OCEANIC PRODUCT VALIDATION

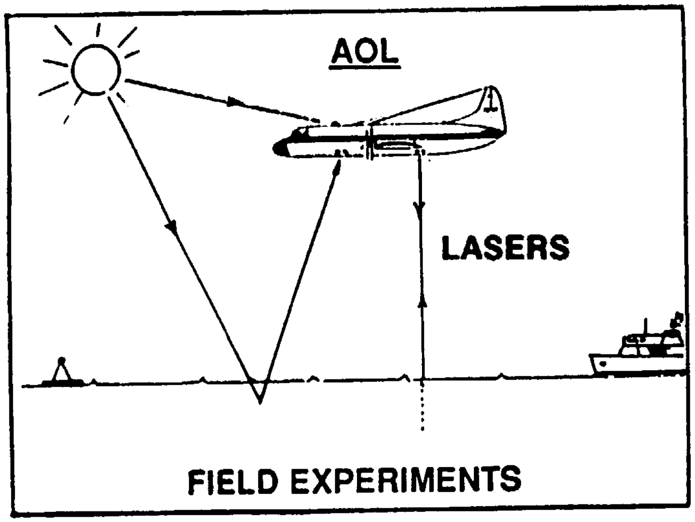
INCLUDING PHYCOERYTHRIN:

- AIRBORNE
- SHIP

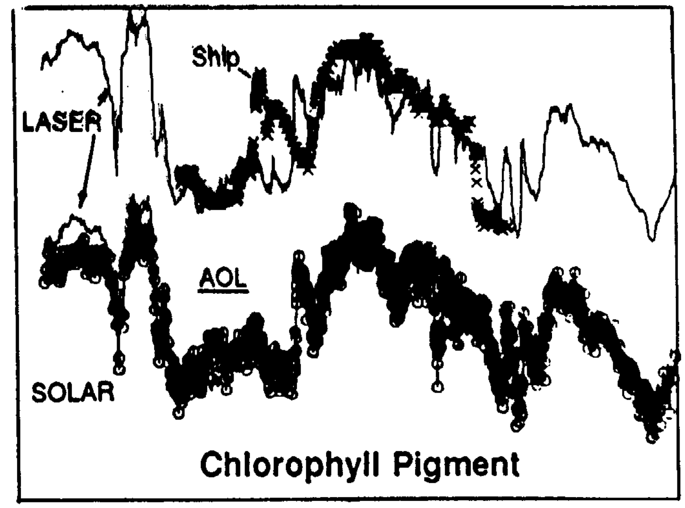
(Frank Hoge NASA/GSFC/WFF)

NASA Airborne Oceanographic Lidar System

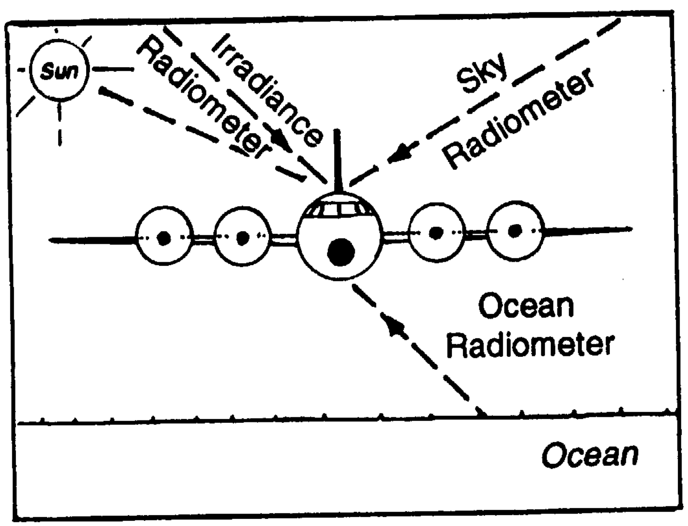
a)



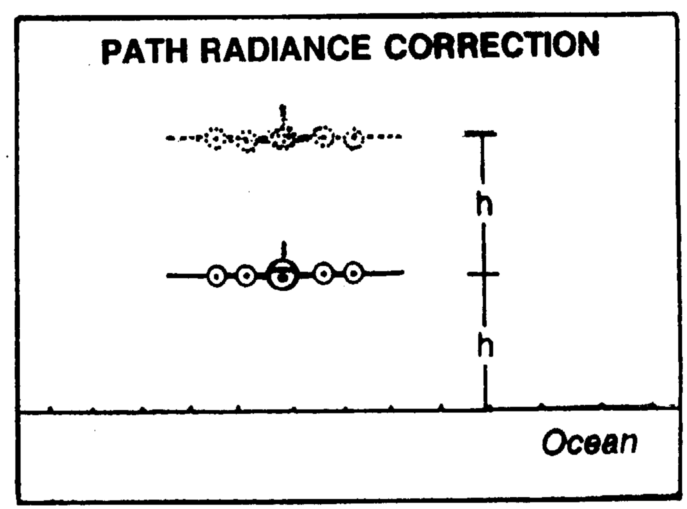
b)



c)



d)



OCEANIC PIGMENTS

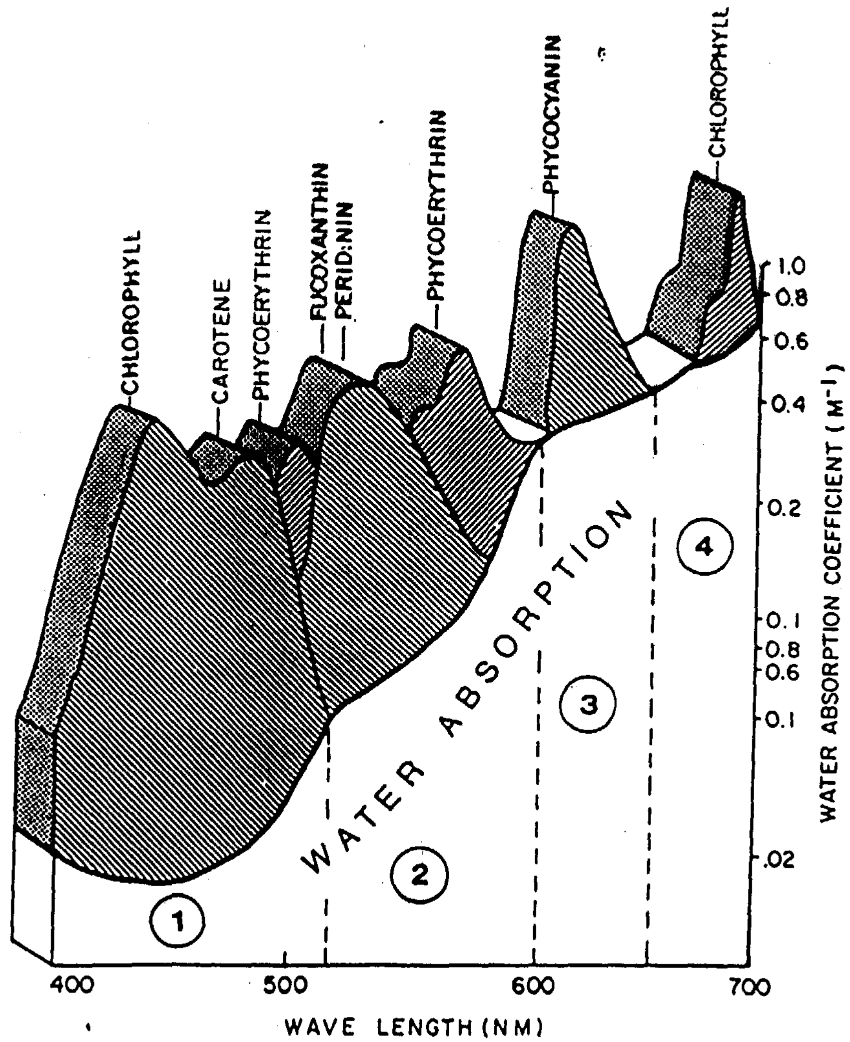
Major

Chlorophyll a,b,c
Phycoerythrin
Phycocyanin
Carotenoids
- diadinoxanthin
- alloxanthin
- zeaxanthin
- fucoxanthin
- butanoyl-fucoxanthin
- hexanoyl-fucoxanthin
- prasinoxanthin

Other

Chlorophyllide a
Pheophorbide a
Pheophytin a
Pheophytin b
Pheophytin b[1]
Allomerized chlorophyll a

- •
- •
- •


CHLOROPHYLL
CAROTENE
PHYCOERYTHRIN
FUCOXANTHIN
PERIDININ
PHYCOERYTHRIN
PHYCOCYANIN
CHLOROPHYLL
WATER ABSORPTION
1
2
3
4
1.0
0.8
0.6
0.4
0.2
0.1
0.8
0.6
0.1
.02
WATER ABSORPTION COEFFICIENT (M-1)
400
500
600
700
WAVE LENGTH (NM)

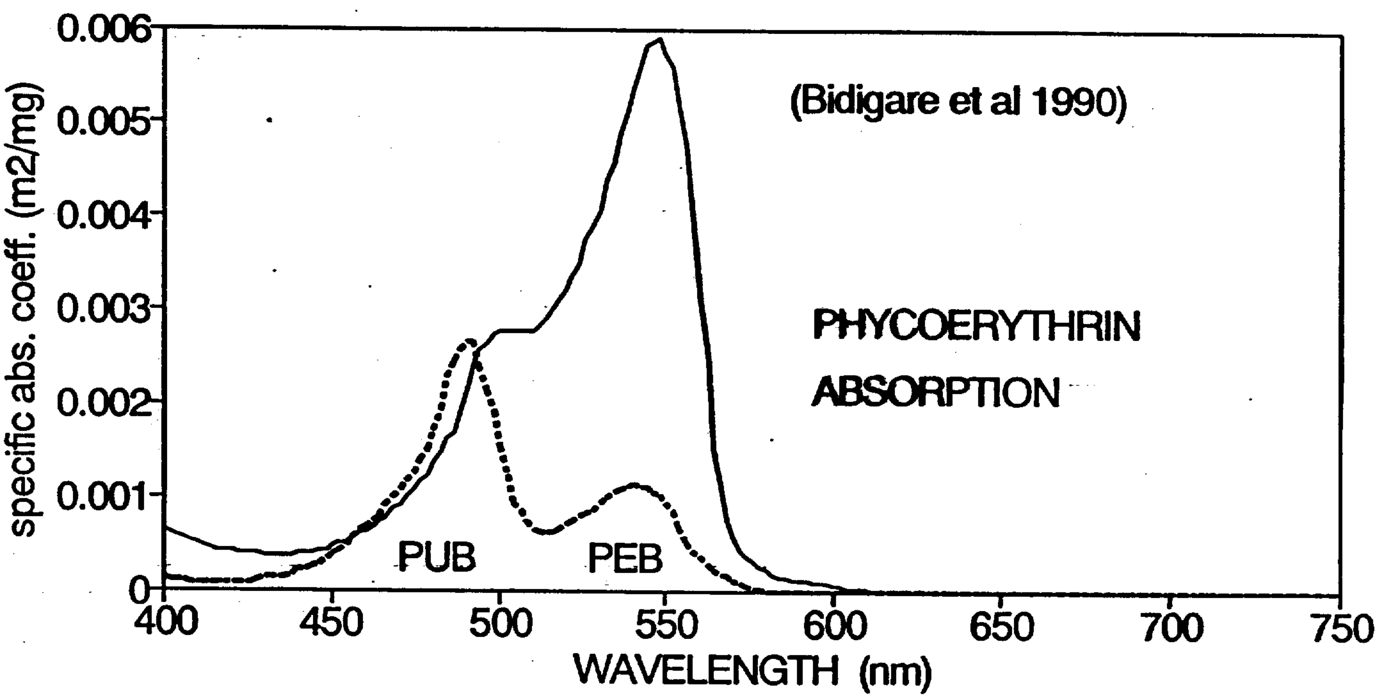
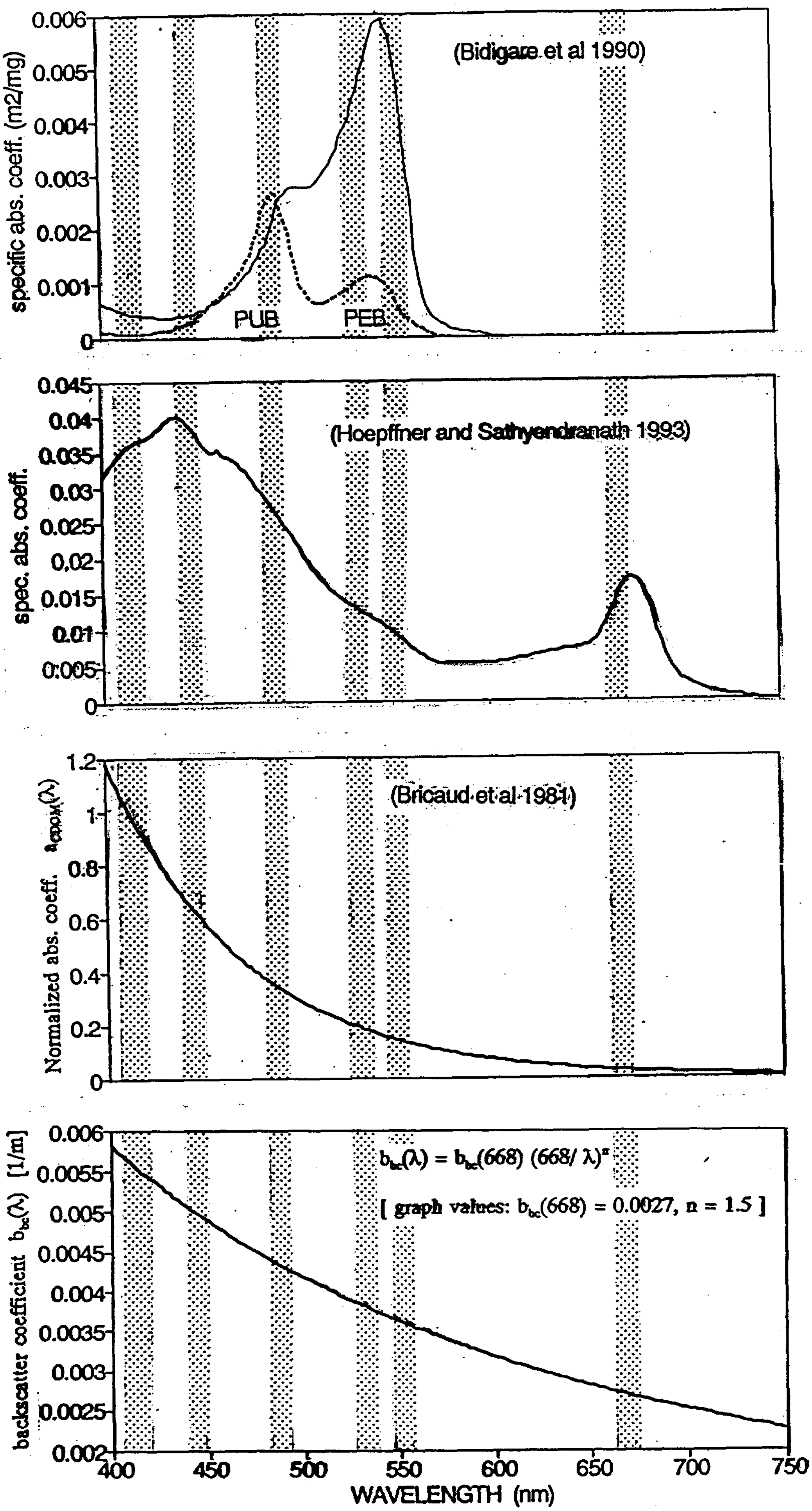

(Bidigare et al 1990)
PHYCOERYTHRIN
ABSORPTION
PUB
PEB
specific abs. coeff. (m2/mg)
0.006
0.005
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
750
WAVELENGTH (nm)

Figure 1



specific abs. coeff. (m2/mg)
0.006
0.005
0.004
0.003
0.002
0.001
0
(Bidigare et al 1990)
PUB
PEB
spec. abs. coeff.
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
(Hoepffner and Sathyendranath 1993)
Normalized abs. coeff. a_CDOM(λ)
1.2
1
0.8
0.6
0.4
0.2
0
(Bricaud et al 1981)
backscatter coefficient b_bc(λ) [1/m]
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
b_bc(λ) = b_bc(668) (668/ λ)^n
[graph values: b_bc(668) = 0.0027, n = 1.5]
400
450
500
550
600
650
700
750
WAVELENGTH (nm)

PIGMENT LINE SHAPES:

~GAUSSIAN

INHERENT OPTICAL PROPERTY (IOP) MODELS

$$b_{bt}(\lambda_i) = b_{bt}(\lambda_b)\ (\lambda_b / \lambda_i)^n ,$$

$$a_{ph}(\lambda_i) = a_{ph}(\lambda_g)\ \exp[-(\lambda_i - \lambda_g)^2 / 2g^2]$$

$$a_d(\lambda_i) = a_d(\lambda_d)\ \exp\ [-S(\lambda_i - \lambda_d)]$$

$$a_{pub}(\lambda_i) = a_{pub}(\lambda_{g,pub})\ \exp[-(\lambda_i - \lambda_{g,pub})^2 / 2g_{pub}^2]$$

$$a_{peb-}(\lambda_i) = a_{peb-}(\lambda_{g,peb-})\ \exp[-(\lambda_i - \lambda_{g,peb-})^2 / 2g_{peb-}^2],$$

$$a_{peb+}(\lambda_i) = a_{peb+}(\lambda_{g,peb+})\ \exp[-(\lambda_i - \lambda_{g,peb+})^2 / 2g_{peb+}^2],$$

(NUMERICAL MODELS CAN BE USED IN PLACE OF ANALYTICAL MODELS !)

LINEAR MATRIX INVERSION

OF

OCEANIC RADIANCE MODELS

DETAILS:

Jour. Geophys. Res. 101, 16,631- 16,648, (1996)

"Satellite Retrieval of Inherent Optical Properties by Linear Matrix Inversion of Oceanic Radiance Models: An Analysis of Model and Radiance Measurement Errors", Hoge, Frank E. and Paul E. Lyon,

Radiance Model (Gordon et al., 1988)

$$L_w(\lambda) = F_0\, t(\theta_0) \cos(\theta_0)\, M\, (l_1 X + l_2 X^2),$$

θ_0 is the solar zenith angle,

$t(\theta_0)$ is the diffuse transmittance of the atmosphere,

F_0 is the extraterrestrial solar irradiance, $l_1 = 0.0949$, $l_2 = 0.0794$.

$M = (1-\rho)(1-\bar{\rho})/m^2(1-rR) \approx 0.529$ [Morel and Gentili 1996].

$X = b_b/(b_b + a)$

b_b is the total backscatter: $b_b = b_{bw} + b_{bt}$

a is the total absorption: $a = a_w + a_{ph} + a_d + a_{FUD} + a_{PED}$.

$X = (b_{bw} + b_{bt}) / [(b_{bw} + b_{bt}) + (a_w + a_{ph} + a_d + a_{FUD} + a_{PED})]$

λ	b_{bw}	a_w
412	0.0033	0.0160
443	0.0024	0.0145
488	0.0016	0.0192
531	0.0011	0.0512
551	0.0009	0.0645
668	0.0004	0.4240

Phycoerythrin Retrieval Sequence

1. $a + b_b\,(1 - 1/X) = 0.$

2. $a_t + b_{bt}\,v = -(a_w + b_{bw}\,v)$.

3. $a_{pub}(\lambda_i) + a_{peb}(\lambda_i) + a_{ph}(\lambda_i) + a_d(\lambda_i) + b_{bt}(\lambda_i)\,v(\lambda_i) = -a_w(\lambda_i) - b_{bw}(\lambda_i)\,v(\lambda_i).$

4. $$a_{pub}(\lambda_{g,pub})\exp[-(\lambda_i - \lambda_{g,pub})^2 / 2g_{pub}^2] + a_{peb}(\lambda_{g,peb})\exp[-(\lambda_i - \lambda_{g,peb})^2 / 2g_{peb}^2]$$
$$+ a_{ph}(\lambda_g)\exp[-(\lambda_i - \lambda_g)^2 / 2g^2] + a_d(\lambda_d)\exp[-S(\lambda_i - \lambda_d)] + b_{bt}(\lambda_b)\,(\lambda_b / \lambda_i)^n\,v(\lambda_i)$$
$$= -a_w(\lambda_i) - b_{bw}(\lambda_i)\,v(\lambda_i).$$

5.

$$\begin{bmatrix}
\exp[-(\lambda_1-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_1-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_1-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_1-\lambda_d)] & (\lambda_b/\lambda_1)^n v(\lambda_i) \\
\exp[-(\lambda_2-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_2-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_2-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_2-\lambda_d)] & (\lambda_b/\lambda_2)^n v(\lambda_i) \\
\exp[-(\lambda_i-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_3-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_3-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_3-\lambda_d)] & (\lambda_b/\lambda_3)^n v(\lambda_i) \\
\exp[-(\lambda_3-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_4-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_4-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_4-\lambda_d)] & (\lambda_b/\lambda_4)^n v(\lambda_i) \\
\exp[-(\lambda_4-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_5-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_5-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_5-\lambda_d)] & (\lambda_b/\lambda_5)^n v(\lambda_i)
\end{bmatrix}$$

$$\bullet \begin{bmatrix} a_{pub}(\lambda_{g,pub}) \\ a_{peb}(\lambda_{g,peb}) \\ a_{ph}(\lambda_{g,ph}) \\ a_d(\lambda_d) \\ b_{bt}(\lambda_b)] \end{bmatrix} = \begin{bmatrix} -a_w(\lambda_1) - b_{bw}(\lambda_1)\,v(\lambda_1) \\ -a_w(\lambda_2) - b_{bw}(\lambda_1)\,v(\lambda_2) \\ -a_w(\lambda_3) - b_{bw}(\lambda_3)\,v(\lambda_3) \\ -a_w(\lambda_4) - b_{bw}(\lambda_4)\,v(\lambda_4) \\ -a_w(\lambda_5) - b_{bw}(\lambda_5)\,v(\lambda_5) \end{bmatrix}$$

6. $\mathbf{Dp = h}$

7. $\mathbf{p = D^{-1}\,h}$ (Direct Inversion)

8. $\mathbf{p = [D^T\,D]^{-1}\,D^T\,h}$ (Least Squares)

$$\begin{bmatrix} \exp[-(\lambda_1-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_1-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_1-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_1-\lambda_d)] & (\lambda_b/\lambda_1)^n\, v(\lambda_j) \\ \exp[-(\lambda_2-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_2-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_2-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_2-\lambda_d)] & (\lambda_b/\lambda_2)^n\, v(\lambda_j) \\ \exp[-(\lambda_i-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_3-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_3-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_3-\lambda_d)] & (\lambda_b/\lambda_3)^n\, v(\lambda_j) \\ \exp[-(\lambda_3-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_4-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_4-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_4-\lambda_d)] & (\lambda_b/\lambda_4)^n\, v(\lambda_j) \\ \exp[-(\lambda_4-\lambda_{g,pub})^2/2g_{pub}^2] & \exp[-(\lambda_5-\lambda_{g,peb})^2/2g_{peb}^2] & \exp[-(\lambda_5-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_5-\lambda_d)] & (\lambda_b/\lambda_5)^n\, v(\lambda_j) \end{bmatrix}$$

$$\bullet \begin{bmatrix} a_{pub}(\lambda_{g,pub}) \\ a_{peb}(\lambda_{g,peb}) \\ a_{ph}(\lambda_{g,ph}) \\ a_d(\lambda_d) \\ b_{bt}(\lambda_b)] \end{bmatrix} = \begin{bmatrix} -a_w(\lambda_1) - b_{bw}(\lambda_1)\, v(\lambda_1) \\ -a_w(\lambda_2) - b_{bw}(\lambda_1)\, v(\lambda_2) \\ -a_w(\lambda_3) - b_{bw}(\lambda_3)\, v(\lambda_3) \\ -a_w(\lambda_4) - b_{bw}(\lambda_4)\, v(\lambda_4) \\ -a_w(\lambda_5) - b_{bw}(\lambda_5)\, v(\lambda_5) \end{bmatrix}$$

$$\begin{bmatrix} \exp[-(\lambda_3-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_3-\lambda_d)] & (\lambda_b/\lambda_3)^n\, v(\lambda_j) \\ \exp[-(\lambda_4-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_4-\lambda_d)] & (\lambda_b/\lambda_4)^n\, v(\lambda_j) \\ \exp[-(\lambda_5-\lambda_{g,ph})^2/2g_{ph}^2] & \exp[-S(\lambda_5-\lambda_d)] & (\lambda_b/\lambda_5)^n\, v(\lambda_j) \end{bmatrix}$$

$$\bullet \begin{bmatrix} a_{ph}(\lambda_{g,ph}) \\ a_d(\lambda_d) \\ b_{bt}(\lambda_b)] \end{bmatrix} = \begin{bmatrix} -a_w(\lambda_3) - b_{bw}(\lambda_3)\, v(\lambda_3) \\ -a_w(\lambda_4) - b_{bw}(\lambda_4)\, v(\lambda_4) \\ -a_w(\lambda_5) - b_{bw}(\lambda_5)\, v(\lambda_5) \end{bmatrix}$$

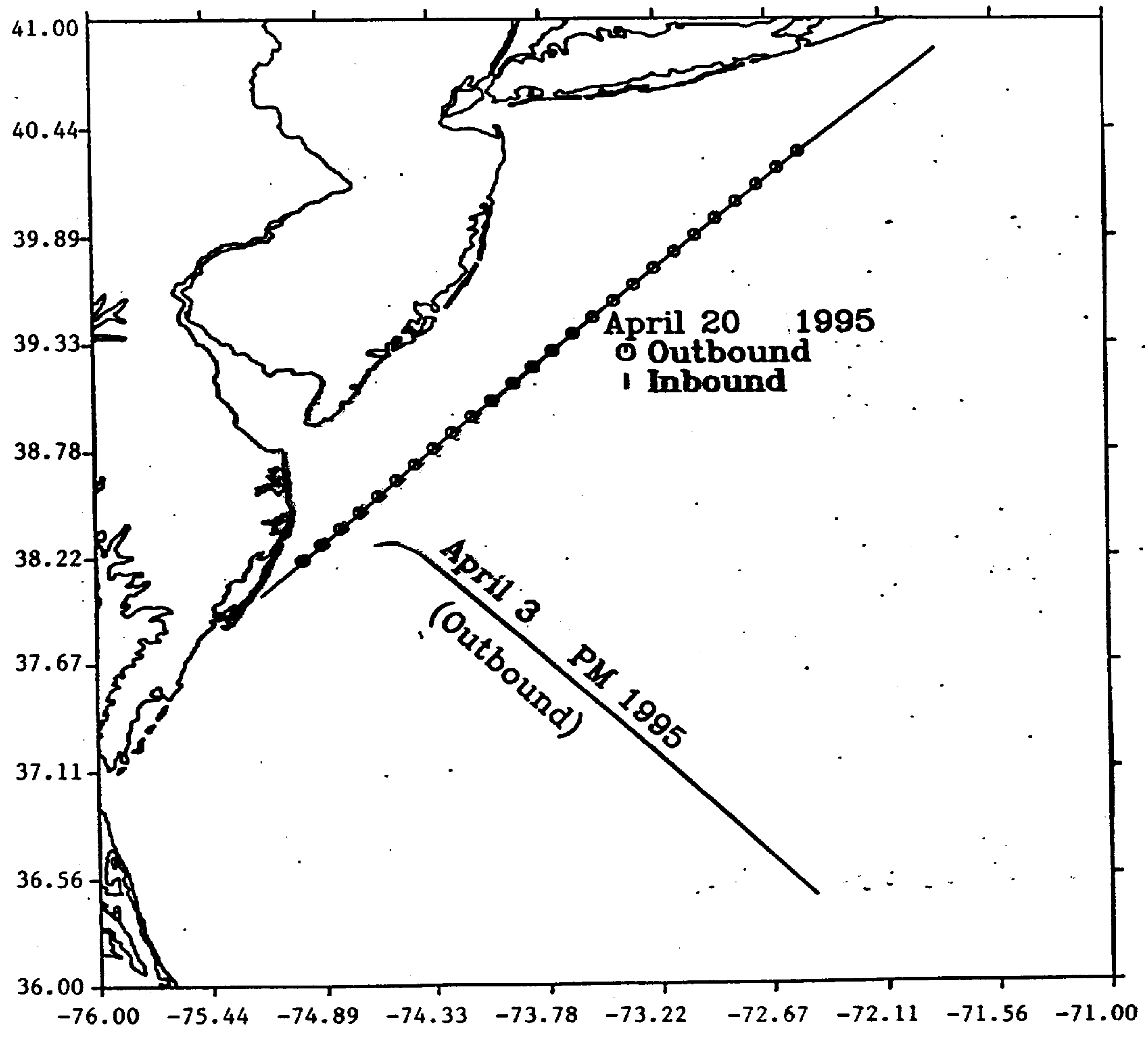

41.00
40.44
39.89
39.33
38.78
38.22
37.67
37.11
36.56
36.00
-76.00
-75.44
-74.89
-74.33
-73.78
-73.22
-72.67
-72.11
-71.56
-71.00
April 20 1995
Outbound
Inbound
April 3 PM 1995
(Outbound)

Figure 1

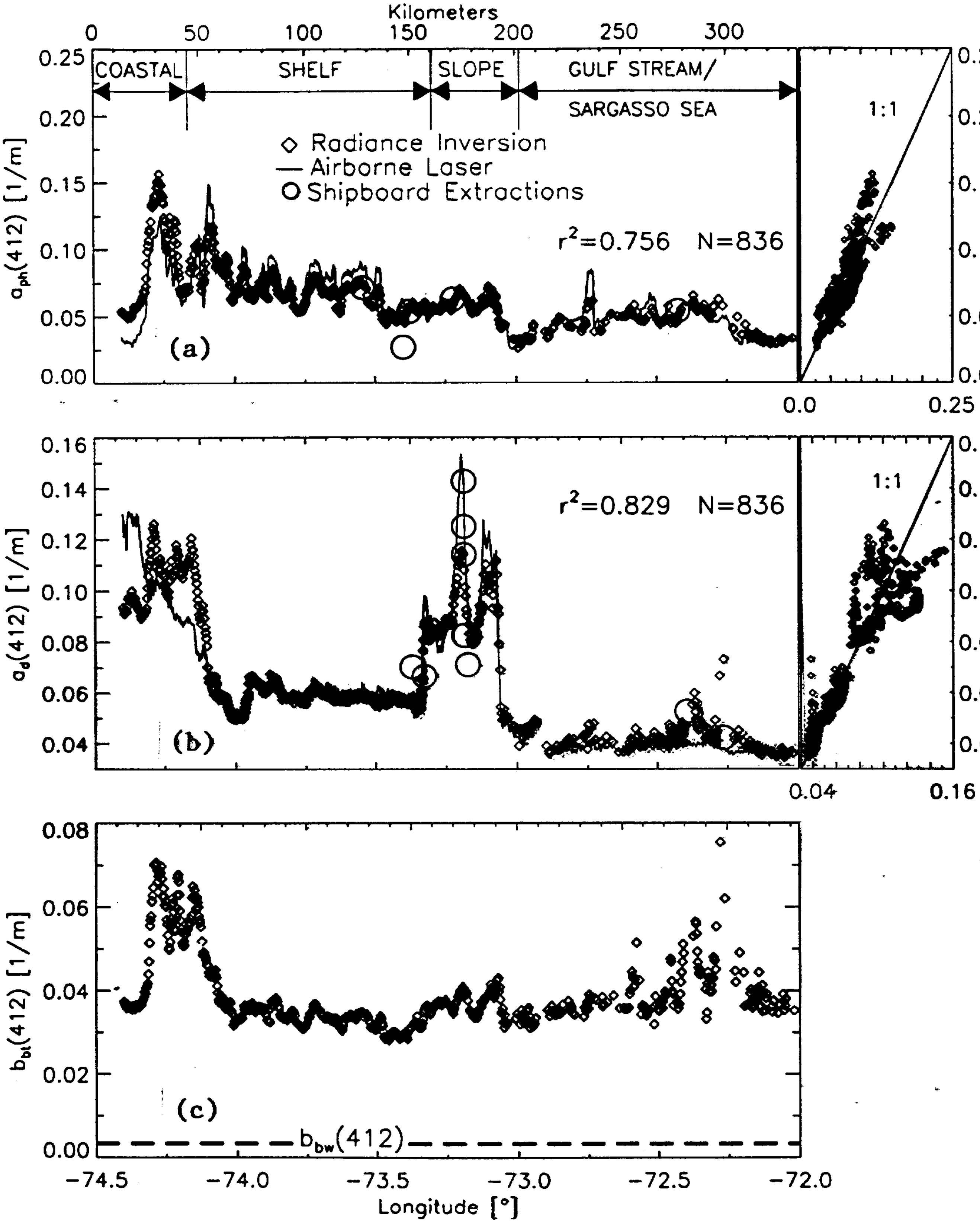
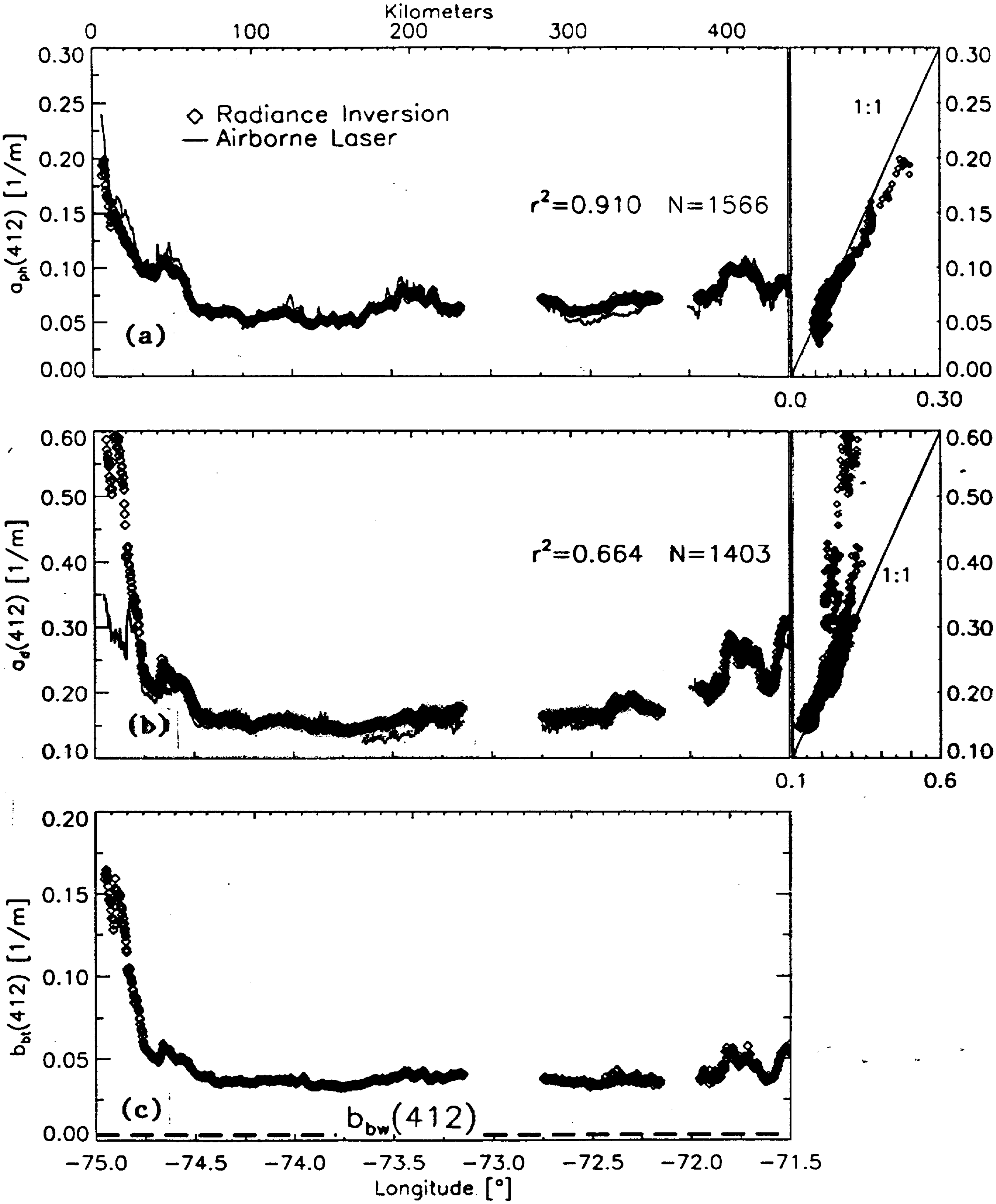

Kilometers
0
50
100
150
200
250
300
COASTAL
SHELF
SLOPE
GULF STREAM/
SARGASSO SEA
Radiance Inversion
Airborne Laser
Shipboard Extractions
r²=0.756 N=836
(a)
1:1
a_ph(412) [1/m]
r²=0.829 N=836
(b)
a_d(412) [1/m]
(c)
b_bt(412) [1/m]
b_bw(412)
-74.5
-74.0
-73.5
-73.0
-72.5
-72.0
Longitude [°]

Figure 2



Kilometers
0
100
200
300
400
0.30
0.25
0.20
0.15
0.10
0.05
0.00
◇ Radiance Inversion
— Airborne Laser
r²=0.910 N=1566
1:1
(a)
0.0
0.30
0.60
0.50
0.40
0.30
0.20
0.10
r²=0.664 N=1403
1:1
(b)
0.1
0.6
0.20
0.15
0.10
0.05
0.00
(c)
b_bw(412)
−75.0
−74.5
−74.0
−73.5
−73.0
−72.5
−72.0
−71.5
Longitude [°]

Figure 3

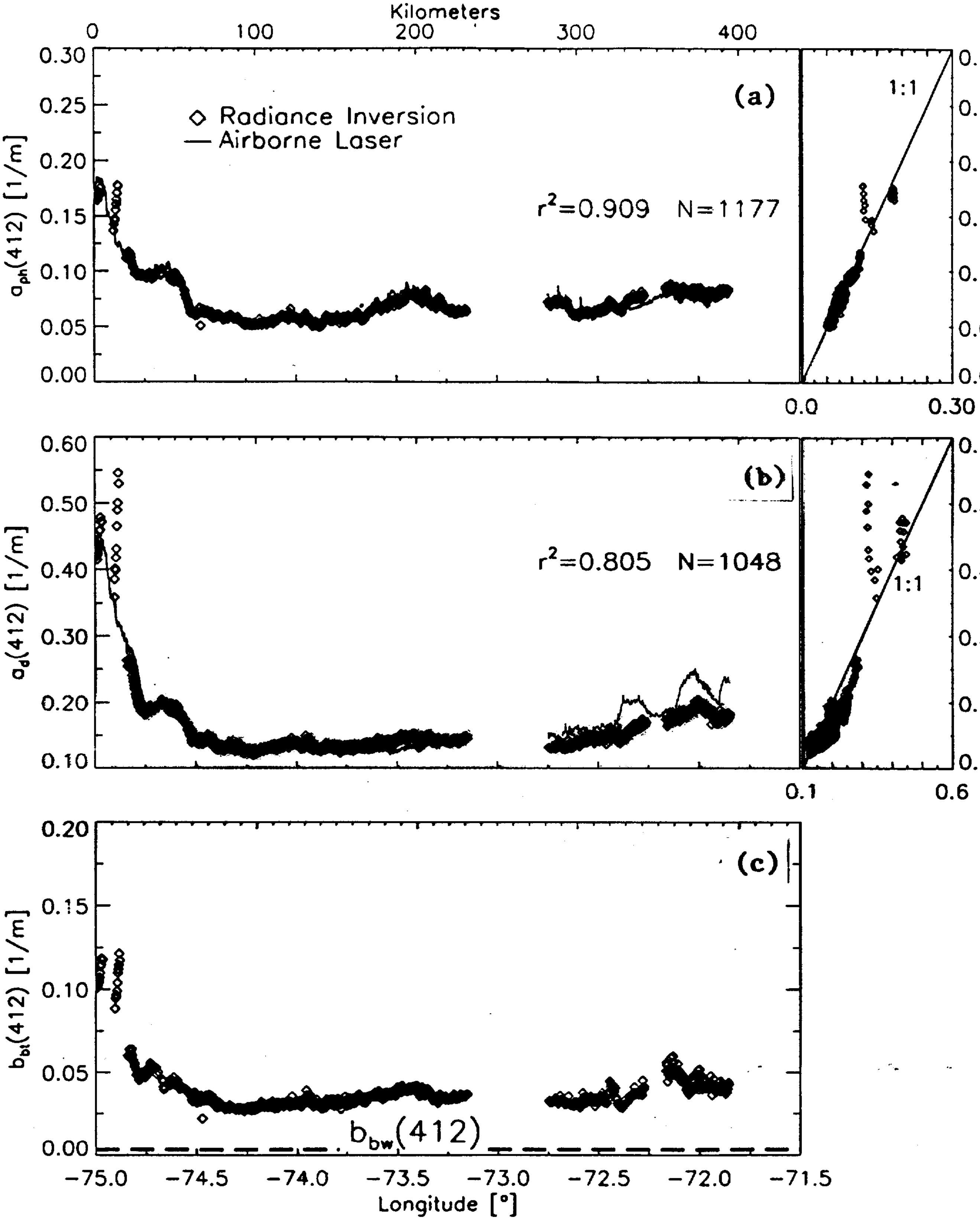

Kilometers
0
100
200
300
400
0.30
0.25
0.20
0.15
0.10
0.05
0.00
(a)
◇ Radiance Inversion
— Airborne Laser
r^2=0.909 N=1177
$a_{ph}(412)$ [1/m]
1:1
0.0
0.30
0.60
0.50
0.40
0.30
0.20
0.10
(b)
r^2=0.805 N=1048
$a_d(412)$ [1/m]
1:1
0.1
0.6
0.20
0.15
0.10
0.05
0.00
(c)
$b_{bt}(412)$ [1/m]
$b_{bw}(412)$
−75.0
−74.5
−74.0
−73.5
−73.0
−72.5
−72.0
−71.5
Longitude [°]

Figure 4

DETAILS:

Applied Optics, In Press, (1999)

Satellite retrieval of inherent optical properties by inversion of an oceanic radiance model: A preliminary algorithm, Hoge, Frank E., C. Wayne Wright, Paul E. Lyon, Robert N. Swift, James K. Yungel, .

RETRIEVAL OF PHYCOERYTHRIN PIGMENT CONCENTRATION

IMPORTANT FACTS

- TWO CHROMOPHORES (PUB,PEB)
- PUB SUBSTITUTION WITHIN PEB CAUSES PEB ABSORPTION BAND SPECTRAL SHIFT

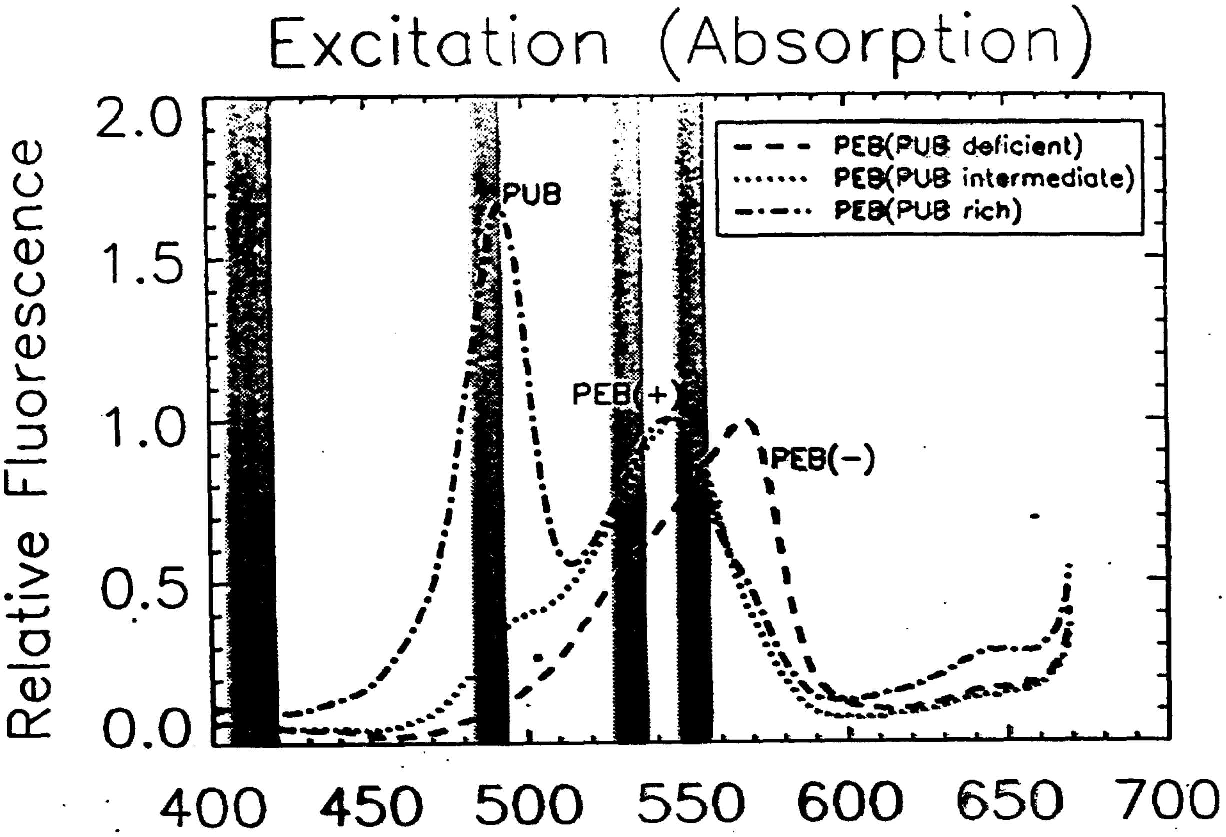
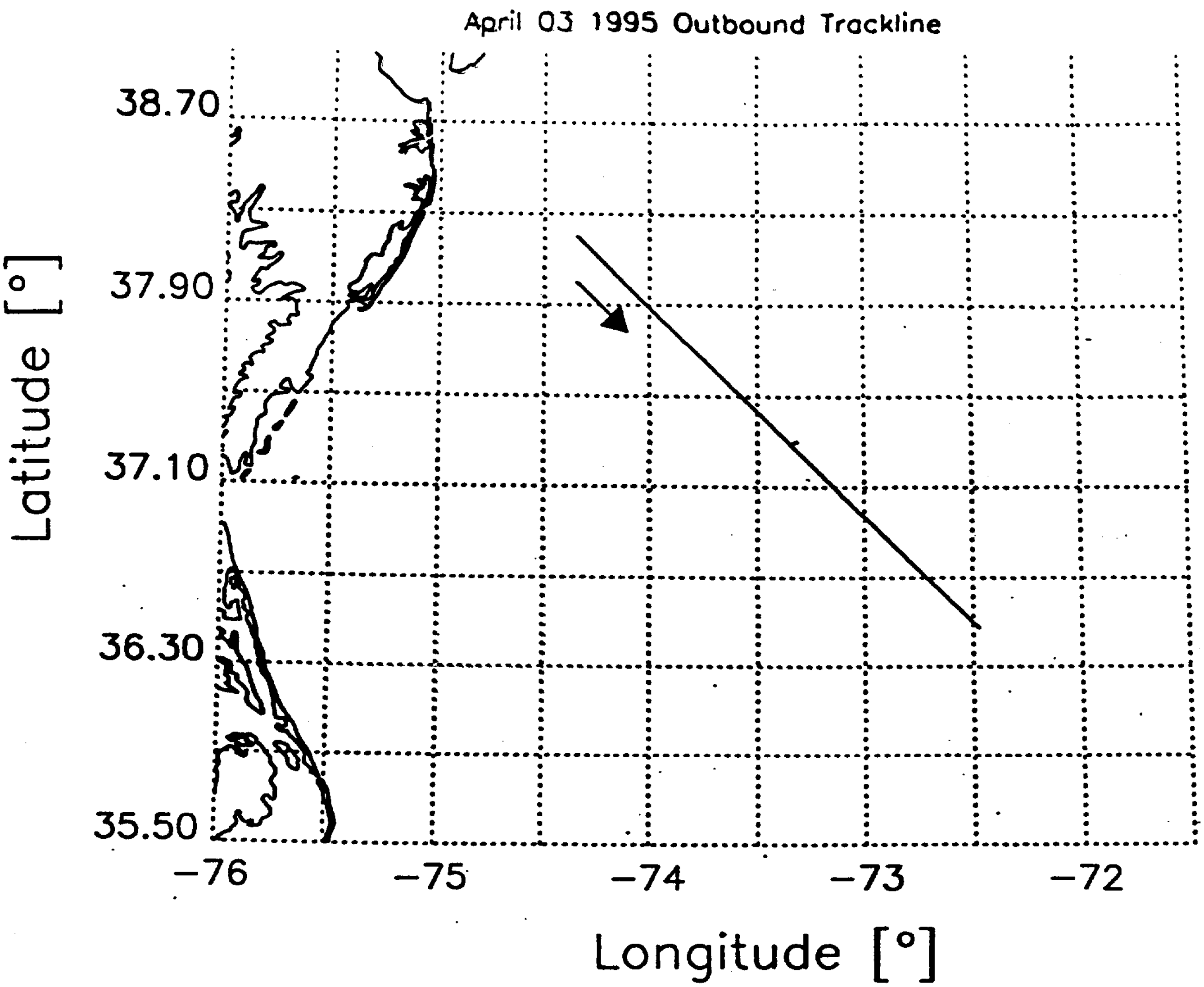

Excitation (Absorption)
Relative Fluorescence
2.0
1.5
1.0
0.5
0.0
400
450
500
550
600
650
700
PEB(PUB deficient)
PEB(PUB intermediate)
PEB(PUB rich)
PUB
PEB(+)
PEB(−)

Figure 1



April 03 1995 Outbound Trackline
38.70
37.90
37.10
36.30
35.50
Latitude [°]
−76
−75
−74
−73
−72
Longitude [°]

Figure 2

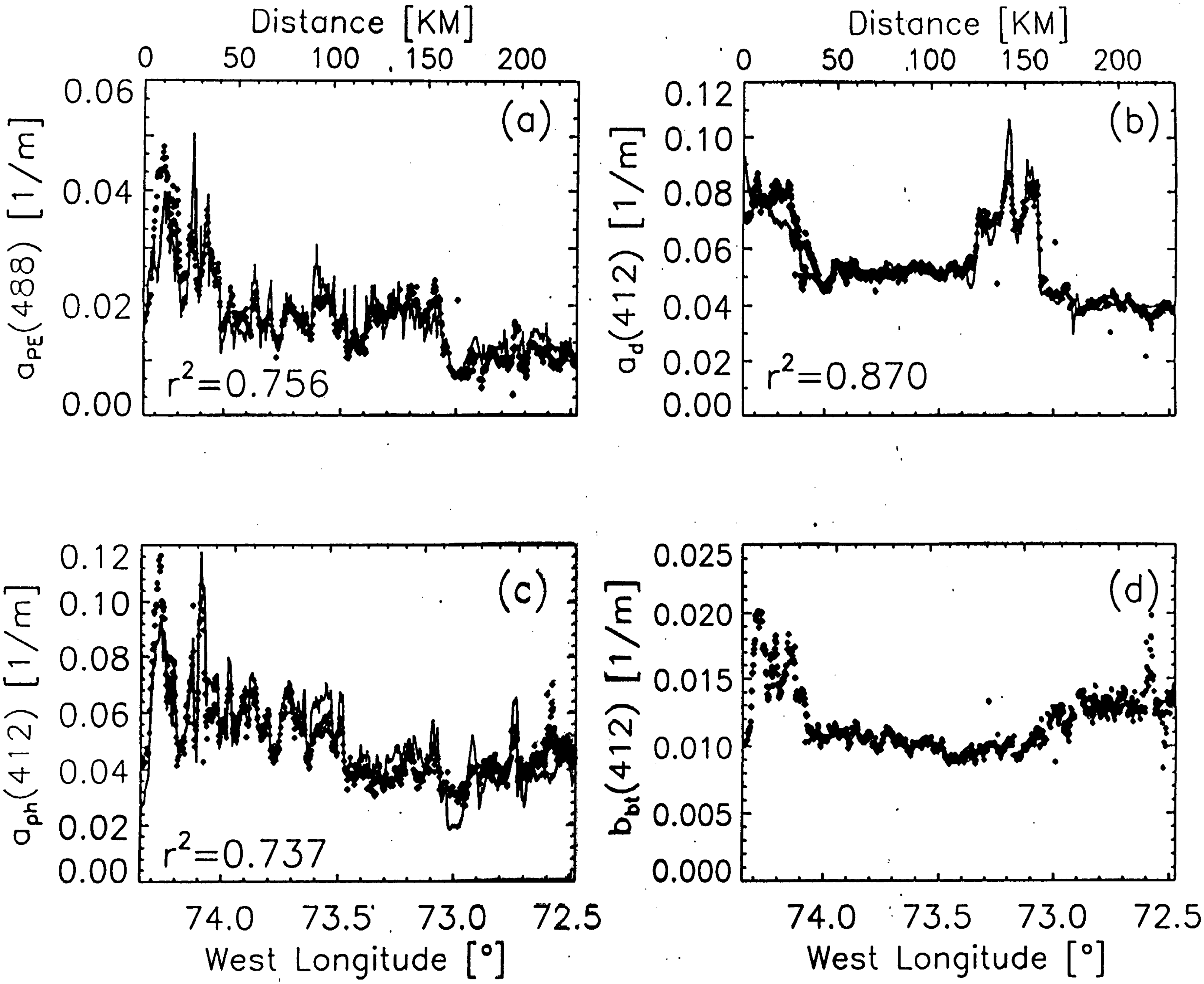

Distance [KM]
0
50
100
150
200
0.06
0.04
0.02
0.00
(a)
$a_{PE}(488)$ [1/m]
r^2=0.756
Distance [KM]
0
50
100
150
200
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(b)
$a_d(412)$ [1/m]
r^2=0.870
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(c)
$a_{ph}(412)$ [1/m]
r^2=0.737
74.0
73.5
73.0
72.5
West Longitude [°]
0.025
0.020
0.015
0.010
0.005
0.000
(d)
$b_{bt}(412)$ [1/m]
74.0
73.5
73.0
72.5
West Longitude [°]

Figure 3

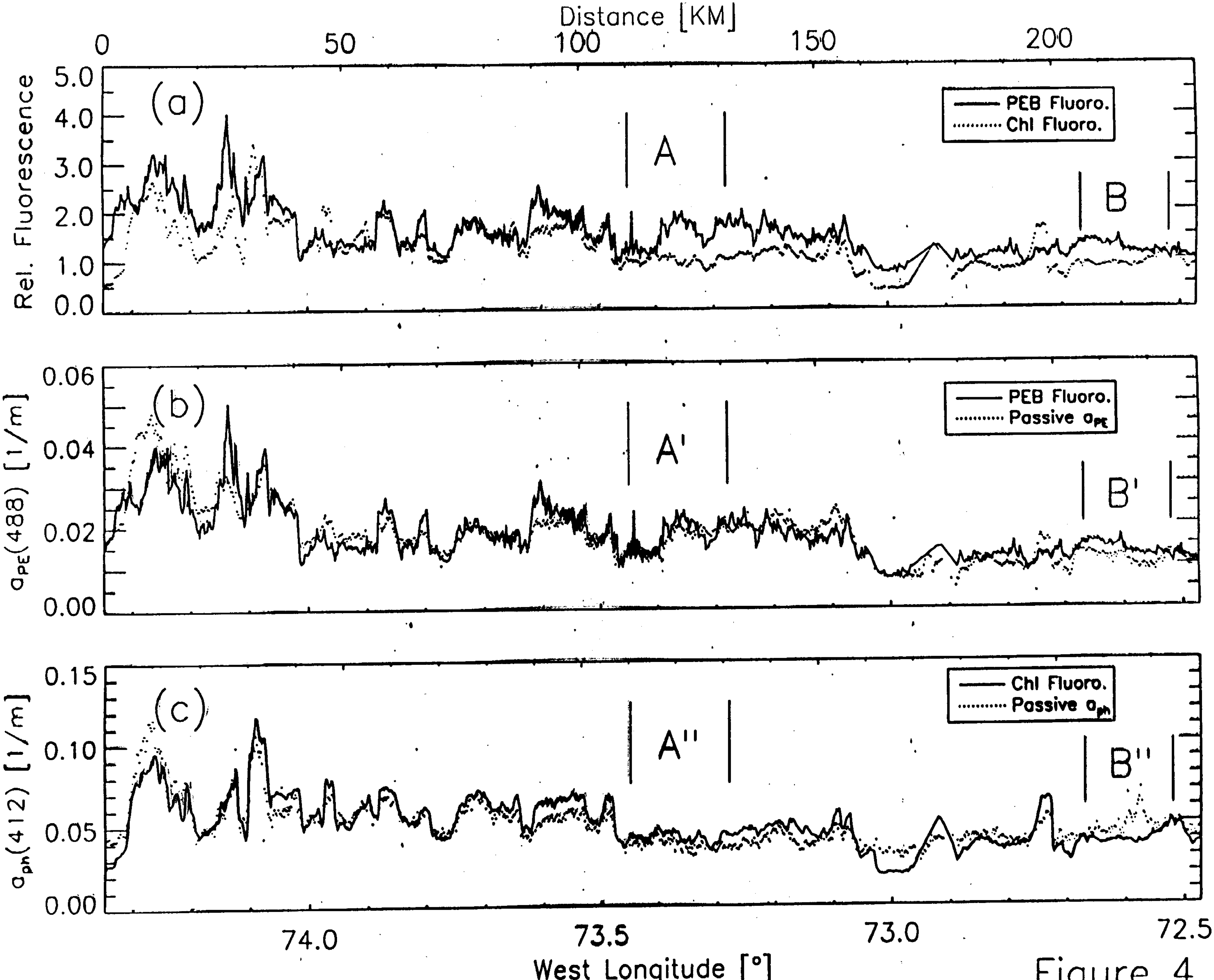
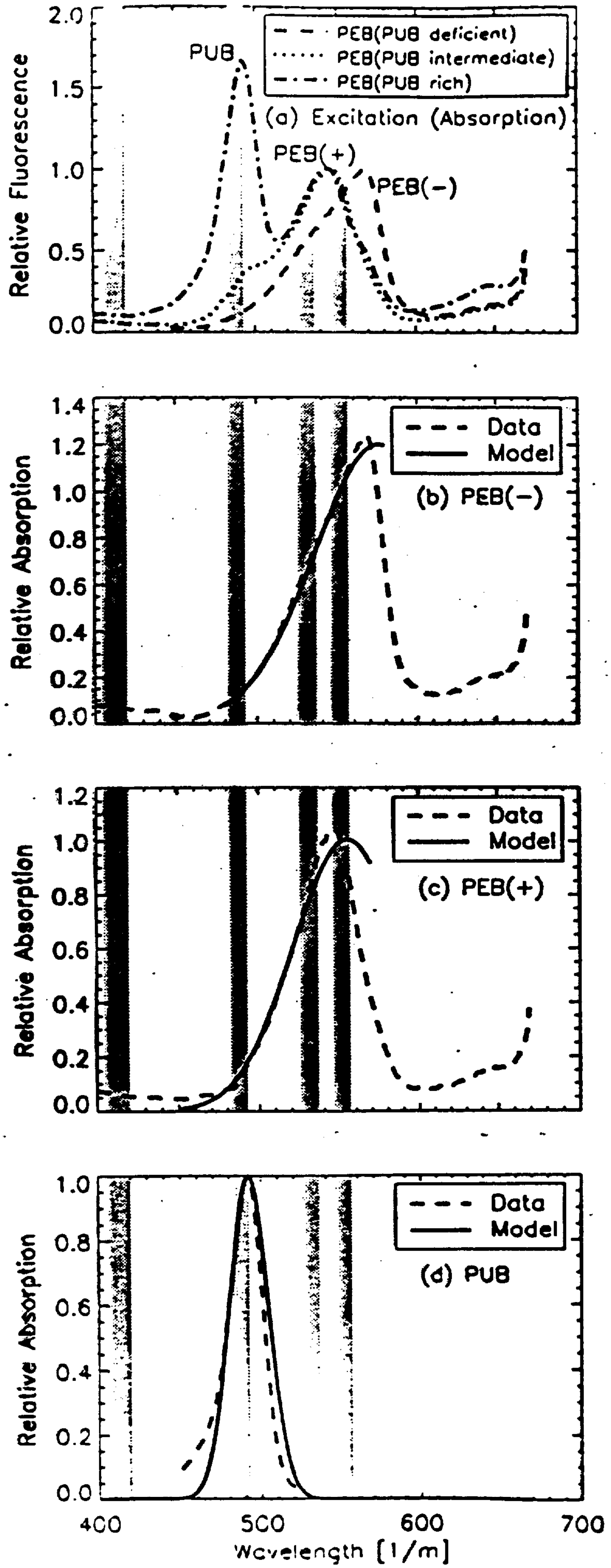
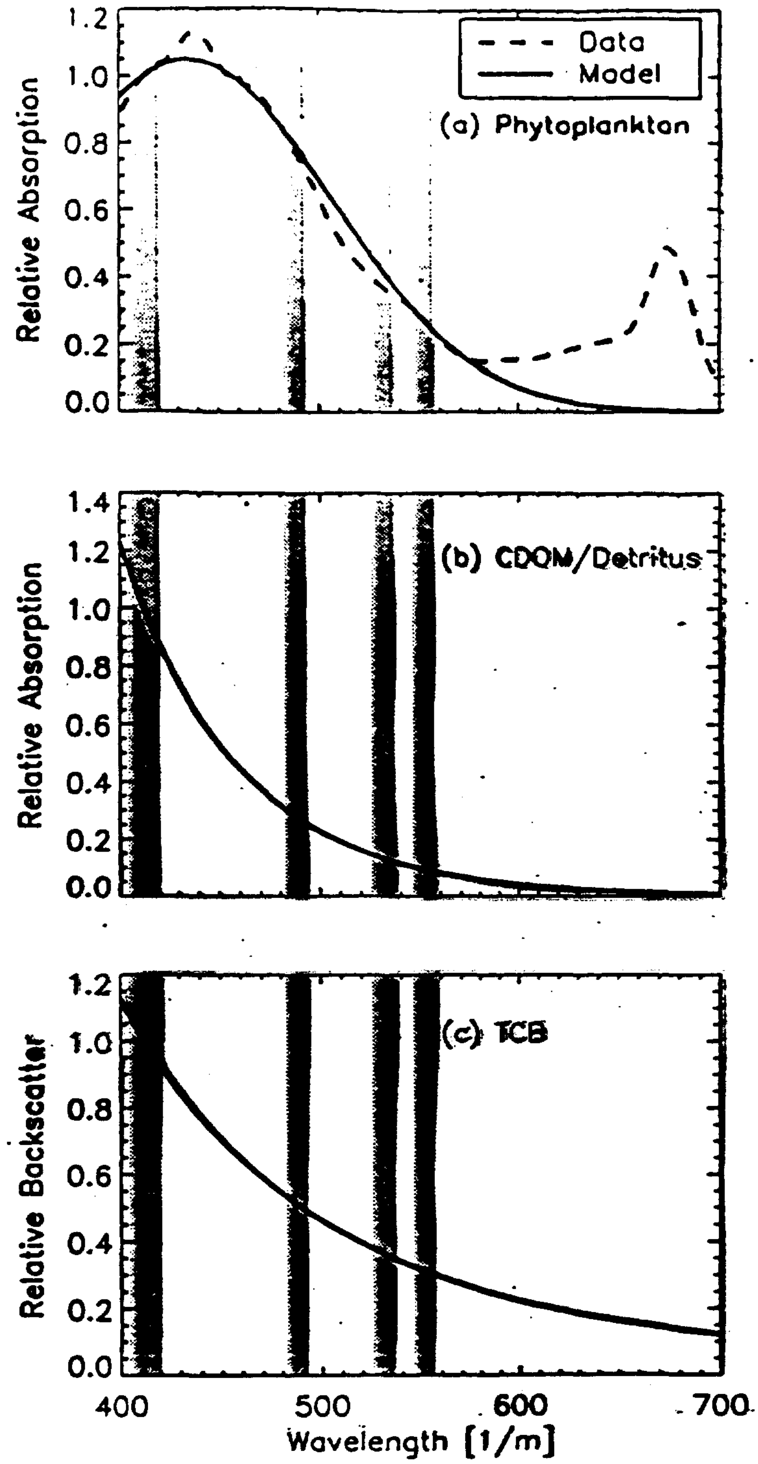

Distance [KM]
0
50
100
150
200
Rel. Fluorescence
5.0
4.0
3.0
2.0
1.0
0.0
(a)
A
B
PEB Fluoro.
Chl Fluoro.
a_{PE}(488) [1/m]
0.06
0.04
0.02
0.00
(b)
A'
B'
PEB Fluoro.
Passive a_{PE}
a_{ph}(412) [1/m]
0.15
0.10
0.05
0.00
(c)
A''
B''
Chl Fluoro.
Passive a_{ph}
74.0
73.5
73.0
72.5
West Longitude [°]

Figure 4



2.0
1.5
1.0
0.5
0.0
Relative Fluorescence
PEB(PUB deficient)
PEB(PUB intermediate)
PEB(PUB rich)
PUB
(a) Excitation (Absorption)
PEB(+)
PEB(−)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Relative Absorption
Data
Model
(b) PEB(−)
(c) PEB(+)
(d) PUB
400
500
600
700
Wavelength [1/m]

Figure C

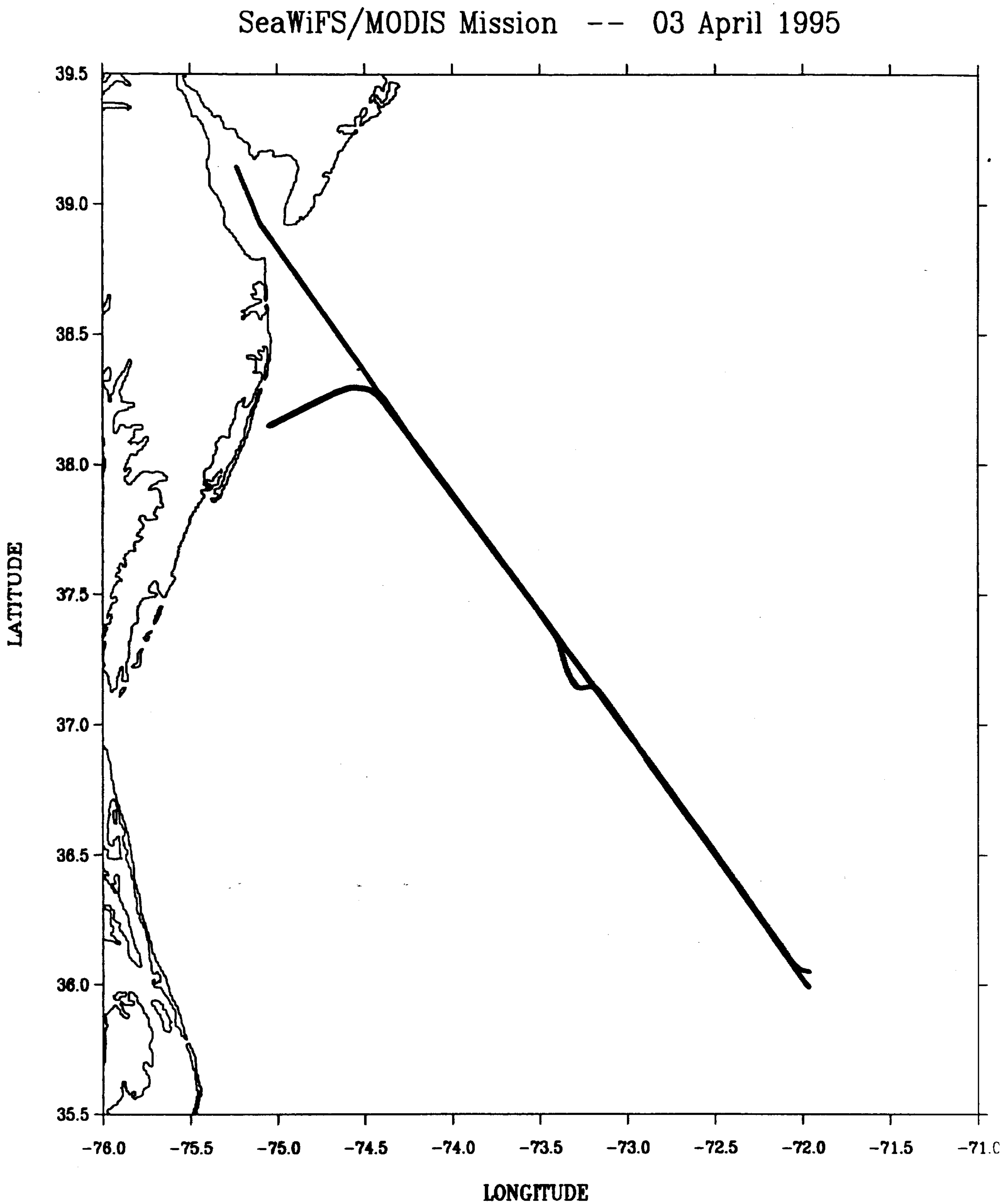

Data
Model
(a) Phytoplankton
Relative Absorption
1.2
1.0
0.8
0.6
0.4
0.2
0.0
(b) CDOM/Detritus
Relative Absorption
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
(c) TCB
Relative Backscatter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
Wavelength [1/m]

Figure

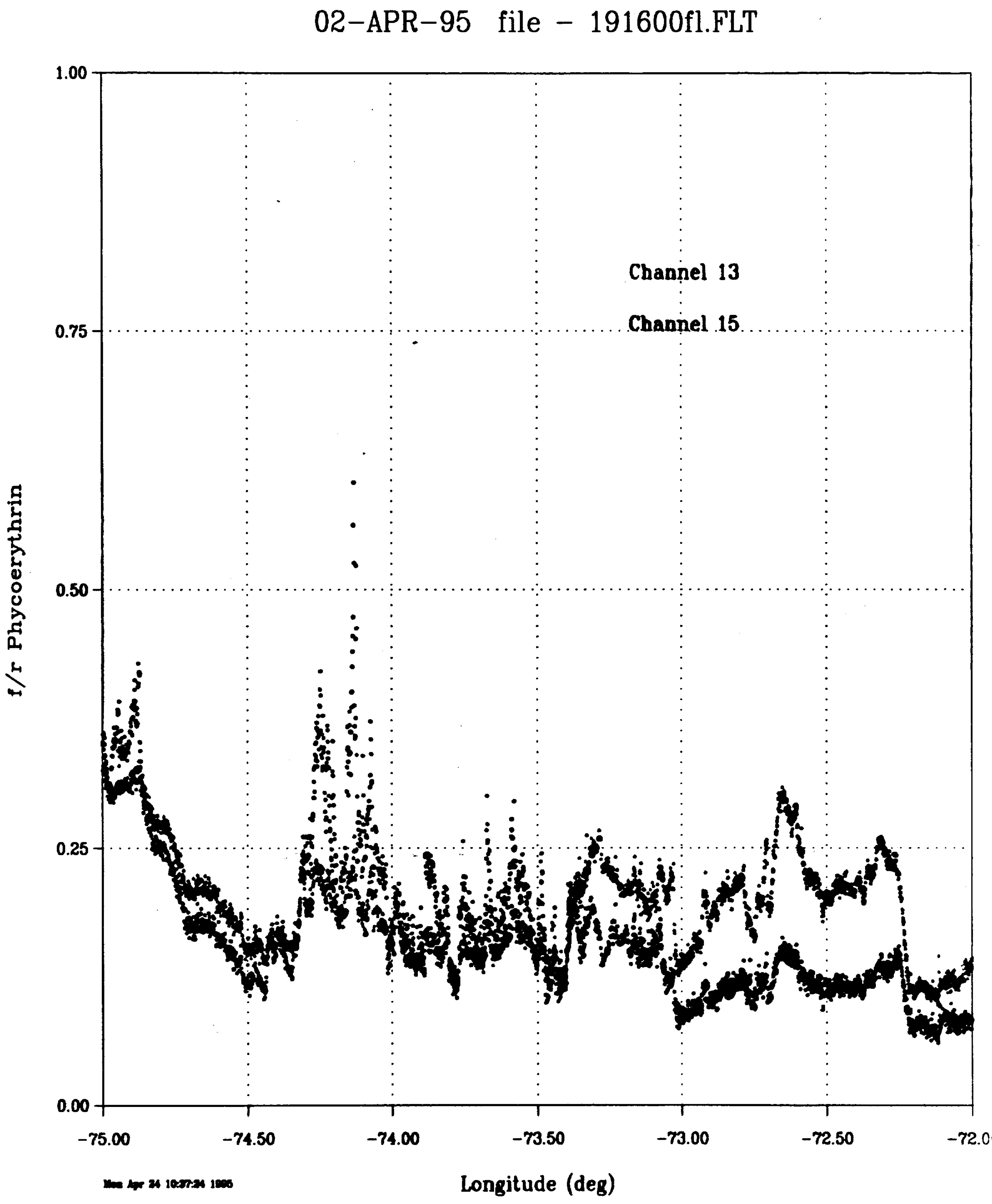
VALIDATION

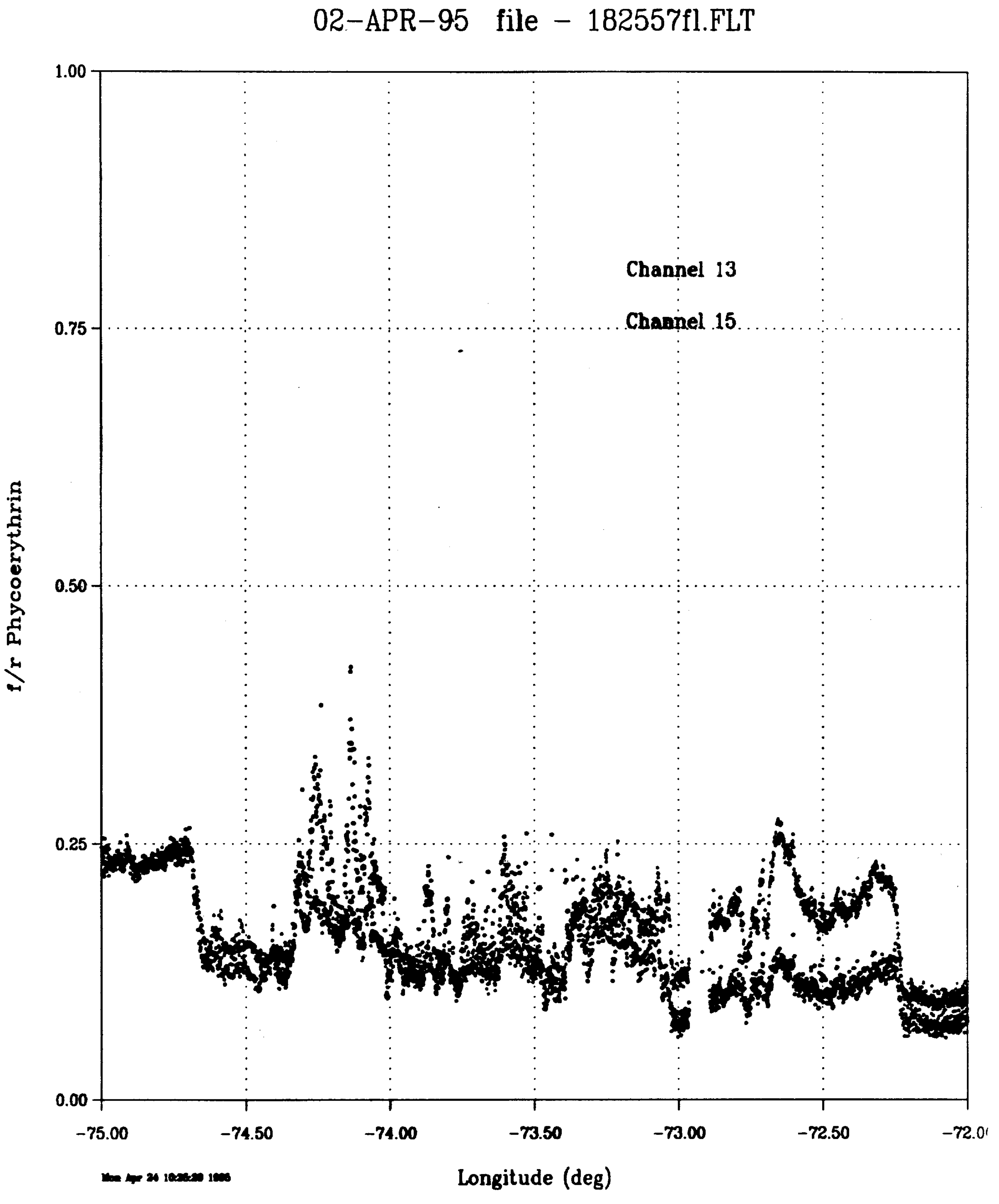
OF

PEB AND PUB



SeaWiFS/MODIS Mission -- 03 April 1995
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
LATITUDE
-76.0
-75.5
-75.0
-74.5
-74.0
-73.5
-73.0
-72.5
-72.0
-71.5
-71.0
LONGITUDE


02-APR-95 file - 191600fl.FLT
1.00
0.75
0.50
0.25
0.00
Channel 13
Channel 15
f/r Phycoerythrin
-75.00
-74.50
-74.00
-73.50
-73.00
-72.50
-72.0
Longitude (deg)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Channel 13
Channel 15
f/r Phycoerythrin
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0.75
0.50
0.25
0.00
-75.00
-74.50
-74.00
-73.50
-73.00
-72.50
Longitude (deg)

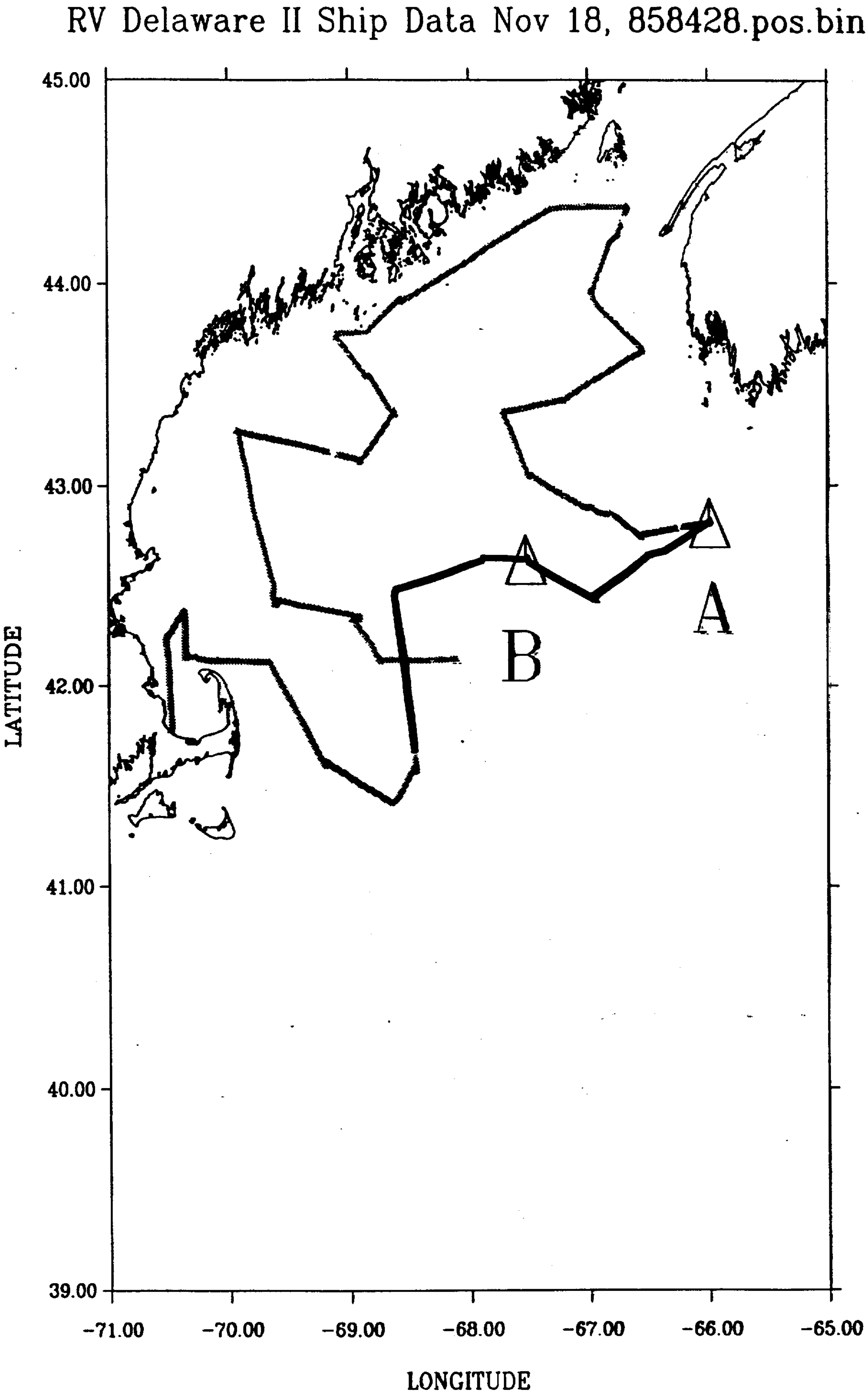
DETAILS:

Applied Optics 37, 4744-4749, 1998

Spatial variability of oceanic phycoerythrin spectral types derived from airborne laser-induced fluorescence measurements, Frank E. Hoge, C. Wayne Wright, Todd M. Kana, Robert N. Swift, and James K. Yungel.

SHIPBOARD LASER FLUOROMETER (SLF)

- •PEB(+) PHYCOERYTHRIN
- •PEB(-) PHYCOERYTHRIN
- •CHLOROPHYLL
- •WATER RAMAN NORMALIZATION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-68.00
-67.00
-66.00
-65.00
LONGITUDE
A
B

Gulf of Maine (ship 323 1 out.bin)