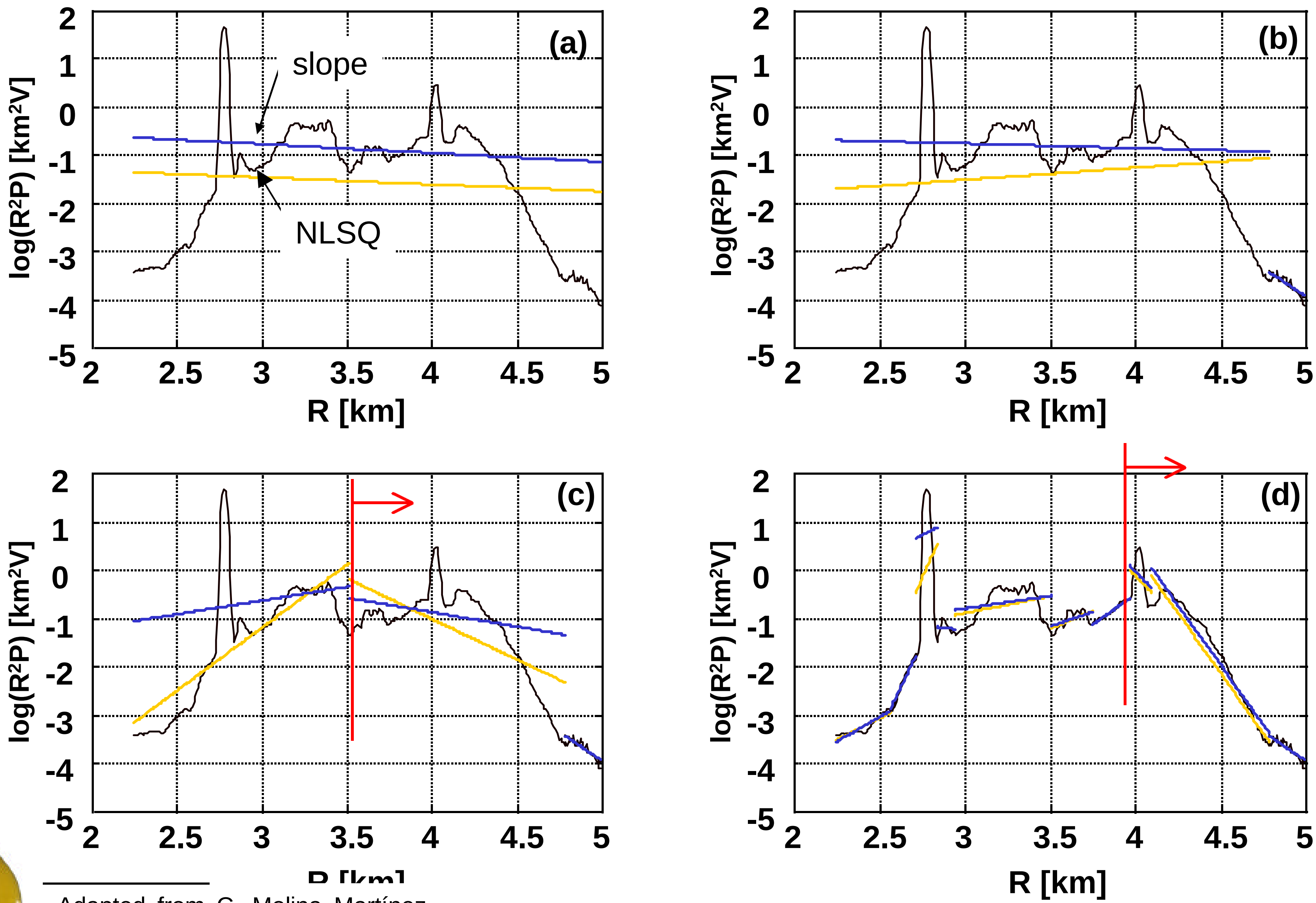
PERFORMANCE

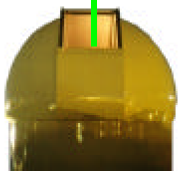
- *Kunz dilemma*
- *Bias*

See also: G.J. Kunz, "Probing of the atmosphere with lidar," Proc. Remote Sensing of the Propagation Environment (AGARD-CP-502), Conf. Date: 30 Sept.-4 Oct. 1991, Conf. Location: Cesme, Turkey. Publisher: AGARD, Neuilly sur Seine, France, 23, pp. 1-11 (France, 1992)



HIBRID METHODS: THE SLICE METHOD



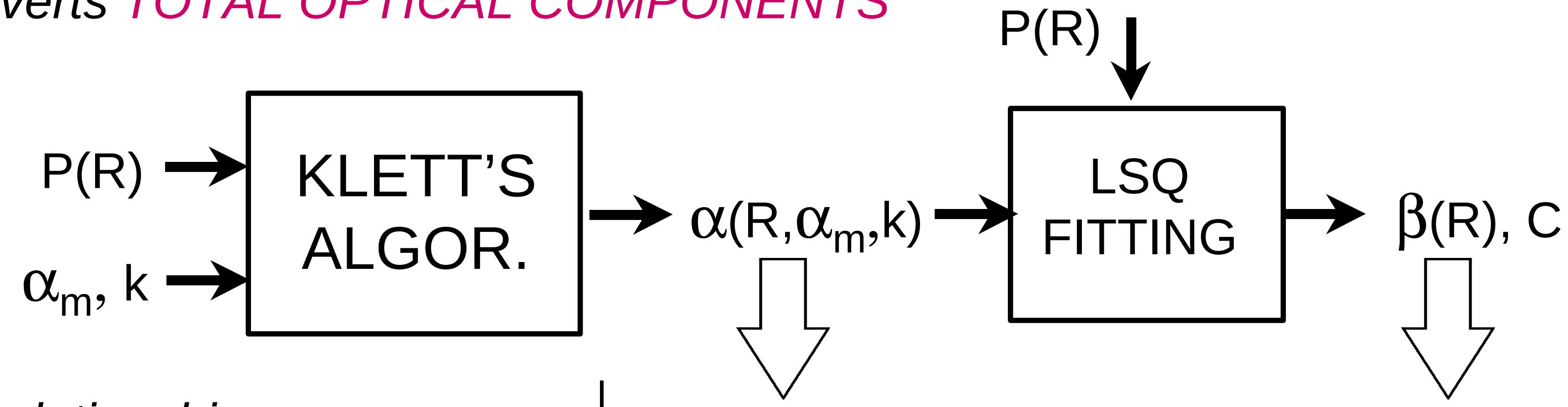


Adapted from C. Molina Martínez, PFC, ETSETB (1998).

(SIMPLE) KLETT'S METHOD (I)

1) SIMPLE KLETT'S METHOD

- *Inverts TOTAL OPTICAL COMPONENTS*



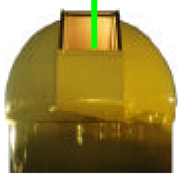
Basic relationships:

- *Assumed correlation (eq.(1))*
- *User calibrations (eq.(2)):*
  - *boundary extinction ® look-up TABLE*
  - *k =1 (struct.), 0.67 (clouds)*
  - *or k=f(a)*
- *Backward form (eq.(3))*

$$\beta(R) = C\alpha(R)^k \qquad (1)$$

$$\begin{cases} S(R) = \ln\left[R^2 P(R)\right] \\ S(R_m) = S_m \leftrightarrow a(R_m) = a_m; \quad k = ? \end{cases} \qquad (2)$$

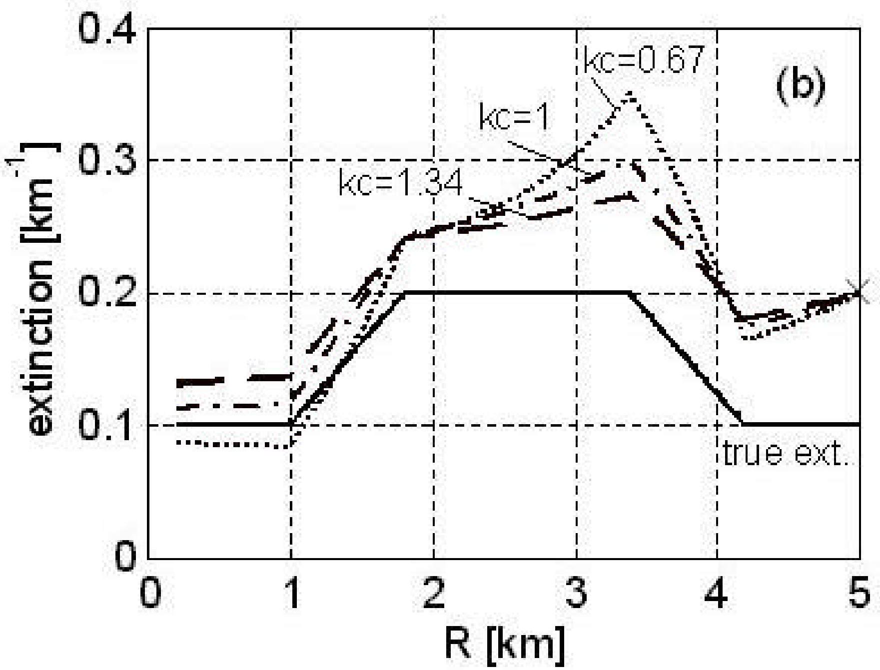
$$a(R) = \frac{\exp\left[(S - S_m)/k\right]}{a_m^{-1} + \frac{2}{k}\int_R^{R_m} \exp\left[(S - S_m)/k\right] dr} \qquad (3)$$

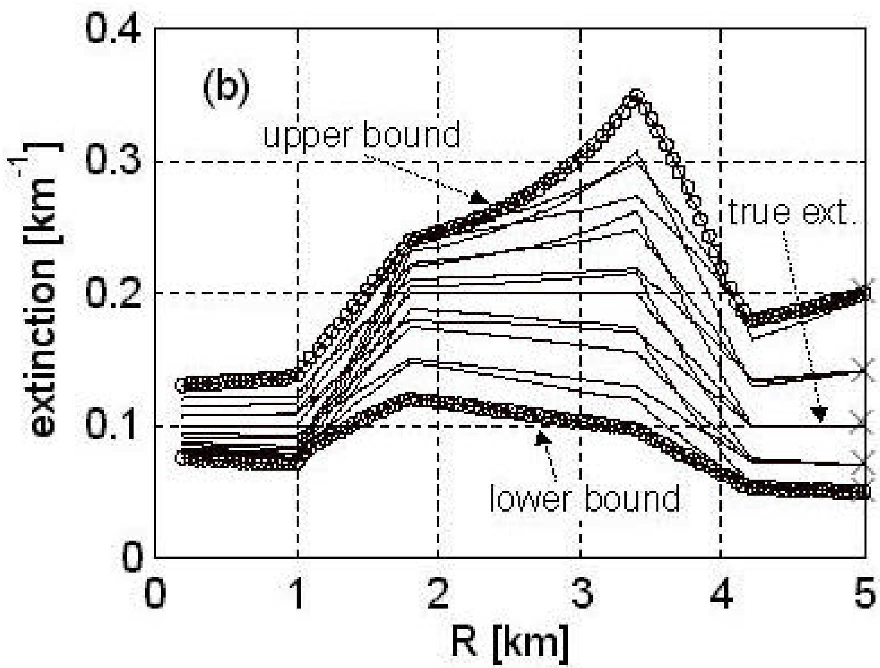


SIMPLE KLETT (II)

KLETT'S METHOD

- *Different extinction families arise in response to different user-calibrations in terms of:*
  - 1) Boundary extintion, α_m
  - 2) Power-law backscatter-to-extinction exponent, k (kc in Fig. below)

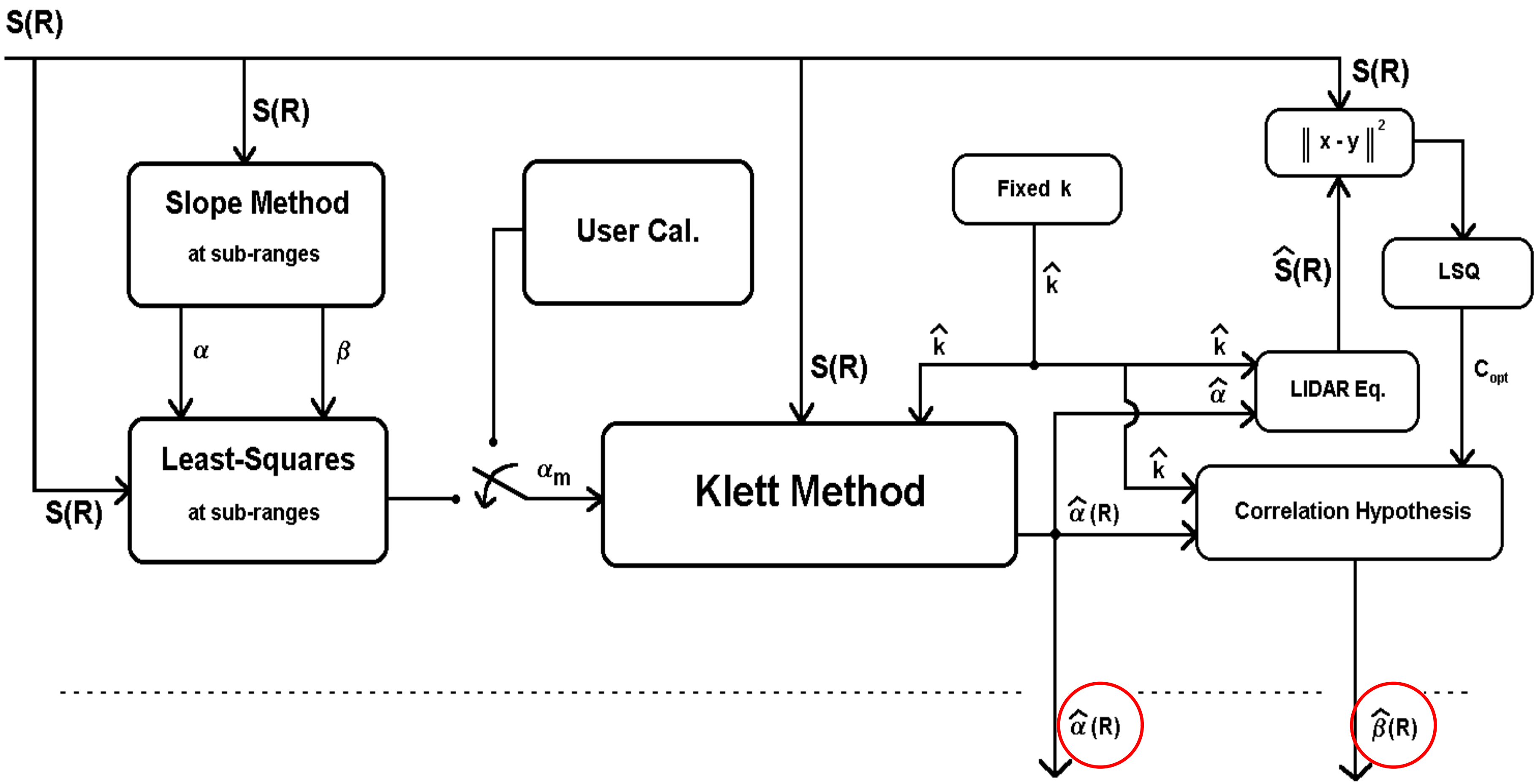




SOURCE FIG: F. Rocadenbosch, A. Comerón, "Error Analysis For The Lidar Backward Inversion Algorithm," Appl. Opt. 38(21), 4461-4474 (1999).

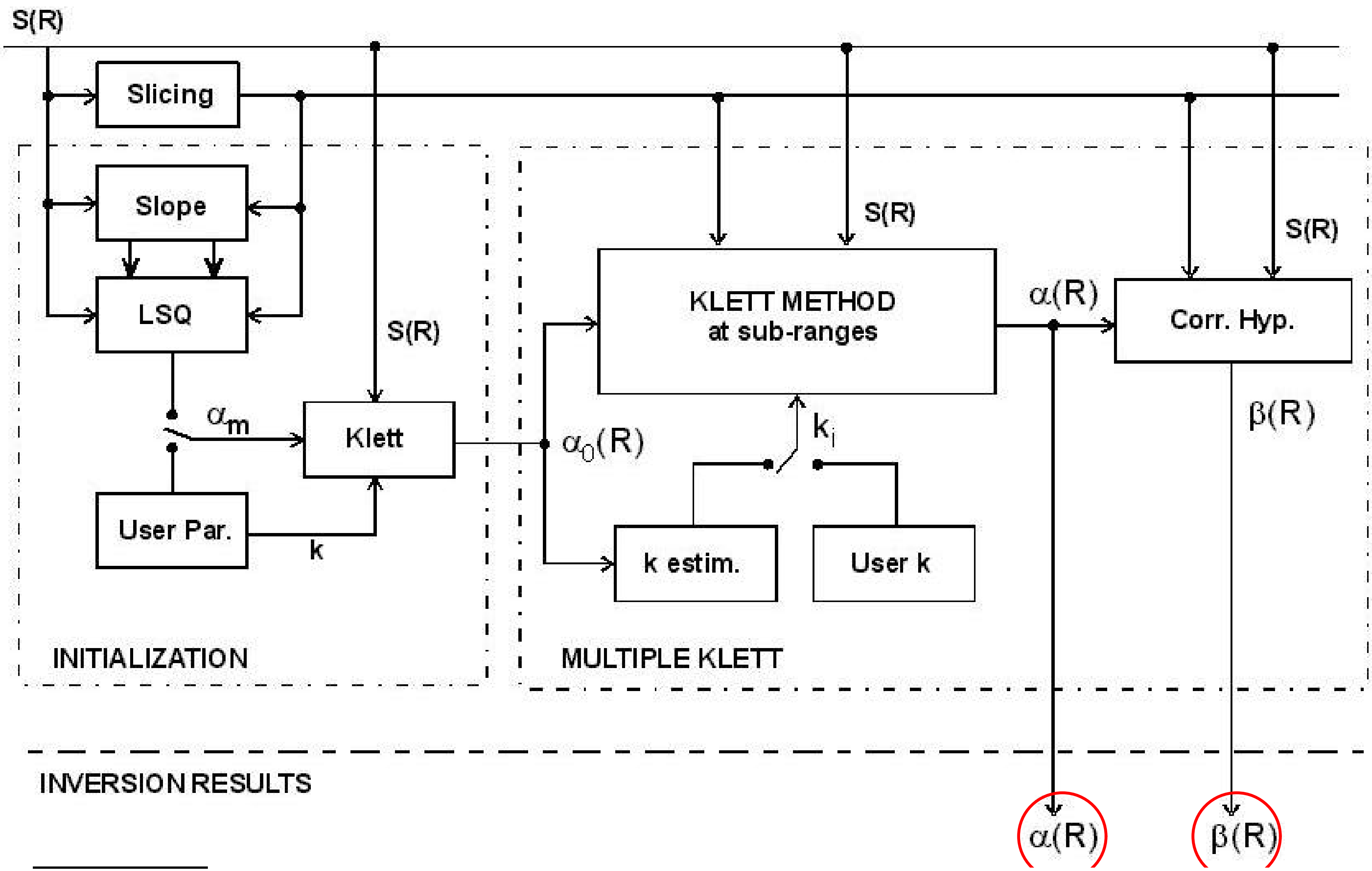
SIMPLE KLETT (III)

OPERATIONAL SIMPLE-KLETT HYBRID ALGORITHM



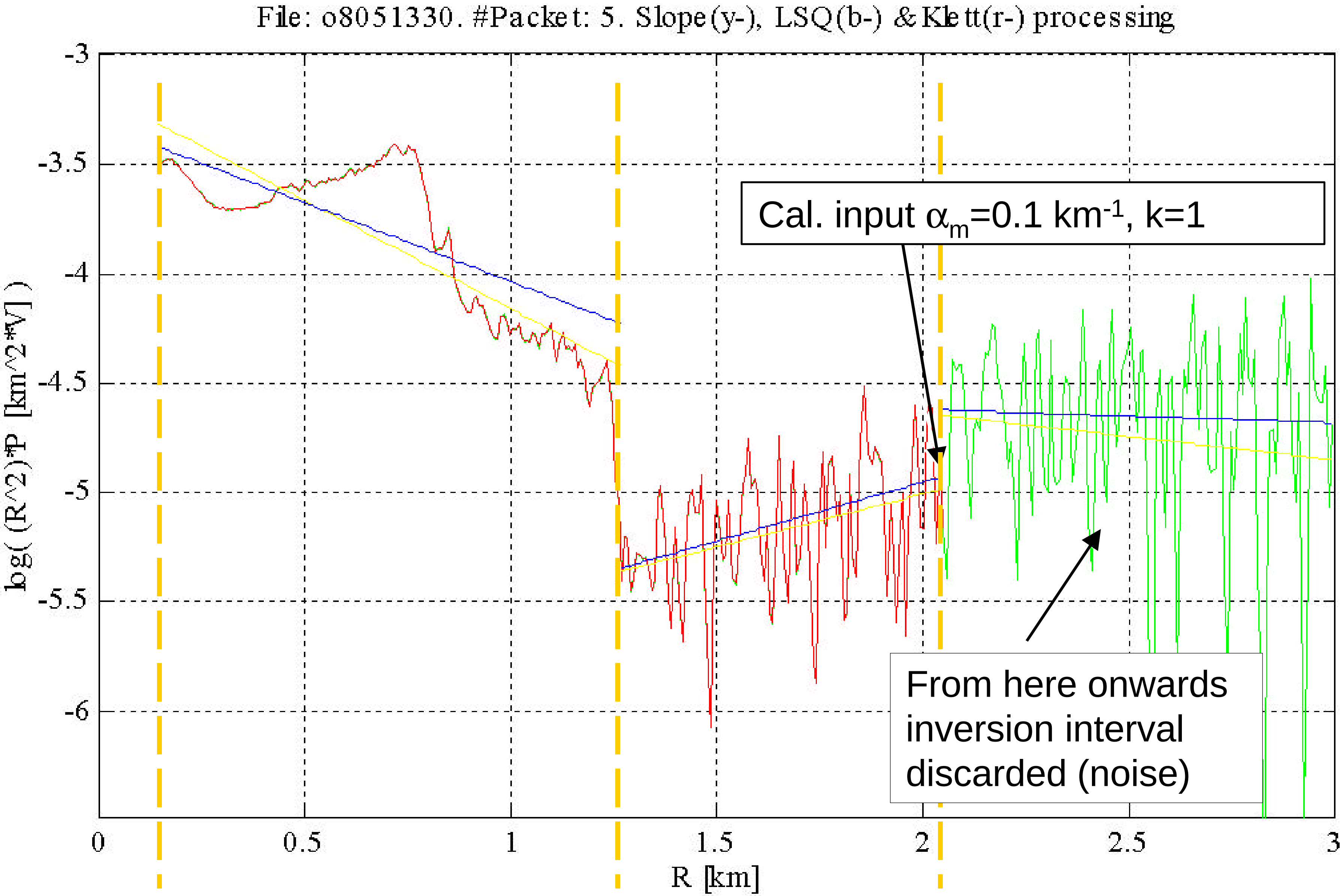
SOURCE FIG: C. Molina Martínez, “Creación de un entorno software para el acceso, segmentación y procesado de medidas lidar”, PFC, ETSETB, 21 Jul. 1998.

HYBRID METHODS: MULTIPLE KLETT (I)

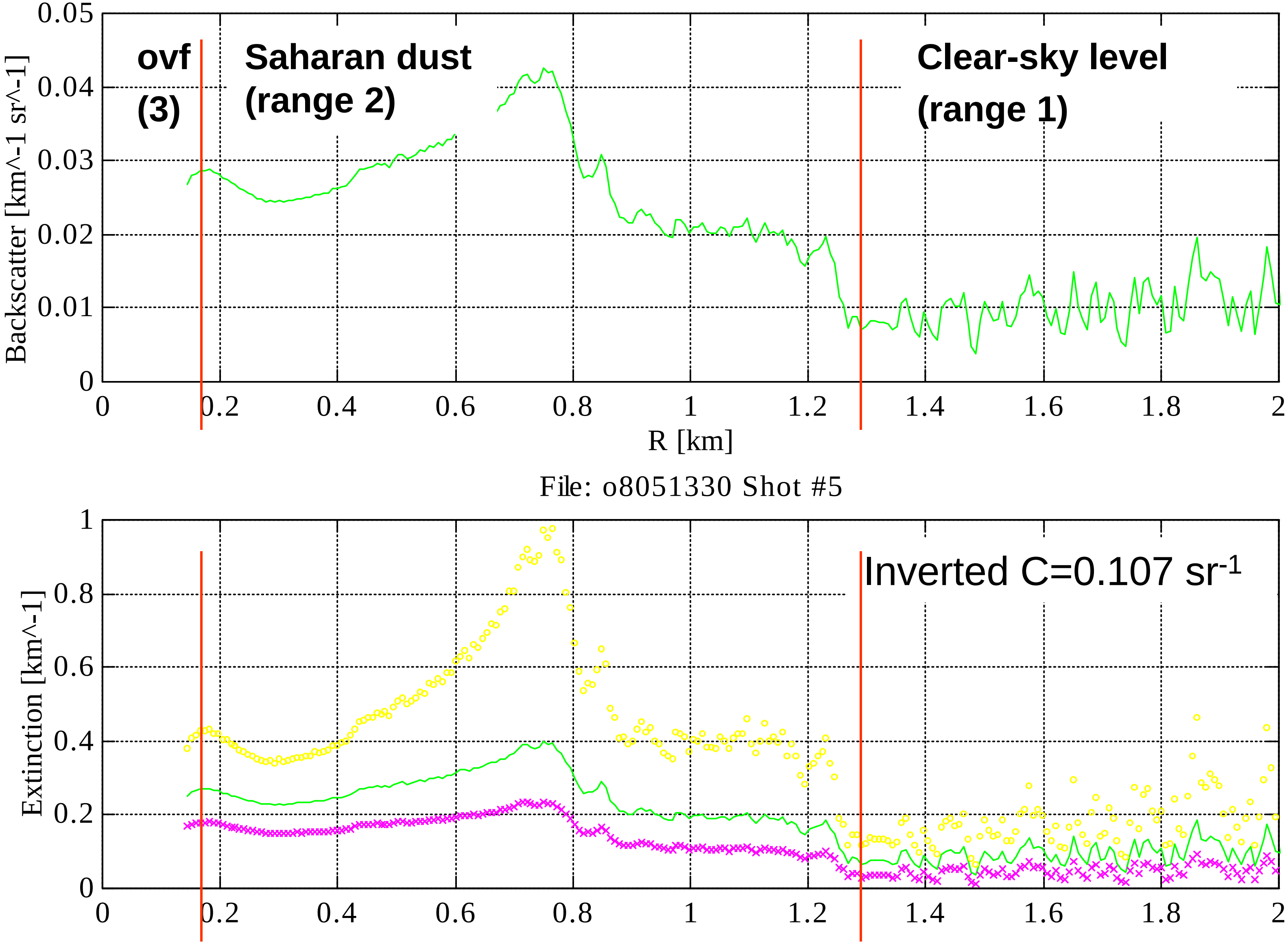


SOURCE FIG: C. Molina Martínez, "Creación de un entorno software para el acceso, segmentación y procesado de medidas lidar", PFC, ETSETB, 21 Jul. 1998.

HYBRID METHODS: MULTIPLE KLETT (II)



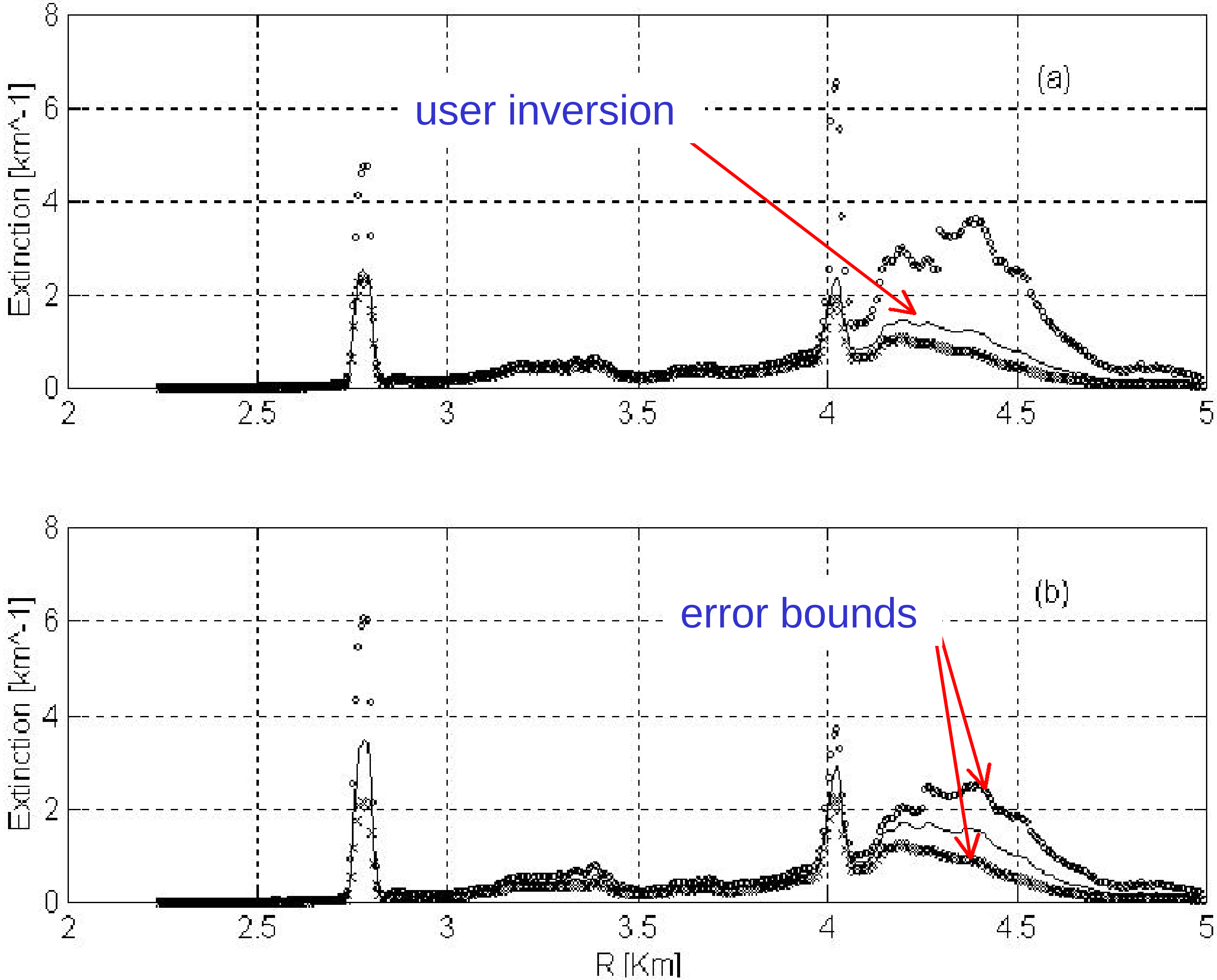
HYBRID METHODS: MULTIPLE KLETT (III)



LIDAR (LASER RADAR)

DEP. OF SIGNAL THEORY AND COMMUNICATIONS

MULTIPLE KLETT VS. SINGLE KLETT



(a) Simple Klett

(b) Multiple Klt.

Inversion example continued from slide 14

SOURCE FIG: C. Molina Martínez, “Creación de un entorno software para el acceso, segmentación y procesado de medidas lidar”, PFC, ETSETB, 21 Jul. 1998.

FROM KLETT TO KFS

Warning Summary:

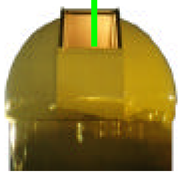
- *For a given α_m calibration, the simple Klett algorithm DOES NOT guarantee inversion of a reasonable C (e.g. look-table lidar ratio)*
- *The α_m calibration is always guessed using a "visual rule-of-thumb"*
- F. Rocadenbosch, A. Comerón, "Error Analysis For The Lidar Backward Inversion Algorithm." Applied Optics **38** (21), 4461-4474 (1999). → enables to *estimate envelope error bounds given a priori errors in a_m, k.*

2) VARIABLE KLETT'S METHOD

- *Inverts TOTAL OPTICAL COMPONENTS*
- *Eq.(3) is solved iteratively, assuming a spline approximation of the a-b-look-up table of the form ®*
- *Range-dependent correlation ratio ®*

$$C = \frac{b_{tot}}{a_{tot}} = f(a) \quad [sr^{-1}]$$

$$b(R) = C(R)a(R)^k; \quad k = 1$$



KFS (I)

3) KLETT-FERNALD-SASANO

- *Distinguishes between MOLECULAR and AEROSOL components*

$$\beta_M(z) = \frac{P(z)z^2 \exp\left\{+2\int_z^{z0}[S_M(u)-S_R(u)]\beta_R(u)du\right\}}{\frac{P(z_0)z_0^2}{\beta_M(z_0)+\beta_R(z_0)} + 2\int_z^{z0} S_M(u)P(u)u^2 \exp\left\{2\int_u^{z0}[S_M(v)-S_R(v)]\beta_R(v)dv\right\}} - \beta_R(z)$$

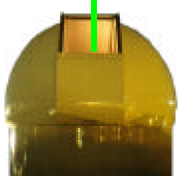
User inputs:

- *Aerosol backscatter boundary calibration, $\beta_M(z_0) \ll \beta_R(z_0)$*
- *Aerosol variable lidar ratio, $S_M(z)$?*
- *Rayleigh extinction*
  - *Height-dependent P(z), T(z) and n(l,z)= f[l,P(z),T(z)]*
  - *Depolarization ® King Factor*

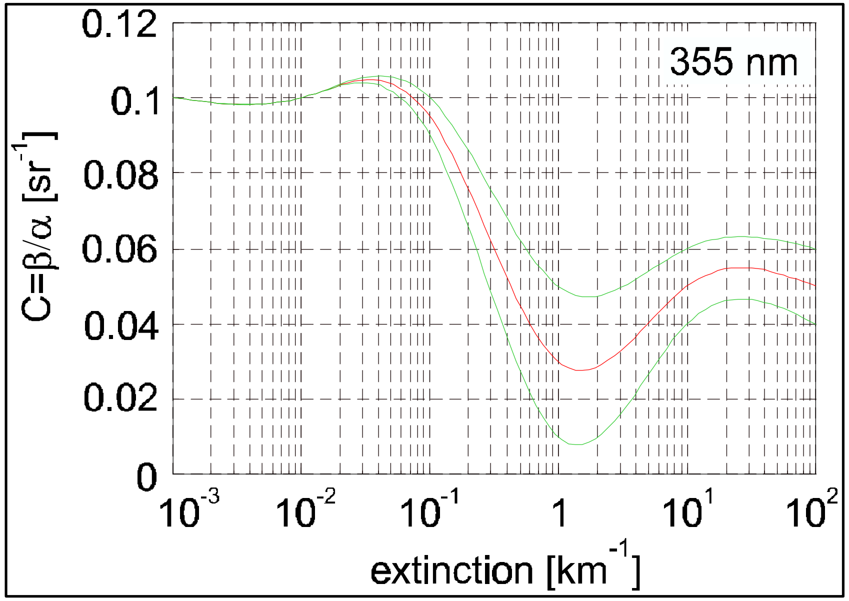
$$S_M = \frac{a_{Mie}}{b_{Mie}}$$

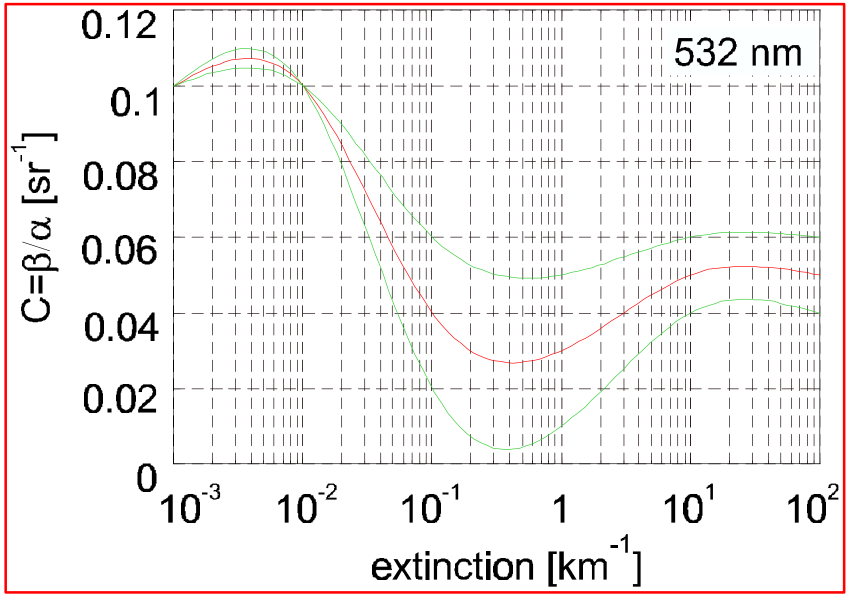
$$\alpha_R \approx \alpha_R^{sca}(z,\lambda,P,T) = \frac{8\pi^3\left[n_{air}^2(P,T,\lambda)-1\right]^2}{3\lambda^4 N_S^2(z,P,T)} KingF(\lambda);$$

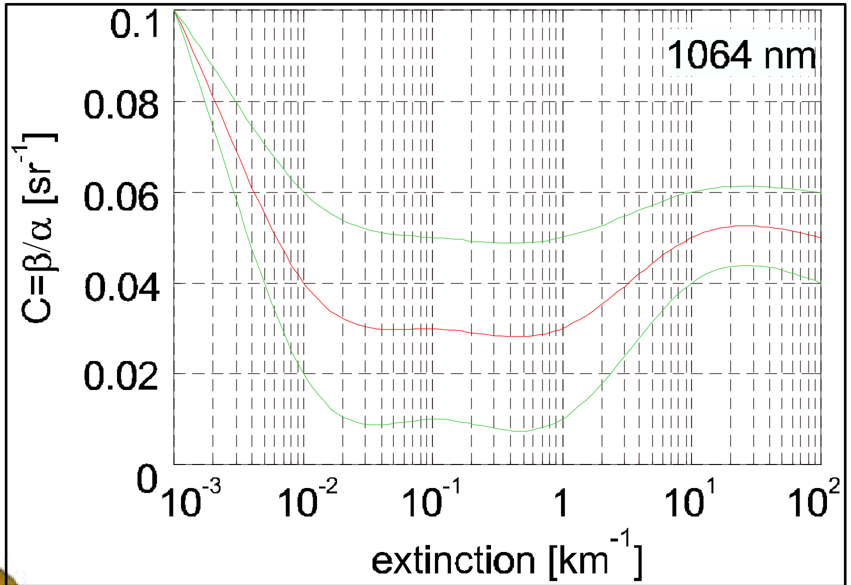
$$S_R = \frac{\alpha_R}{\beta_R} = \frac{8\pi}{3}$$



ASSUMPTIONS ON LIDAR RATIO







We plot $1/S_M$ (look-up table)

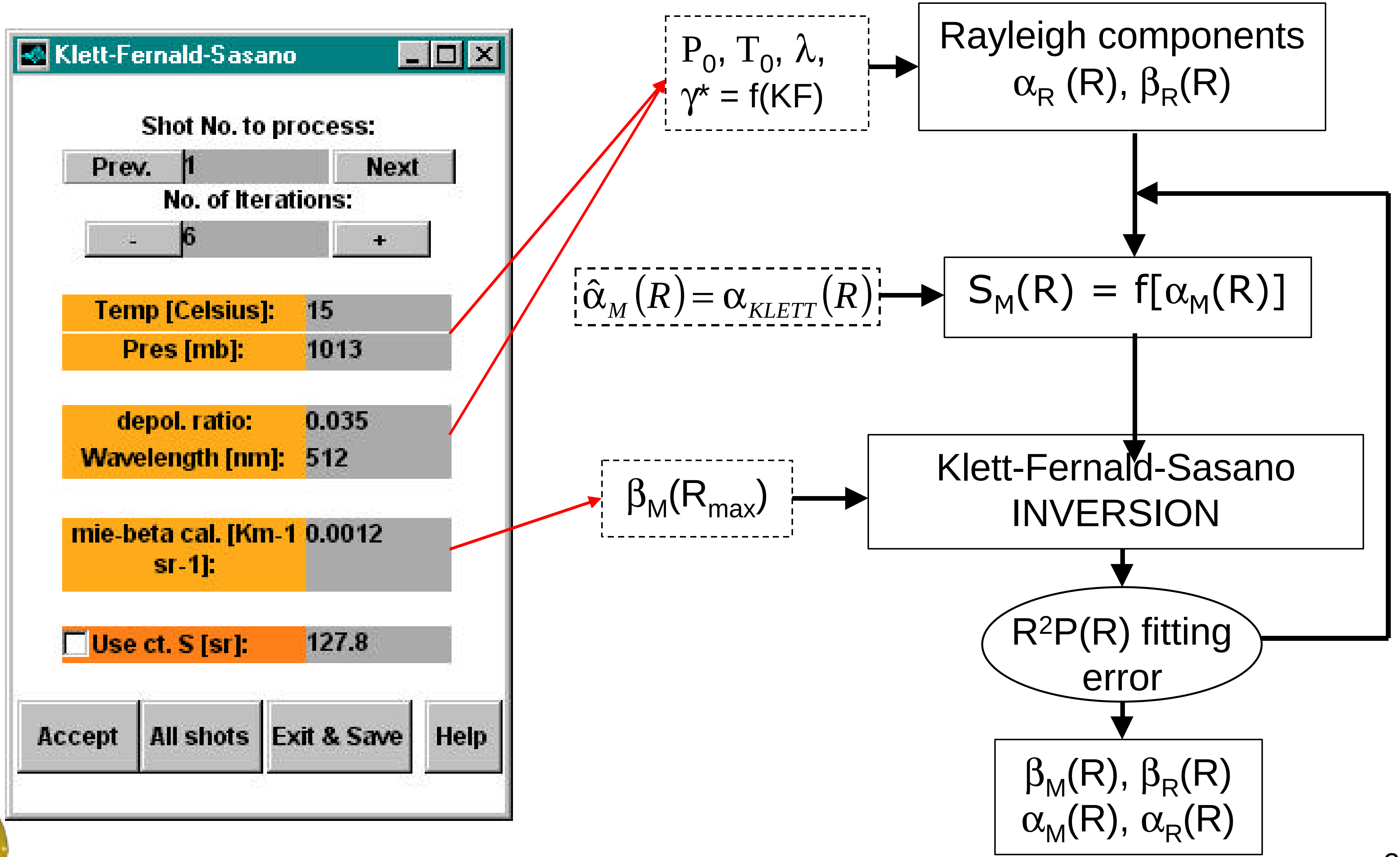
– Note that

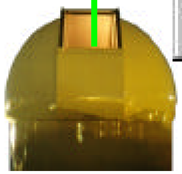
$$S_M = \frac{a_{Mie}}{b_{Mie}} \quad [sr] \neq \frac{1}{C}$$

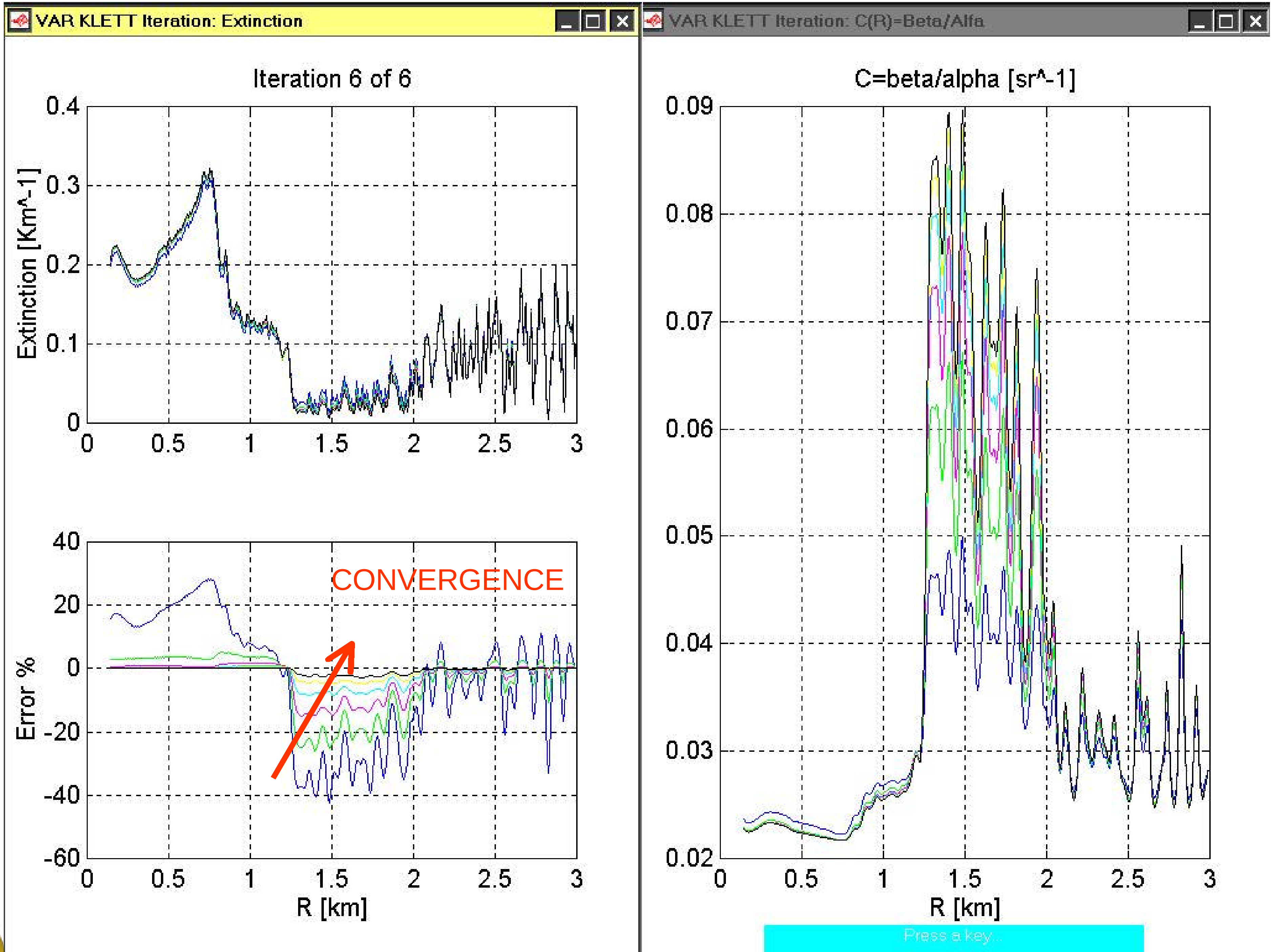
– Need to cross-examine with retrievals from co-operative instrumentation (e.g. Sunphotometer) or multiangle profiles to adjust S_M

KFS (II)

3) VARIABLE KLETT-FERNALD-SASANO (Continued)






VAR KLETT Iteration: Extinction
Iteration 6 of 6
Extinction [Km^-1]
0.4
0.3
0.2
0.1
0
0 0.5 1 1.5 2 2.5 3
40
20
0
-20
-40
-60
Error %
CONVERGENCE
0 0.5 1 1.5 2 2.5 3
R [km]
VAR KLETT Iteration: C(R)=Beta/Alfa
C=beta/alpha [sr^-1]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0 0.5 1 1.5 2 2.5 3
R [km]
Press a key...

COMPARISON BETWEEN KLETT'S AND KFS' KERNELS

SINGLE-ANGLE: Most elastic lidar inversion algorithms can be summarised in kernel-function form as

Klett's method: $a_M(R) = G_{Klett}\left[R^2 P(R), a_{tot}(R_0), S_{tot}(R)\right] - a_R(R),$

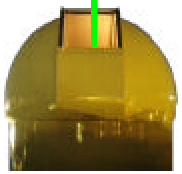
KFS's method: $a_M(R) = F_{KFS}\left[R^2 P(R), a_M(R_0), S_R, S_M(R)\right] - a_R(R)$

Requires:

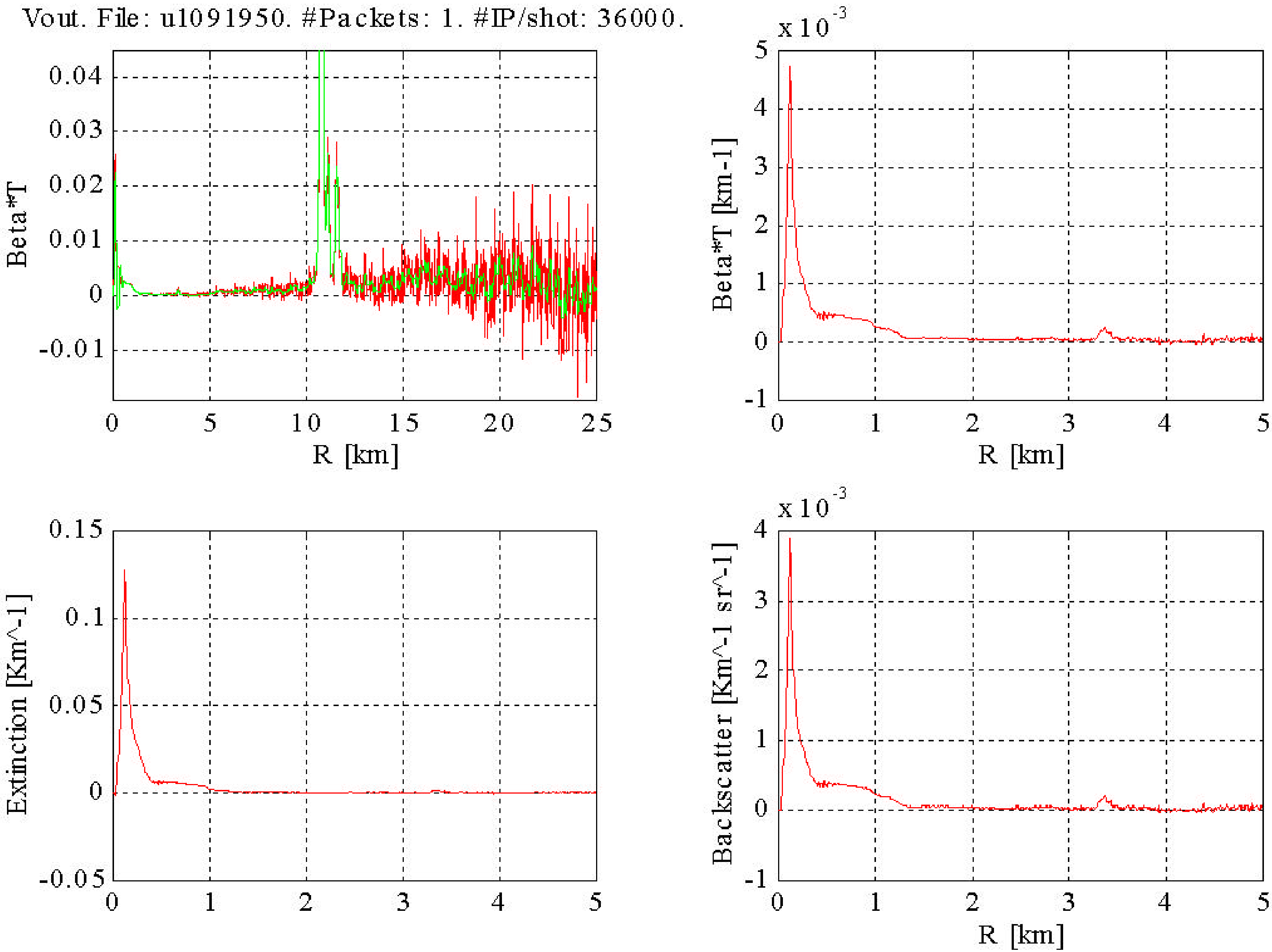
- *User boundary calibration,* $a_M(R_0)$
- *User-given aerosol lidar ratio,* $S_M(R) = \dfrac{a_M(R)}{b_M(R)}$
- *Press&Temp. profiles,*

SUMMARY KEYS:

- *Homogeneus (Slope, NLSQ) vs. inhomogeneous atmosphere (Klett's and KFS' variants)*
- *Retrieval of total (Klett) vs. aerosol&molecular components (KFS)*
- *KFS is the state-of-the-art widely accepted operative algorithm*



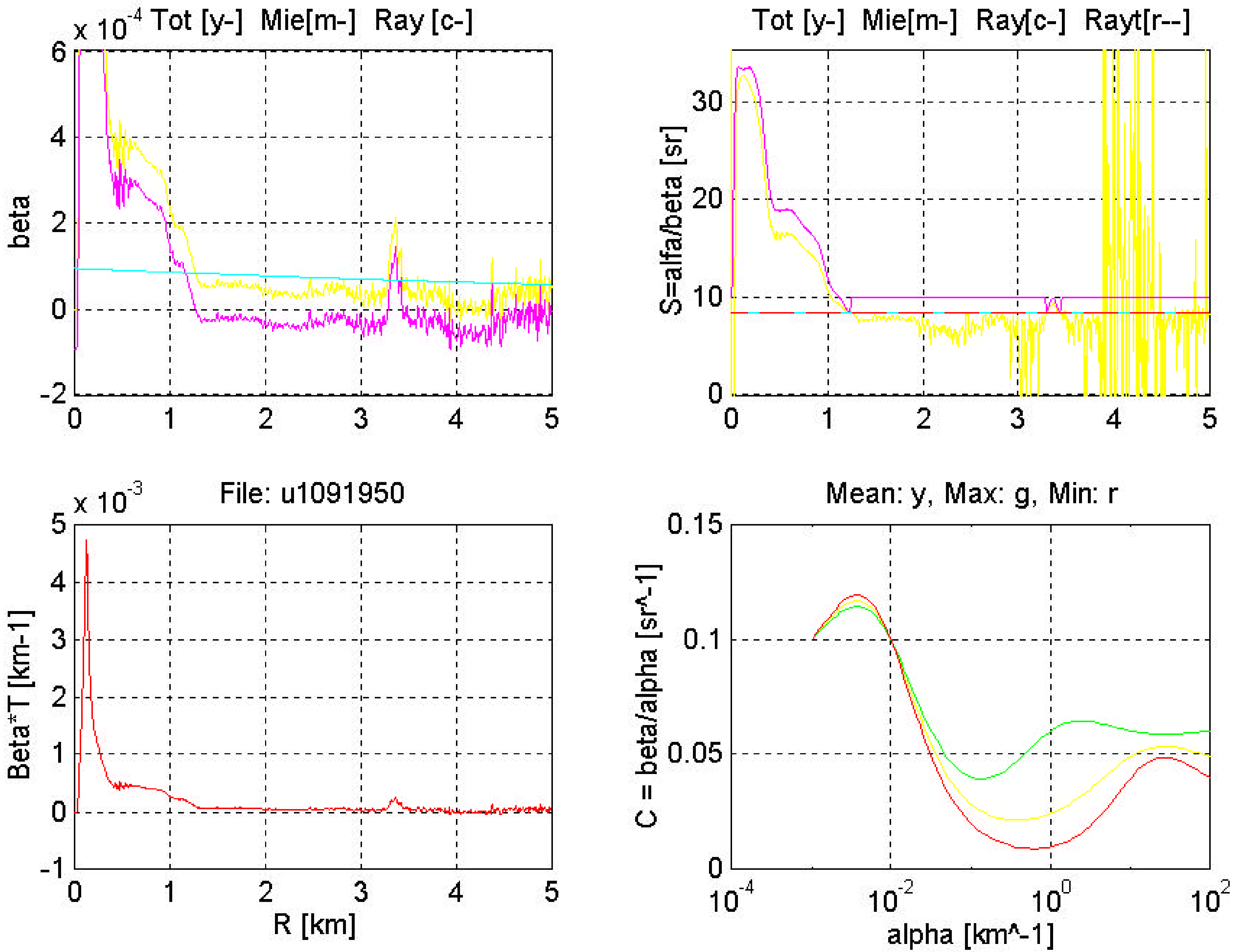
A FEW INVERSION WARNINGS: KFS (CASE I)

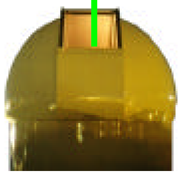


LIDAR (LASER RADAR)

DEP. OF SIGNAL THEORY AND COMMUNICATIONS

A FEW INVERSION WARNINGS: KFS (CASE I)





A FEW INVERSION WARNINGS: KFS (CASE II)