ATMOSPHERIC CORRECTION
of OCEAN IMAGERY

FOR

SeaWiFS and MODIS

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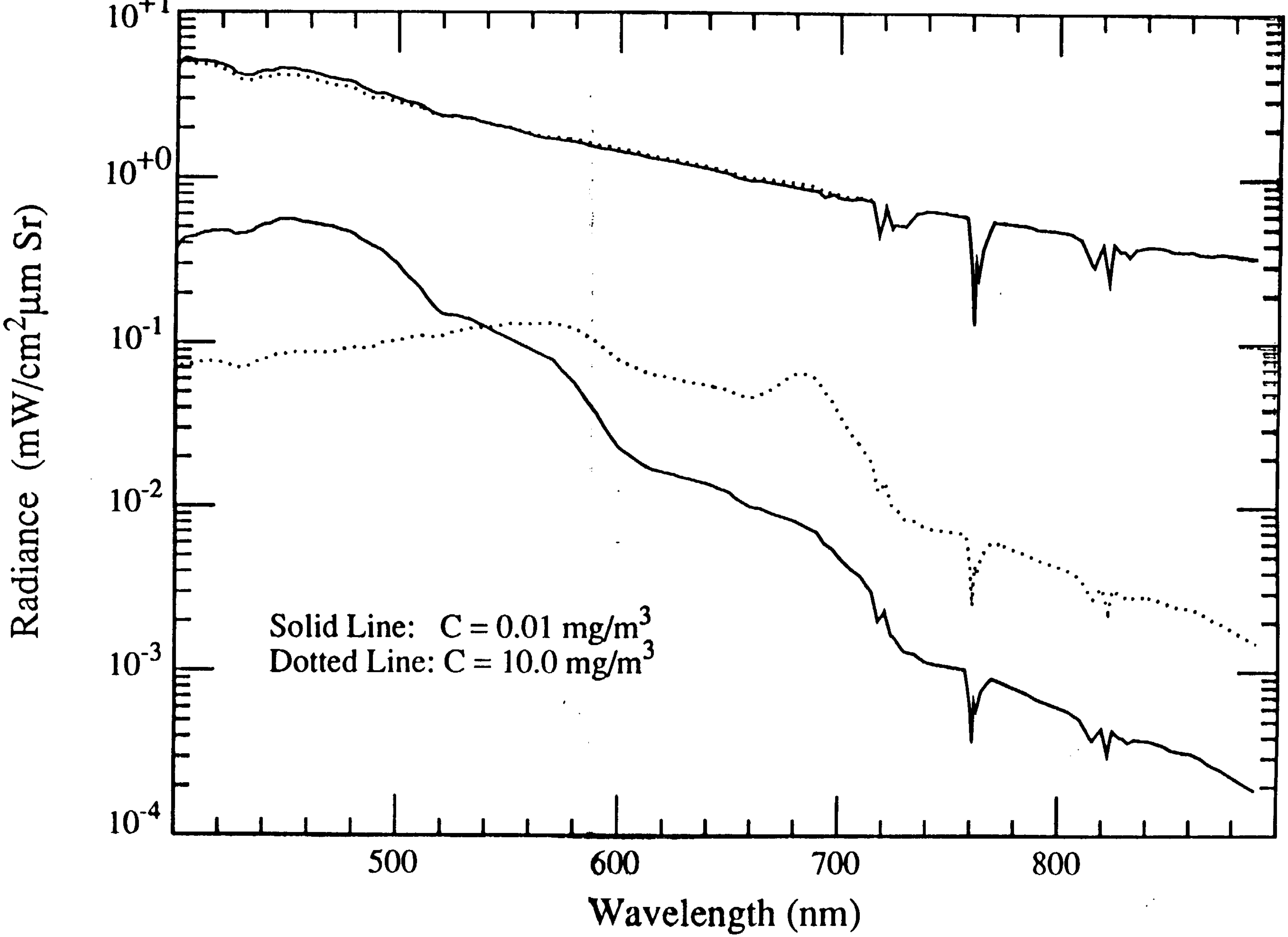
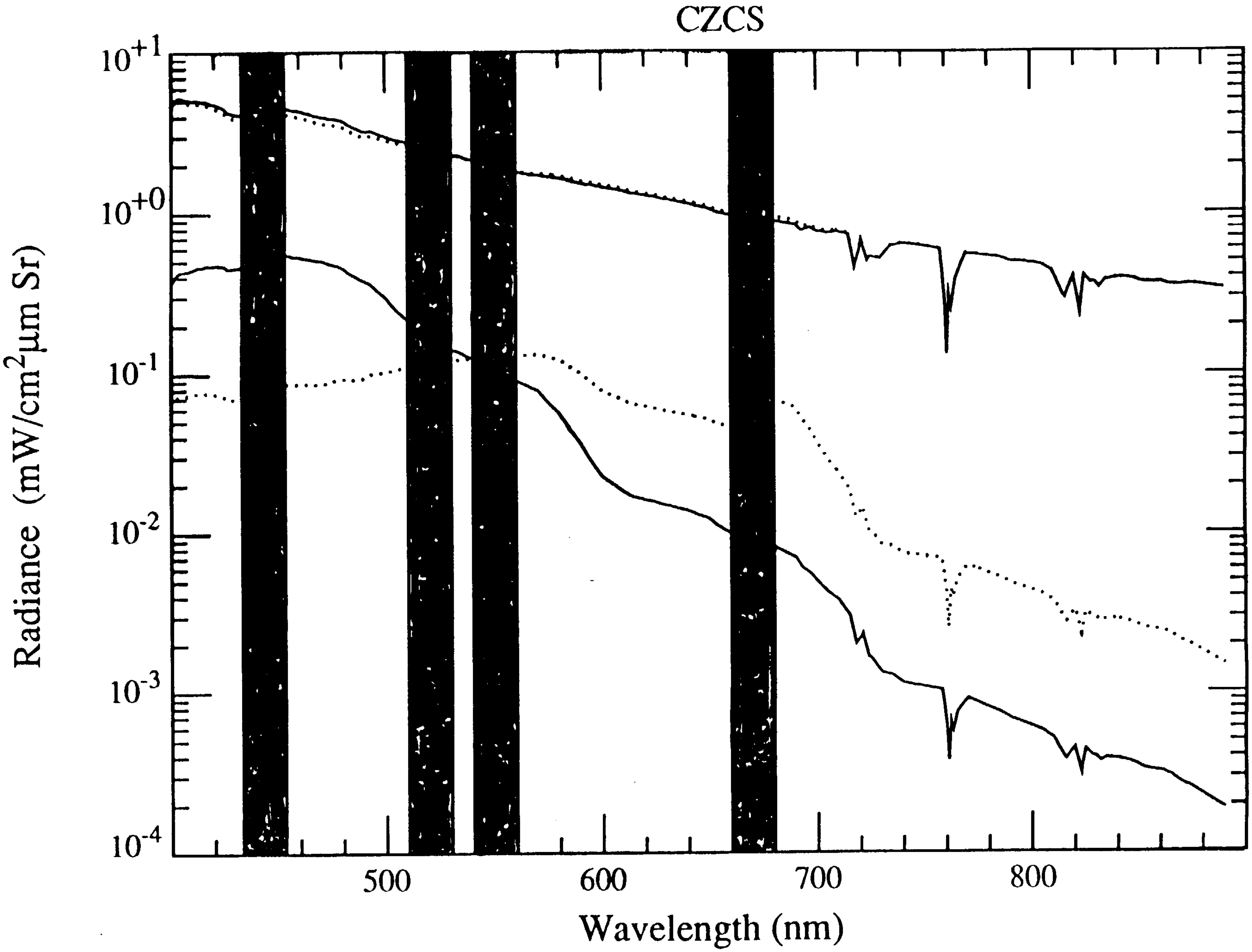
Attachment 1.15

OUTLINE

1. INTRODUCTION
2. REVIEW OF FIRST-ORDER CORRECTION (CZCS)
3. PROPOSED SECOND-ORDER **ALGORITHM** (SEAWIFS)
4. IMPLEMENTATION

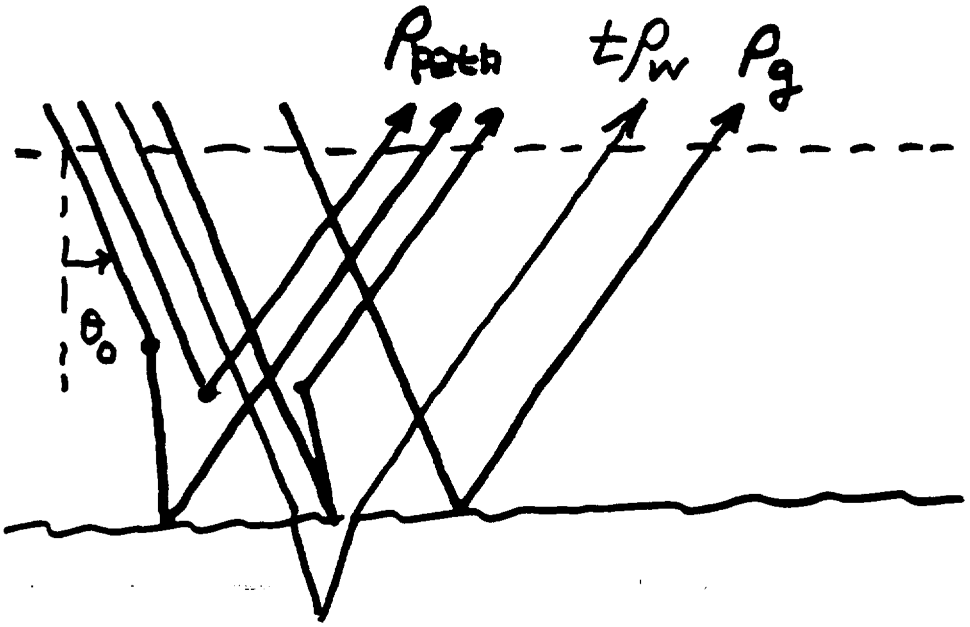


10+1
10+0
10-1
10-2
10-3
10-4
Radiance (mW/cm²μm Sr)
500
600
700
800
Wavelength (nm)
Solid Line: C = 0.01 mg/m³
Dotted Line: C = 10.0 mg/m³


CZCS
10^{+1}
10^{+0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Radiance (mW/cm^{2}µm Sr)
500
600
700
800
Wavelength (nm)

Atmospheric Correction

$$\rho_t = \rho_{\text{path}} + \rho_g + t\,\rho_w; \qquad \rho = \frac{\pi L}{F_0 \cos\theta_0}$$

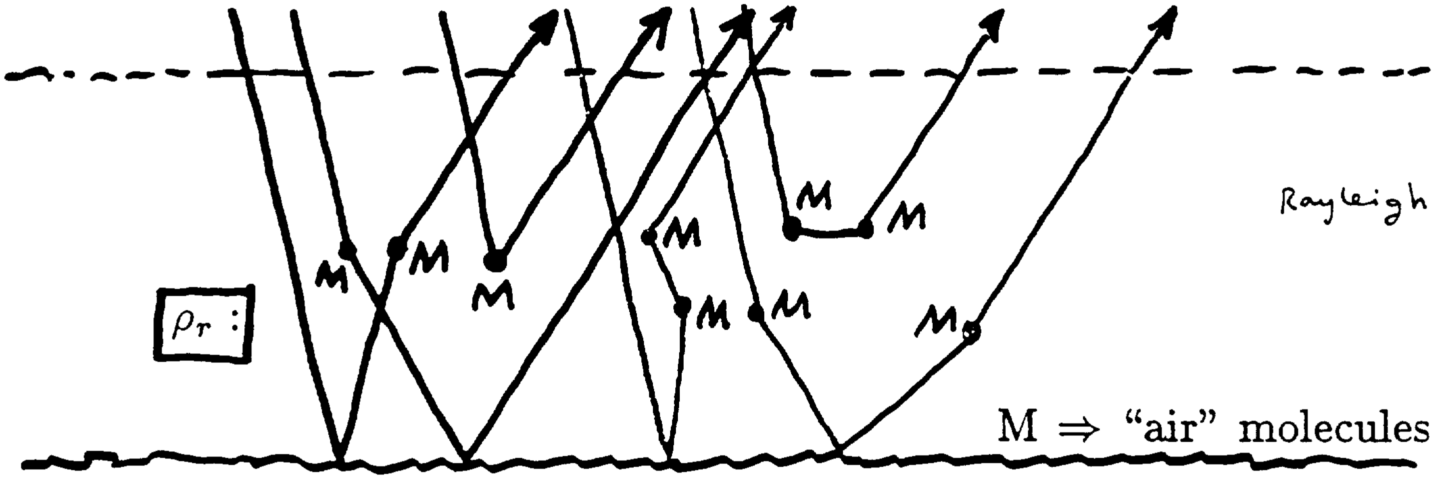


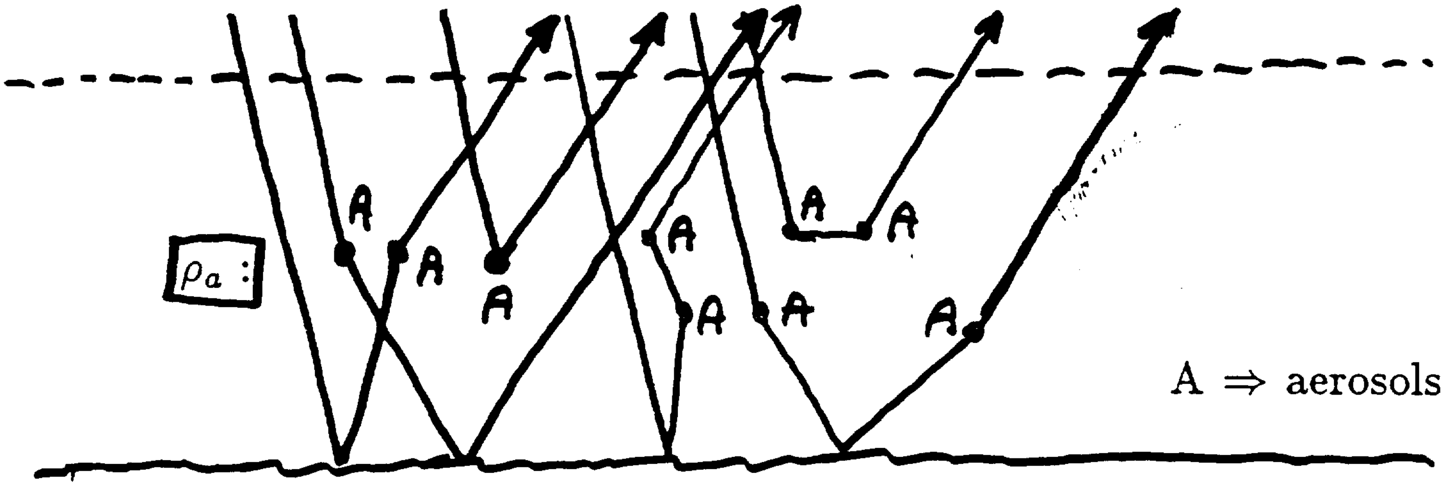
IGNORE ρ_g, THEN

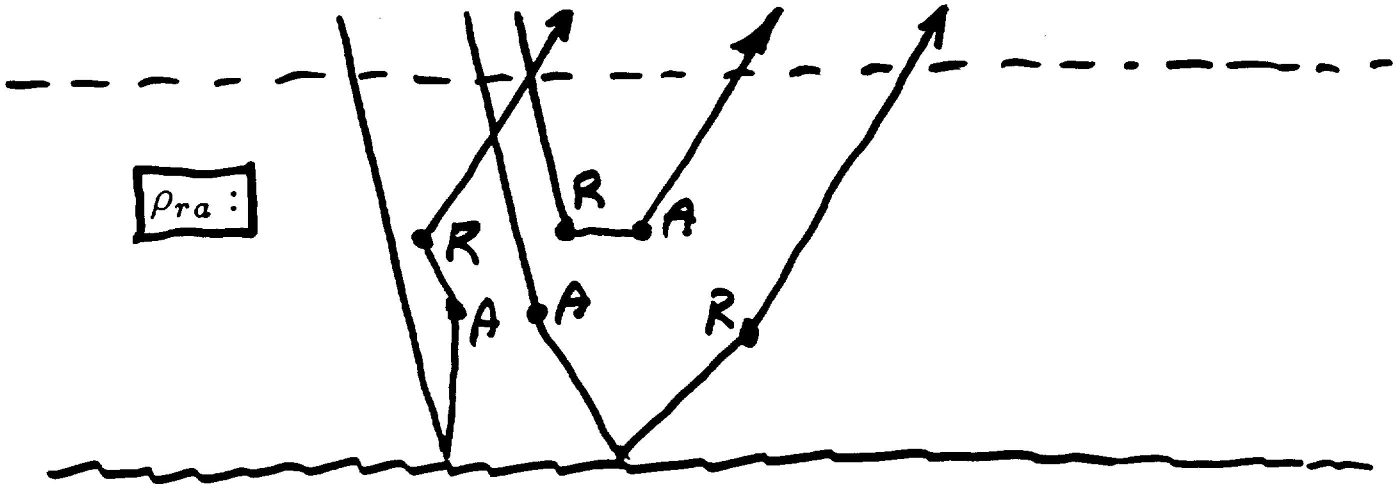
$$\rho_t = \rho_{\text{path}} + t\,\rho_w.$$

NOW LOOK AT THIS IN MORE DETAIL.

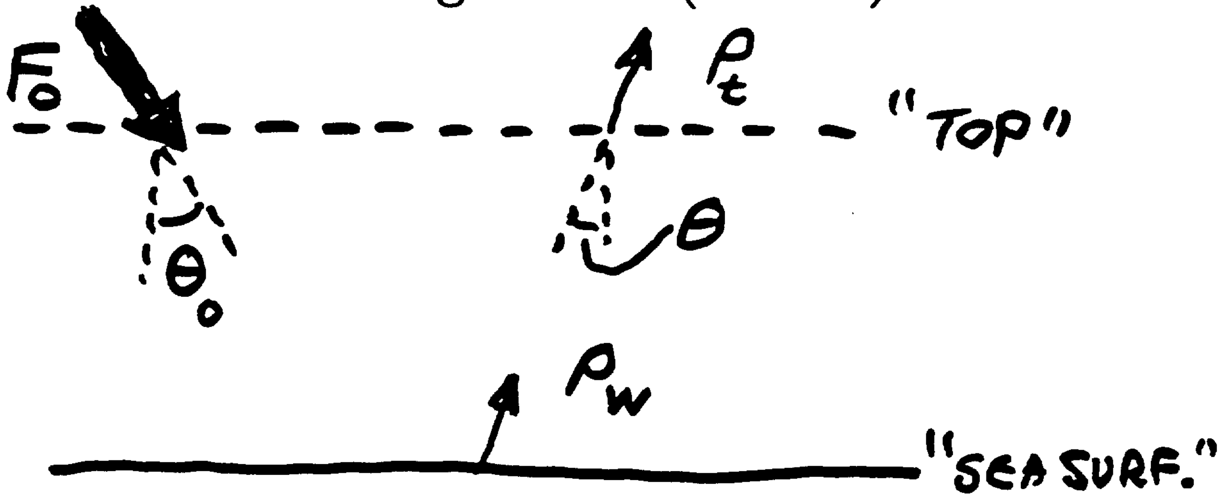
$$\boxed{\rho_t = \rho_r + \rho_a + \rho_{ra} + t\,\rho_w.}$$



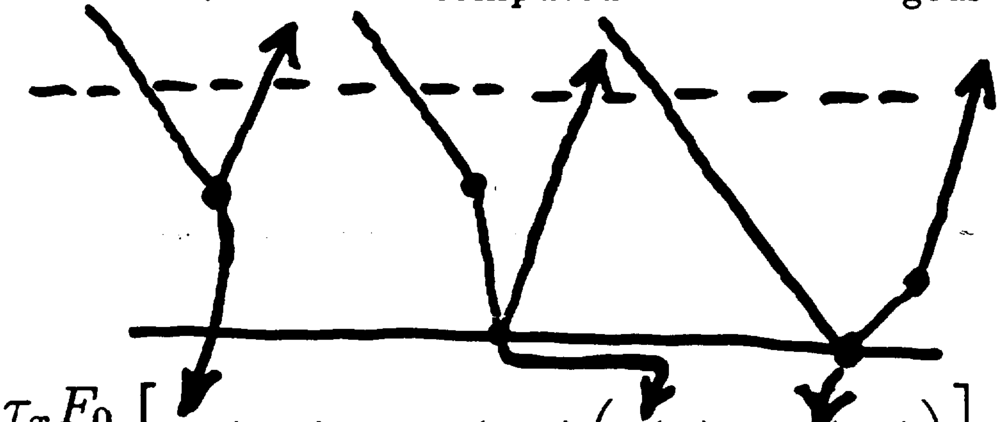




First-Order Algorithm (CZCS)



$$\underbrace{\rho_t}_{\text{measured}} = \underbrace{\rho_a}_{?} + \underbrace{\rho_r}_{\text{computed}} + t(\mu)\,\underbrace{\rho_w}_{\text{goal}}$$



$$\rho_x = \frac{\omega_x \tau_x F_0}{4\pi \cos\theta}\left[P_x(\alpha_-) + P_x(\alpha_+)\Big(\varrho(\mu) + \varrho(\mu_0)\Big)\right]$$

$$\cos\alpha_\pm = \pm\mu\mu_0\sqrt{(1-\mu^2)}\sqrt{(1-\mu_0^2)}\cos\Delta\phi$$

$$x = r \quad \text{or} \quad a, \quad \mu = \cos\theta, \quad \mu_0 = \cos\theta_0$$

Define

$$S(\lambda, \lambda_0) = \frac{\rho_a(\lambda)}{\rho_a(\lambda_0)}$$

Then for single scattering

$$S = \frac{\omega_a(\lambda)\tau_a(\lambda)F_0(\lambda)}{\omega_a(\lambda_0)\tau_a(\lambda_0)F_0(\lambda_0)} \left[\frac{P_a(\lambda, \alpha_-) + P_a(\lambda, \alpha_+)[\varrho(\mu) + \varrho(\mu_0)]}{P_a(\lambda_0, \alpha_-) + P_a(\lambda_0, \alpha_+)[\varrho(\mu) + \varrho(\mu_0)]}\right]$$

$$= \epsilon(\lambda, \lambda_0)\frac{F_0(\lambda)}{F_0(\lambda_0)}$$

NOTE:

For a given aerosol "type" $\epsilon(\lambda, \lambda_0)$ is independent of the aerosol **concentration**, and is almost independent of **position** over the image.

Consider two bands at λ and λ_0. $\utilde{\quad}$ = unknown

$$\begin{aligned}
\utilde{t(\lambda)}\,\utilde{\rho_w(\lambda)} &= \rho_t(\lambda) - \rho_r(\lambda) - \utilde{\rho_a(\lambda)} \\
&= \rho_t(\lambda) - \rho_r(\lambda) - \utilde{S(\lambda, \lambda_0)}\,\utilde{\rho_a(\lambda_0)} \\
&= \rho_t(\lambda) - \rho_r(\lambda) - \utilde{S(\lambda, \lambda_0)}\Big[\rho_t(\lambda_0) - \rho_r(\lambda_0) - \utilde{t(\lambda_0)}\,\utilde{\rho_w(\lambda_0)}\Big]
\end{aligned}$$

where

$$t(\lambda) = \exp\Big[-\Big(\tau_r/2 + \tau_{Oz} + \underset{(<1/6)}{(\utilde{1 - \omega_a F})\utilde{\tau_a}}\Big)/\mu\Big]$$

(1) ignore $(1 - \omega_a F)\tau_a$
(2) choose λ_0 such that $\rho_w(\lambda_0) = 0$

$$\utilde{\rho_w(\lambda)} = t(\lambda)^{-1}\Big(\rho_t(\lambda) - \rho_r(\lambda) - \utilde{S(\lambda, \lambda_0)}\Big[\rho_t(\lambda_0) - \rho_r(\lambda_0)\Big]\Big)$$

$$\searrow$$

$$\utilde{\epsilon(\lambda, \lambda_0)}\frac{F_0(\lambda)}{F_0(\lambda_0)}$$

Apply to CZCS

Goal: Determine ρ_w at 443, 520, and 550 nm in order to estimate the pigment concentration.

Problem: Only *one* band for which $\rho_w \approx 0$ and we need two.

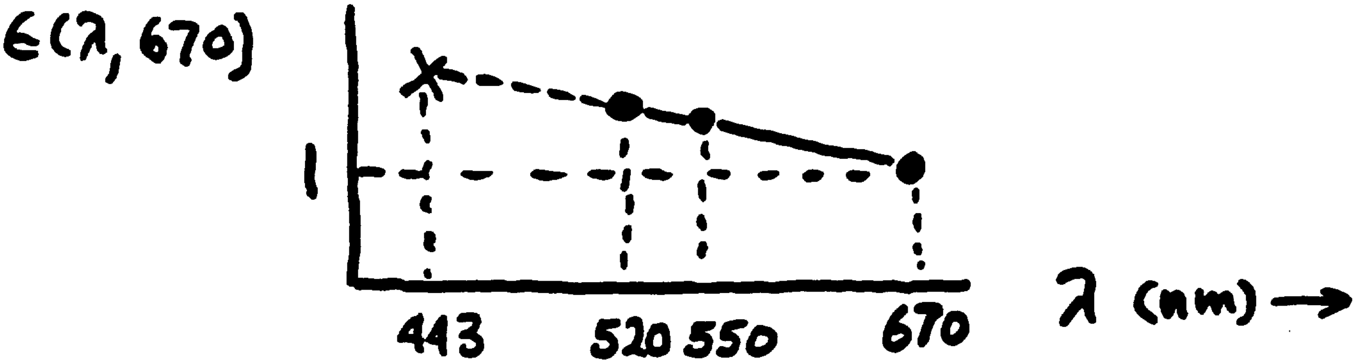
For low pigments can use Clear Water Radiance Concept:

When $C \leq 0.25$ mg/m^3, $[\rho_w]_n$ in

$$\rho_w(\lambda) = [\rho_w(\lambda)]_N \cos\theta_0 \exp\Big[-(\tau_r/2 + \tau_{Oz})/\cos\theta_0\Big],$$

is independent of C at 520, 550, and 670 nm.

Thus, use "clear water" regions to find $\epsilon(520, 670)$, $\epsilon(550, 670)$, and $\epsilon(670, 670)$. Extrapolate these to find $\epsilon(443, 670)$ and use this ϵ set throughout the entire image.



Note: This hinges on $\epsilon(\lambda, \lambda_0) \approx$ const. for given *aerosol type*.

SLIDES

TO SHOW $\epsilon \approx$ CONST

Difficulties:

1) May be no "clear water" in the image of interest.

2) The aerosol type may vary over the image causing the ϵ's to vary.

3) The aerosol phase function depends weakly on wavelength which implies that the ϵ's will depend on position in the image even if all of the other approximations (single scattering) are valid.

4) It also ignores several processes:
    a) Multiple Scattering
    b) Surface Roughness
    c) Vertical Structure
    d) Whitecaps
    e) Variations in Ozone
    f) Variations in Pressure
    g) Variations ρ_w with Viewing Angle

CZCS ALGORITHM ERRORS
(OVER AND ABOVE ERRORS IN THE ϵ'S)

ASSUMPTION	$t(\lambda)\Delta\rho(\lambda)$	λ
$\rho_{ra} = 0$	$\sim 0.002 \quad (\tau_a \approx 0.3)$	443
FLAT OCEAN	~ 0.0007 (7.5 M/S)	443
$\Delta\tau_{oz} = 0$	~ 0.0008 (± 50 DU)	550
$\Delta P_0 = 0$	~ 0.002 (± 15 MB)	412
NO WHITECAPS	~ 0.002 (7.5 M/S)	412–865

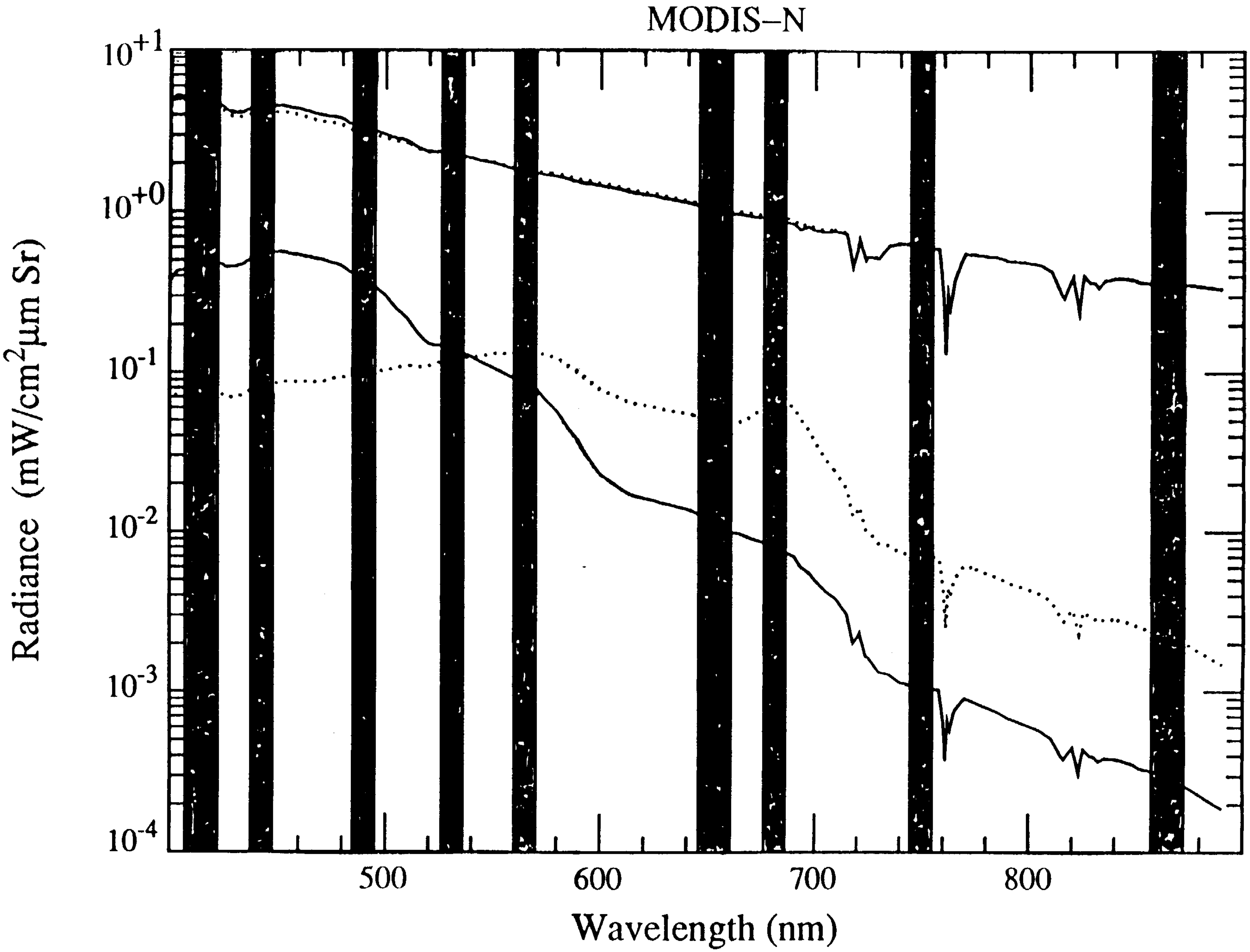
NOTE:

$$\mathrm{NE}\Delta\rho_{\mathrm{CZCS}}(443) = 0.0011$$

$$\mathrm{NE}\Delta\rho_{\mathrm{CZCS}}(550) = 0.00064$$

$$\mathrm{NE}\Delta\rho_{\mathrm{SeaWiFS}}(443) = 0.00049$$

$$\mathrm{NE}\Delta\rho_{\mathrm{SeaWiFS}}(550) = 0.00031$$


MODIS–N
Radiance (mW/cm^{2}μm Sr)
10^{+1}
10^{+0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
500
600
700
800
Wavelength (nm)

SeaWiFS

Performance for $\theta_0 = 60^\circ$ at the scan edge

Band	λ	ρ_{max}	ρ_{typ}	ρ_w	NE$\Delta\rho$	CZCS
1	402–422	0.50	0.34	0.040	0.00068	—
2	433–453	0.46	0.29	0.038	0.00049	0.0011
3	480–500	0.36	0.23	0.024	0.00035	—
4	510–530	0.32	0.19	0.0096	0.00031	0.00058
5	555–575	0.26	0.16	0.0040	0.00031	0.00064
6	655–675	0.17	0.105	0.0004	0.00024	0.00051
7	745–785	0.15	0.081	–	0.00017	—
8	845–785	0.13	0.069	–	0.00015	—

To utilize the full sensitivity of SeaWiFS, the error in atmospheric correction should be $\lesssim$ 0.0003 – 0.0007.

Note:

$$\mathrm{NE}\Delta\rho_{\text{SeaWiFS}} \approx \frac{1}{2}\mathrm{NE}\Delta\rho_{\text{CZCS}}$$

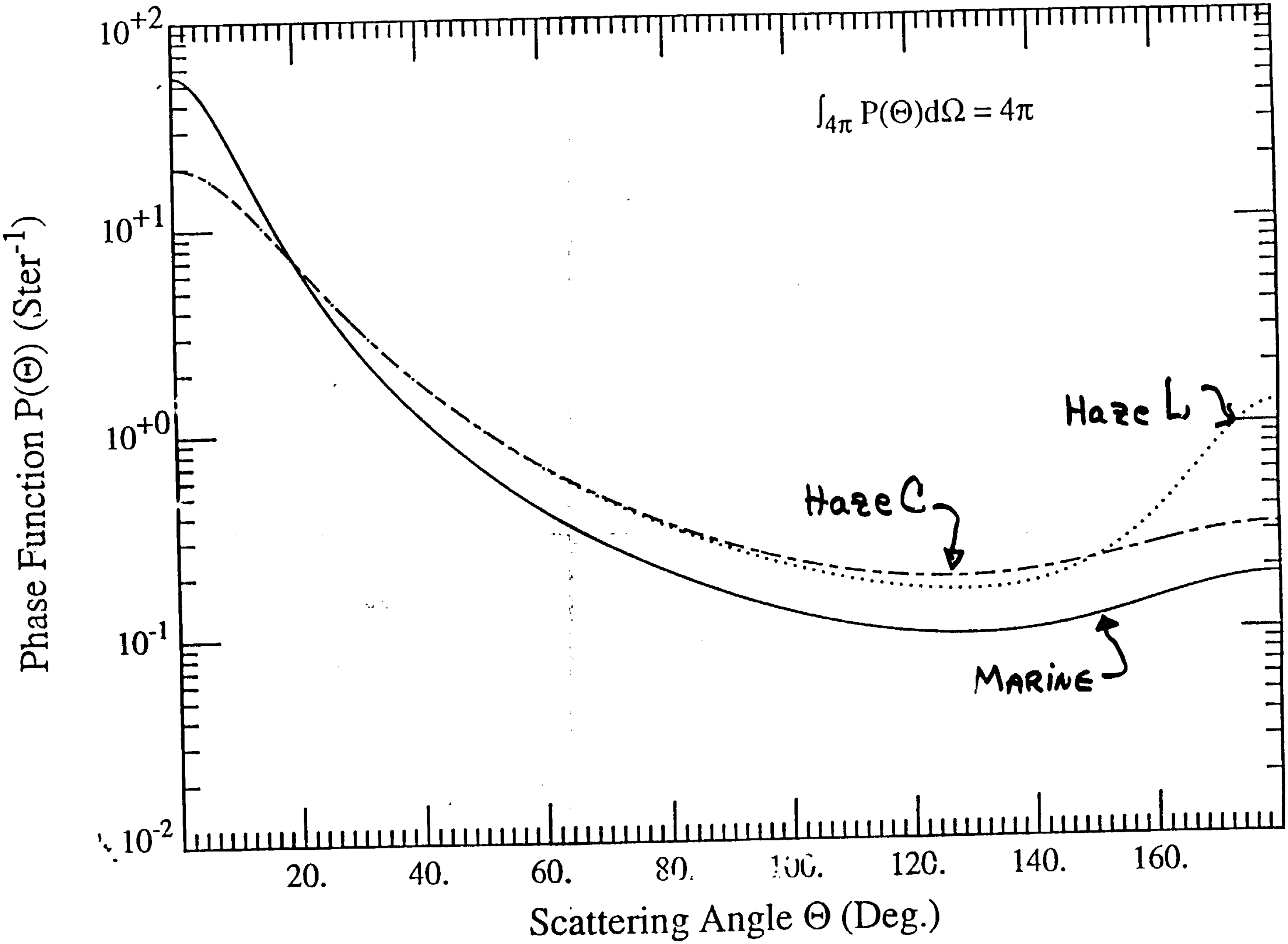
$$\mathrm{NE}\Delta\rho_{\text{MODIS}} \approx \frac{1}{2}\mathrm{NE}\Delta\rho_{\text{SeaWiFS}}$$

EXAMPLE OF ALGORITHM PERFORMANCE

EXAMINE THE ALGORITHM IN THE FOLLOWING MANNER:

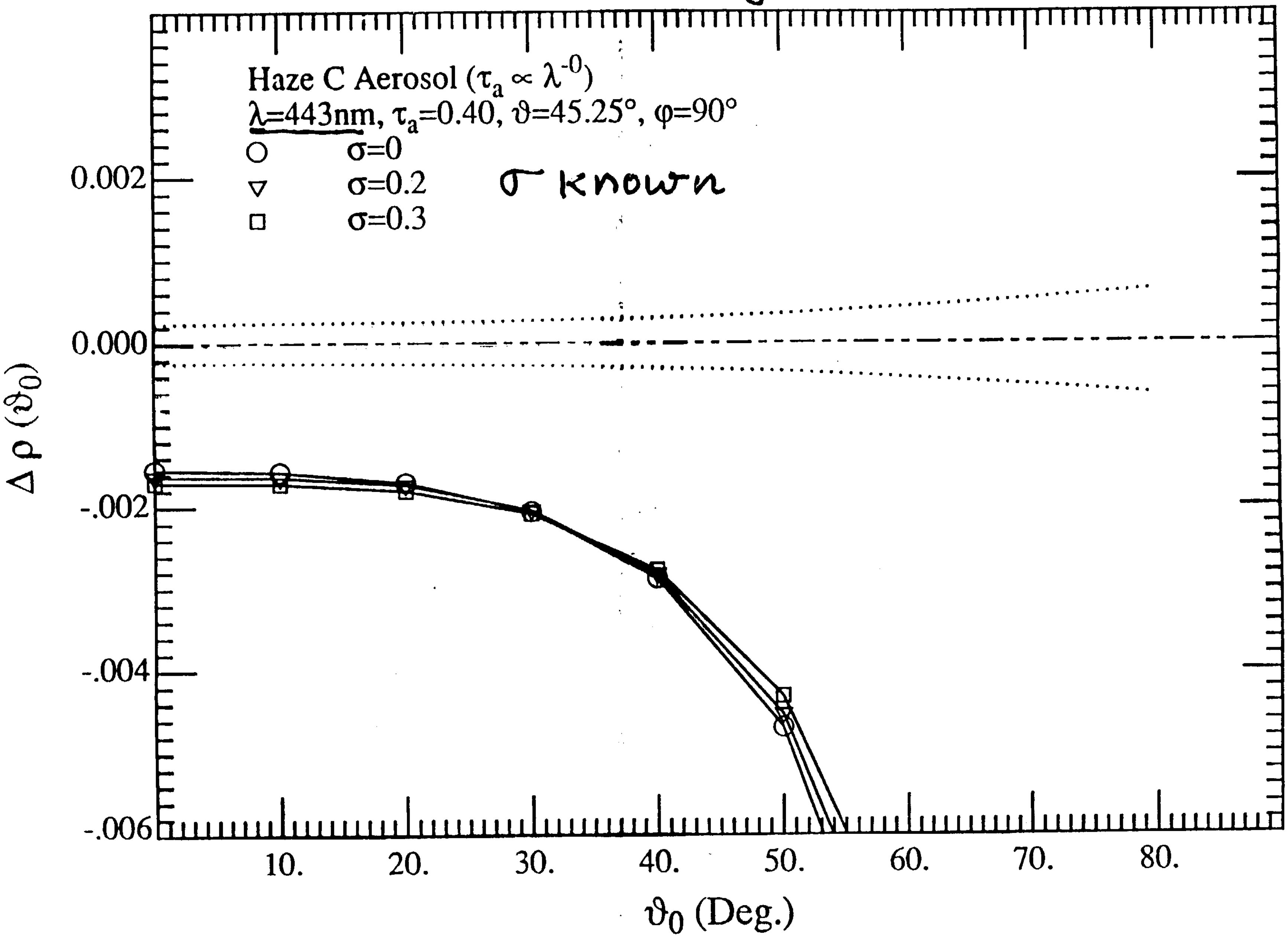
1. ASSUME CZCS BANDS AT 443, 565, AND 665 NM.
2. ASSUME $C < 0.25$ MG/M^3 $\Longrightarrow \rho_w(565)$ AND $\rho_w(665)$ AND KNOWN.
3. USE ALGORITHM TO FIND $\rho_w(443) \Longrightarrow C$.

IN SUCH A SCENARIO, WE KNOW $C < 0.25$ MG/M^3 AND ARE TRYING TO FIND ITS ACTUAL VALUE. THIS SITUATION OFTEN OCCURS WITH CZCS, E.G., THE SARGASSO SEA IN SUMMER.

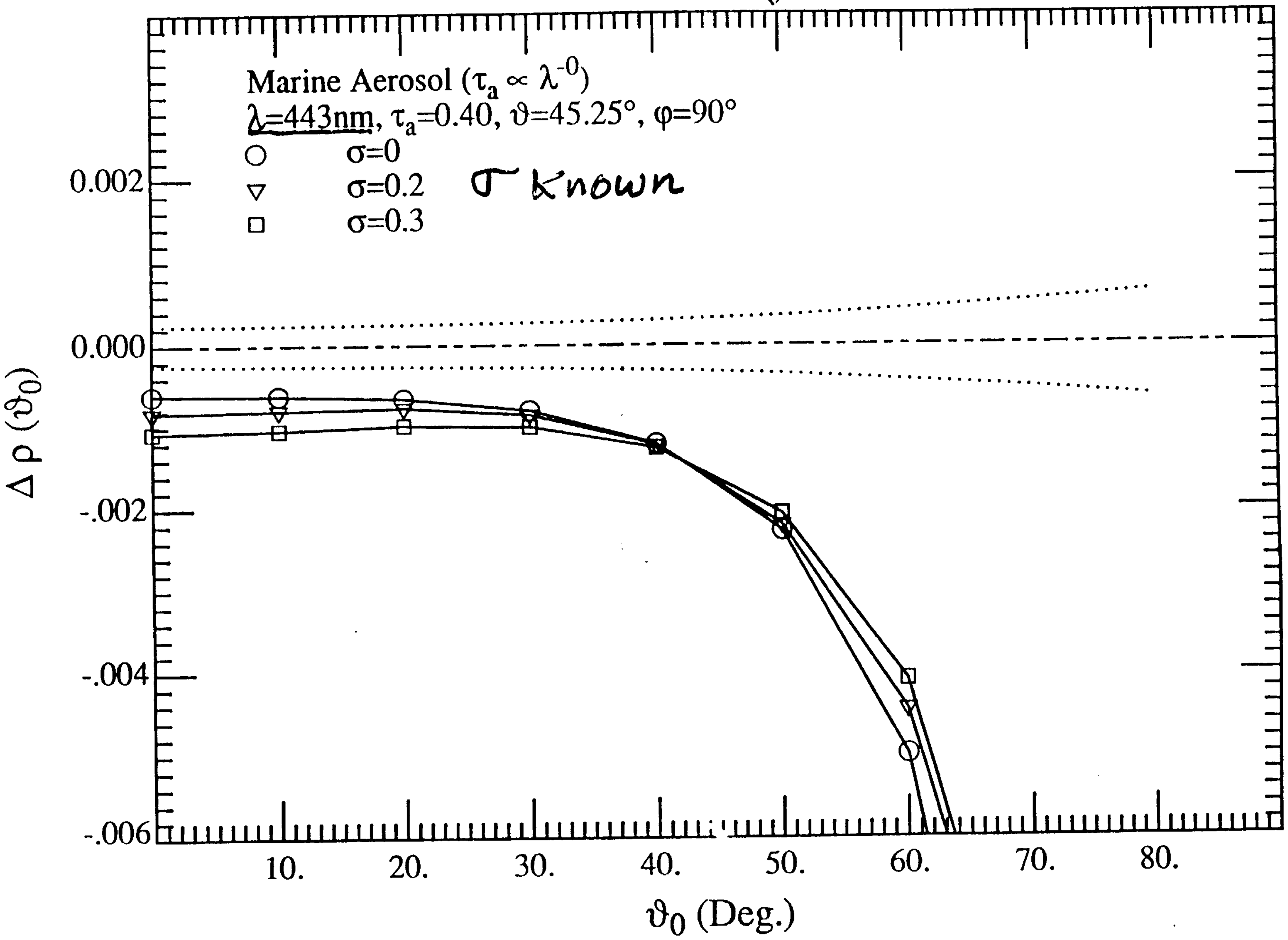

10^{+2}
10^{+1}
10^{+0}
10^{-1}
10^{-2}
Phase Function $P(\Theta)$ (Ster^{-1})
$\int_{4\pi} P(\Theta) d\Omega = 4\pi$
Haze L
Haze C
MARINE
20.
40.
60.
80.
100.
120.
140.
160.
Scattering Angle Θ (Deg.)

Figur 2

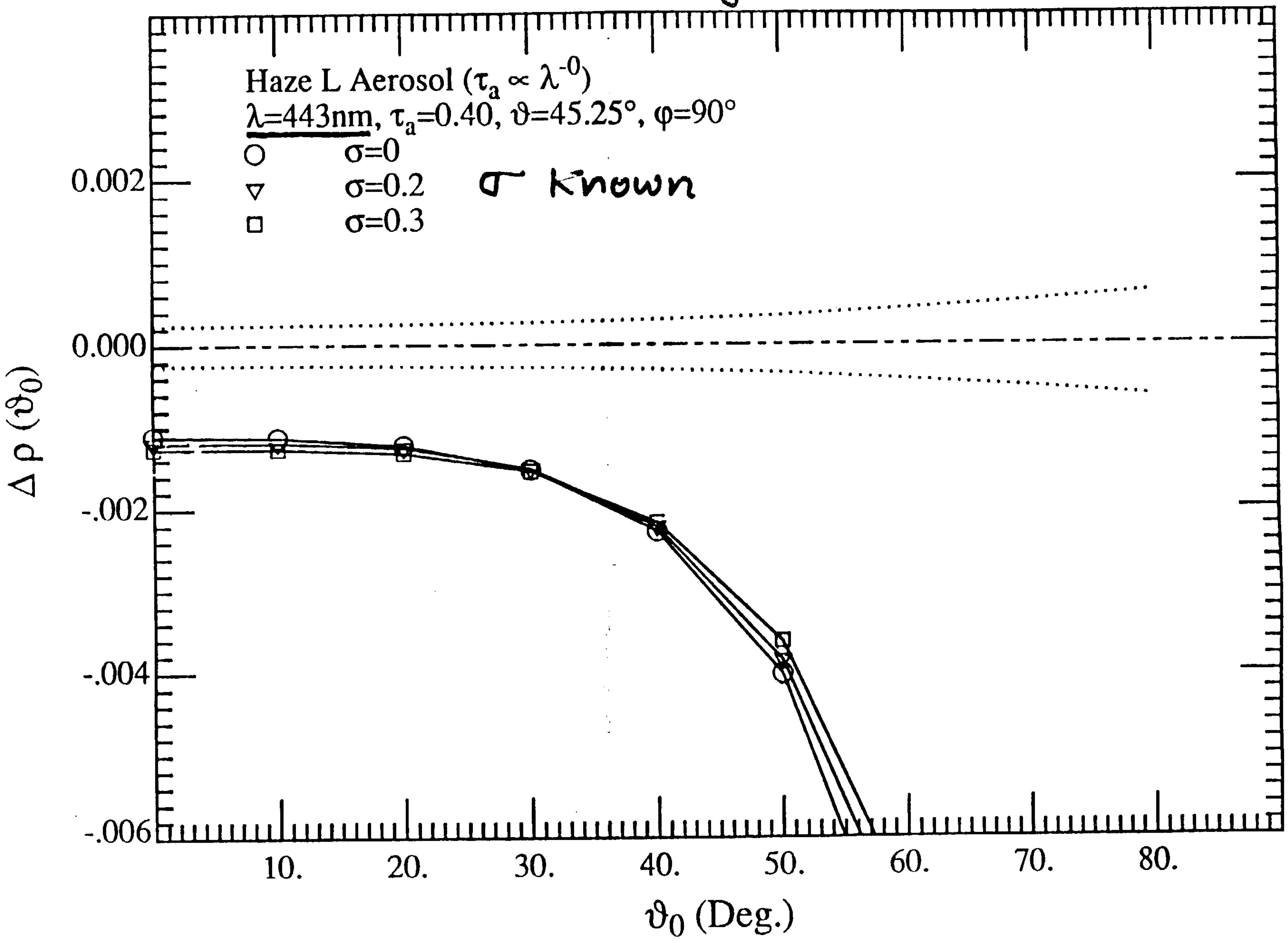
CZCS Algorithm



CZCS Algorithm



CZCS Algorithm



Sketch of Preliminary Algorithm Ideas

ASSUME ρ_w IS KNOWN AT 565 AND 665 AND DESIRED AT 443.

COMPUTE ρ_t INCLUDING ALL PROCESSES AND ρ_r WHICH IS ρ_t WHEN THERE IS NO AEROSOL.

THEN SINCE

$$\rho_t = \rho_r + \rho_a + \rho_{ra} + t\rho_w$$

WE HAVE

$$\rho_a + \rho_{ra} = \rho_t - \rho_r - t\rho_w$$

WHICH PROVIDES $\rho_a + \rho_{ra}$ AT 565 AND 665 NM.

FROM THESE WE MUST ESTIMATE $\rho_a + \rho_{ra}$ AT 443 NM.

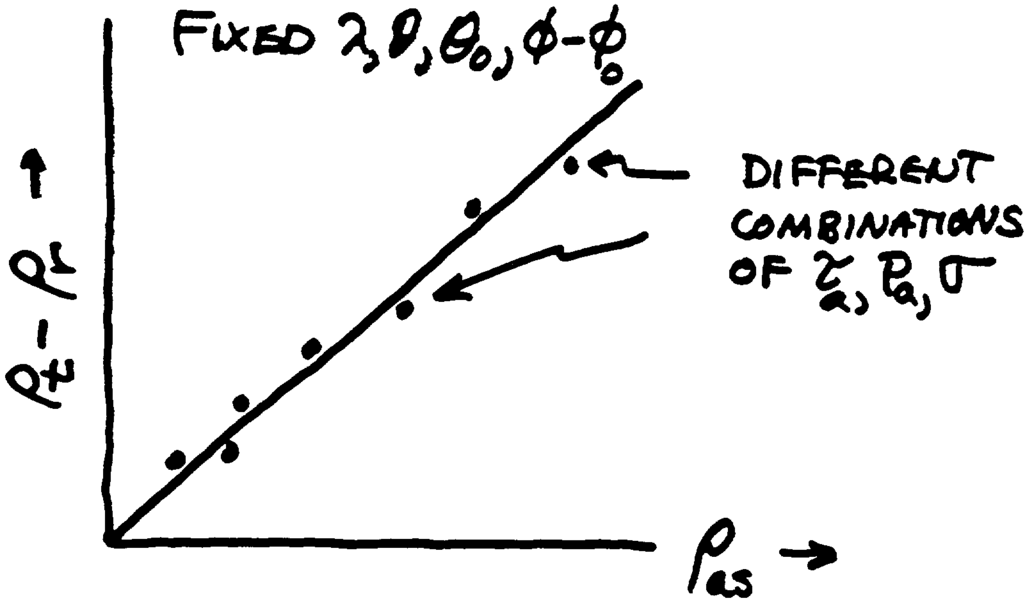
TO DO THIS WE FOLLOW GORDON AND CASTANO (1989) AND RELATE $\rho_a + \rho_{ra}$ TO ρ_{as} — THE AEROSOL REFLECTANCE IN THE SINGLE SCATTERING/FLAT OCEAN APPROXIMATION:

$$\rho_{as} = \omega_a(\lambda)\tau_a(\lambda)p_a(\theta, \theta_0, \lambda)/4\pi \cos\theta \cos\theta_0,$$

WHERE

$$p_a(\theta, \theta_0, \lambda) = P_a(\theta_-, \lambda) + \big(\rho(\theta) + \rho(\theta_0)\big)P_a(\theta_+, \lambda),$$

$$\cos\theta_\pm = \pm\cos\theta_0 \cos\theta - \sin\theta_0 \sin\theta \cos(\phi - \phi_0).$$

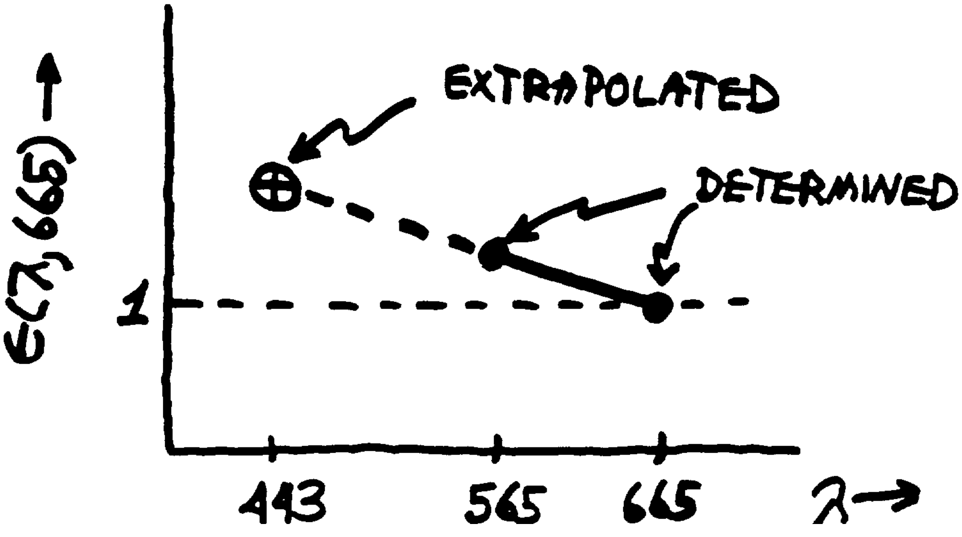


$$\rho_t(\lambda) - \rho_r(\lambda) = C_1(\lambda) + C_2(\lambda)\rho_{as}(\lambda)$$

Then,

$$\frac{\rho_{as}(\lambda_i)}{\rho_{as}(\lambda_j)} = \frac{\omega_a(\lambda_i)\tau_a(\lambda_i)p_a(\theta,\theta_0,\lambda_i)}{\omega_a(\lambda_j)\tau_a(\lambda_j)p_a(\theta,\theta_0,\lambda_j)} \equiv \epsilon(\lambda_i,\lambda_j)$$

Now, since $\rho_w(565)$ and $\rho_w(665)$ are known, $\rho_{as}(565)$ and $\rho_{as}(665)$ can be determined. These provide $\epsilon(565,665)$ and $\epsilon(665,665)$, and we extrapolate to find $\epsilon(443,665)$



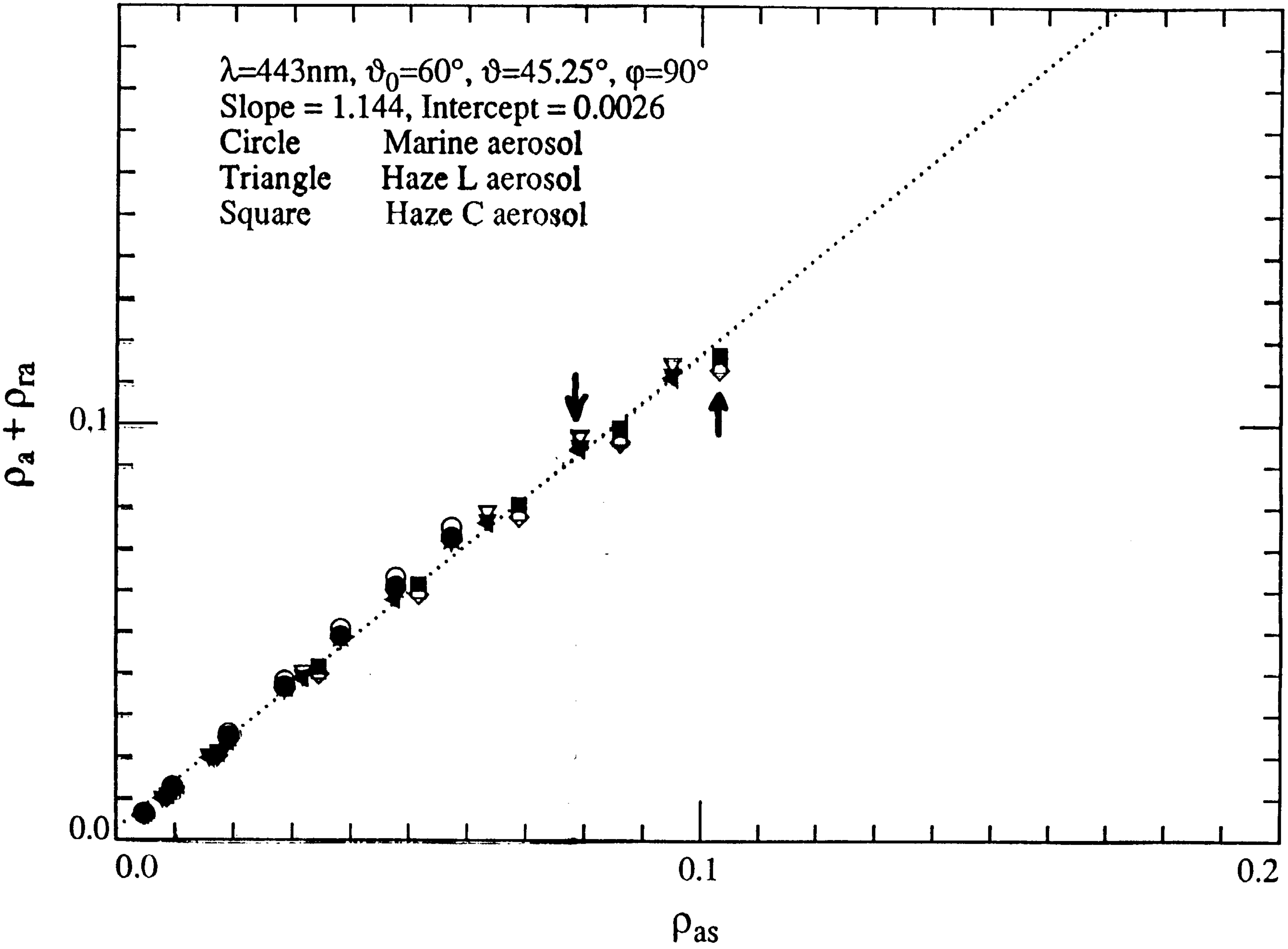
FINALLY,

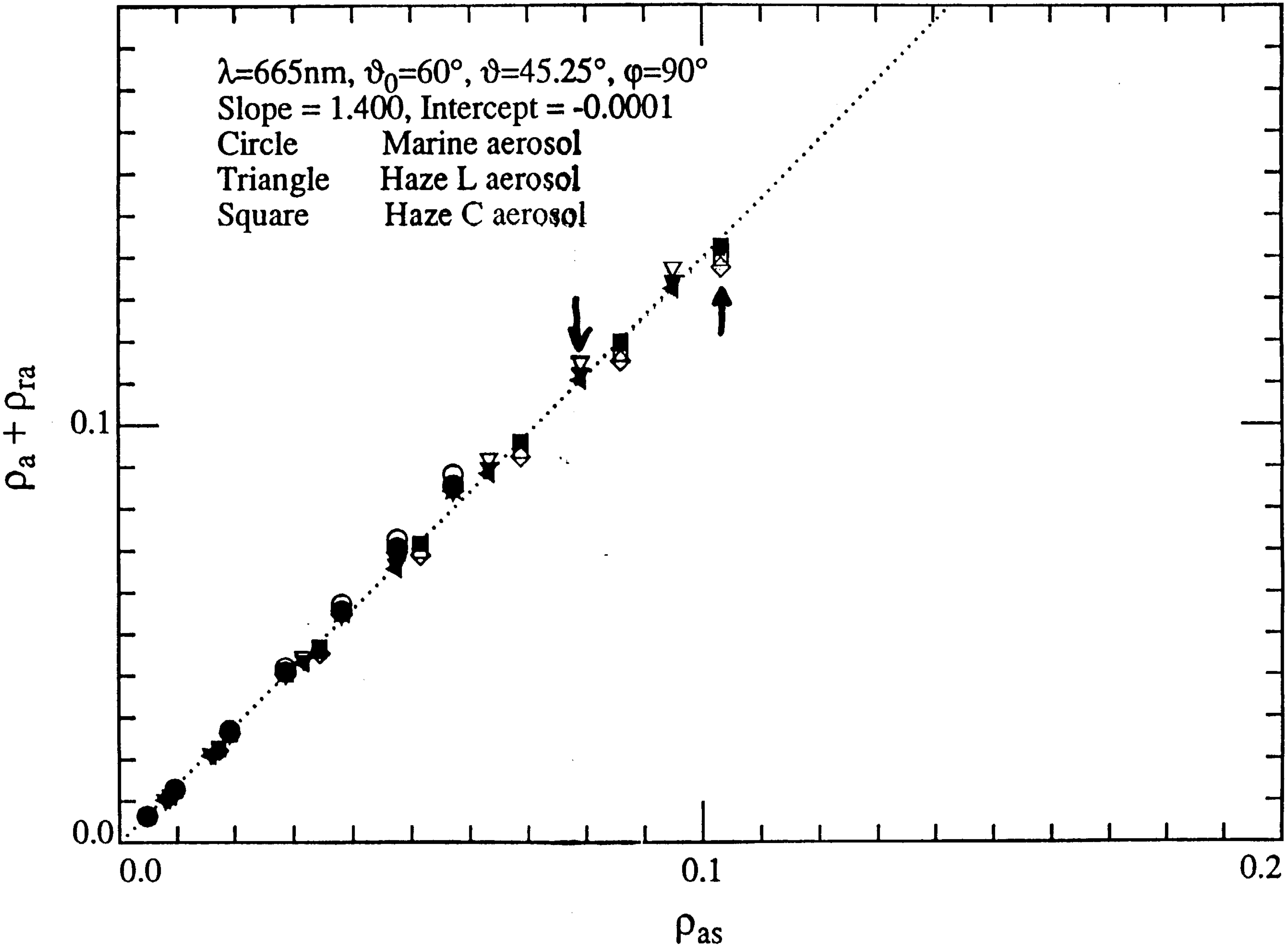
$$\rho_{as}(443) = \epsilon(443, 665)\rho_{as}(665)$$

AND

$$\underbrace{\rho_a(443) + \rho_{ra}(443)} = C_1(443) + C_2(443)\,\rho_{as}(443)$$

$$t(443)\rho_w(443) = \underset{\substack{\uparrow \\ \text{MEASURED}}}{\rho_t(443)} - \underset{\substack{\uparrow \\ \text{CALCULATED}}}{\rho_r(443)} - \overbrace{\rho_a(443) - \rho_{ra}(443)}^{\downarrow}$$


λ=443nm, ϑ0=60°, ϑ=45.25°, φ=90°
Slope = 1.144, Intercept = 0.0026
Circle Marine aerosol
Triangle Haze L aerosol
Square Haze C aerosol
0.1
0.0
0.0
0.1
0.2
ρa + ρra
ρas


λ=665nm, ϑ0=60°, ϑ=45.25°, φ=90°
Slope = 1.400, Intercept = -0.0001
Circle Marine aerosol
Triangle Haze L aerosol
Square Haze C aerosol
0.0
0.1
0.0
0.1
0.2
ρa + ρra
ρas

TEST OF PROPOSED ALGORITHM

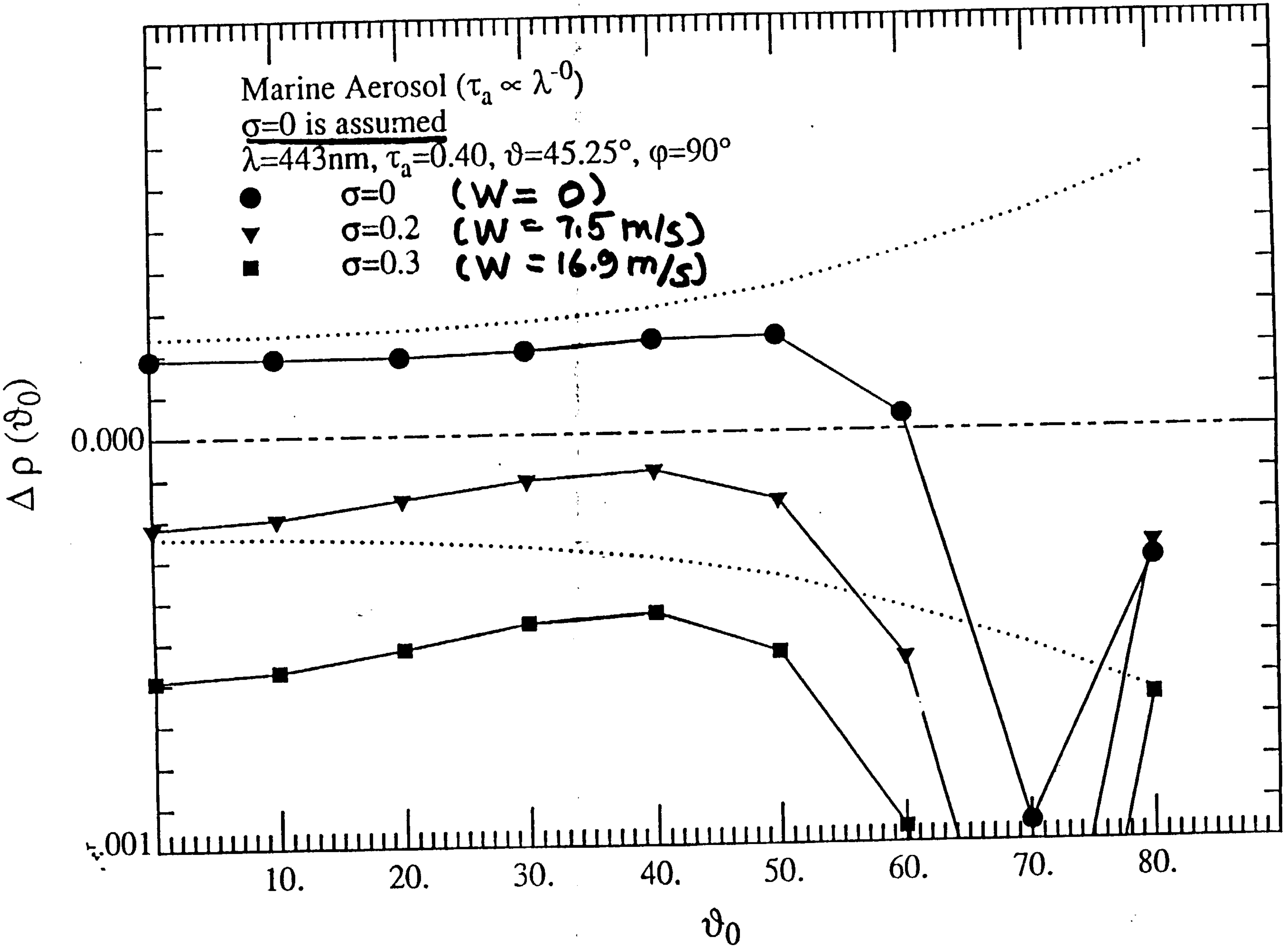
TEST ALGORITHM VIA SIMULATION IN THE SAME MANNER AS BEFORE:

1. ASSUME THE SENSOR IS A MORE SENSITIVE CZCS, I.E., BANDS AT 443, 565, AND 665 NM.

2. ASSUME $C < 0.25$ MG/M$^3 \Longrightarrow \rho_w(565)$ AND $\rho_w(665)$ AND KNOWN.

3. USE ALGORITHM TO FIND $\rho_w(443) \Longrightarrow C$.

IN SUCH A SCENARIO, WE KNOW $C < 0.25$ MG/M^3 AND ARE TRYING TO FIND ITS ACTUAL VALUE. THIS SITUATION OFTEN OCCURS WITH CZCS, E.G., THE SARGASSO SEA IN SUMMER.



Marine Aerosol ($\tau_a \propto \lambda^{-0}$)
σ=0 is assumed
λ=443nm, τ_a=0.40, ϑ=45.25°, φ=90°
● σ=0 (W= 0)
▼ σ=0.2 (W = 7.5 m/s)
■ σ=0.3 (W = 16.9 m/s)
0.000
-.001
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0
$\Delta\rho(\vartheta_0)$

Figure 6.

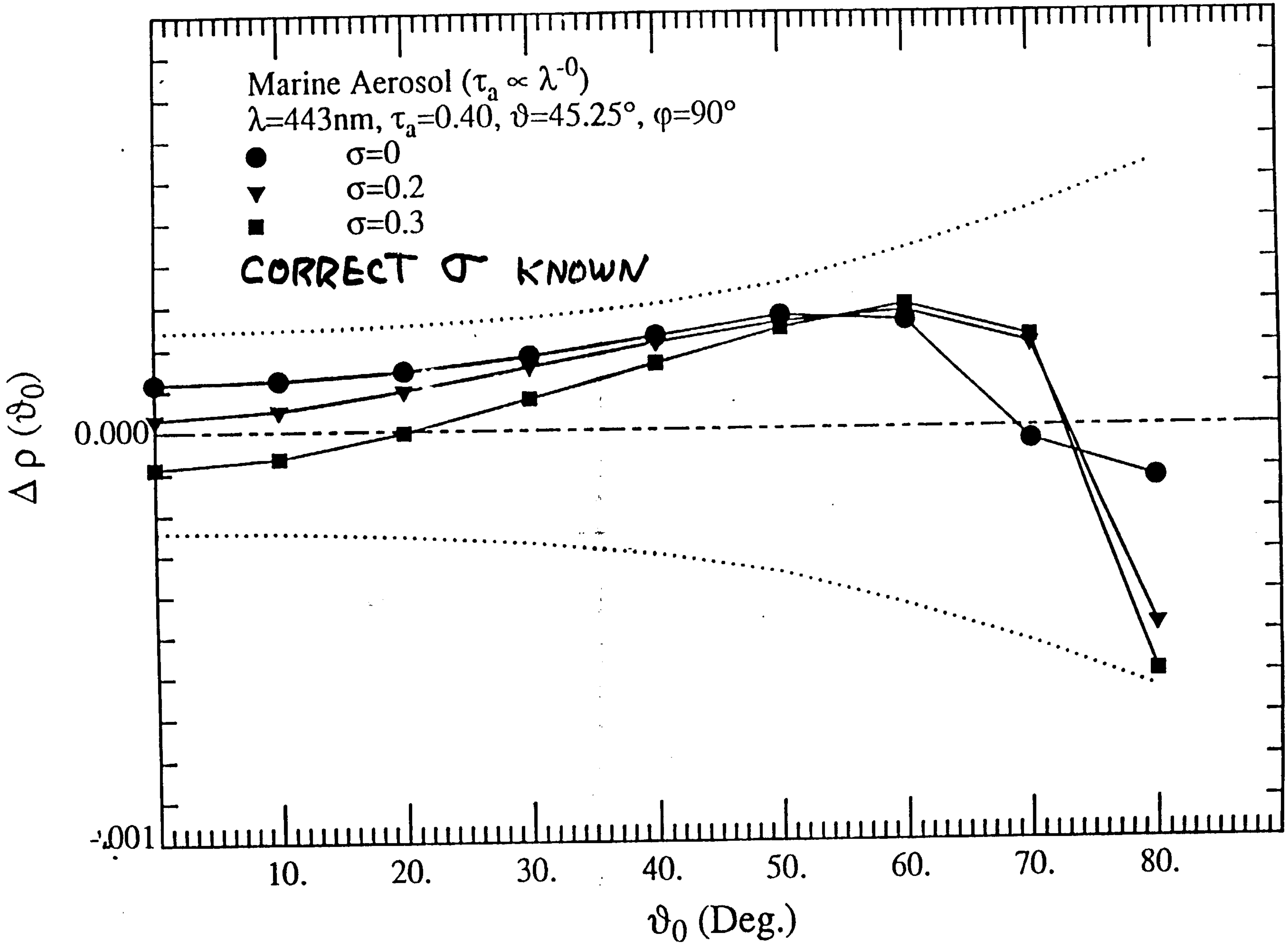
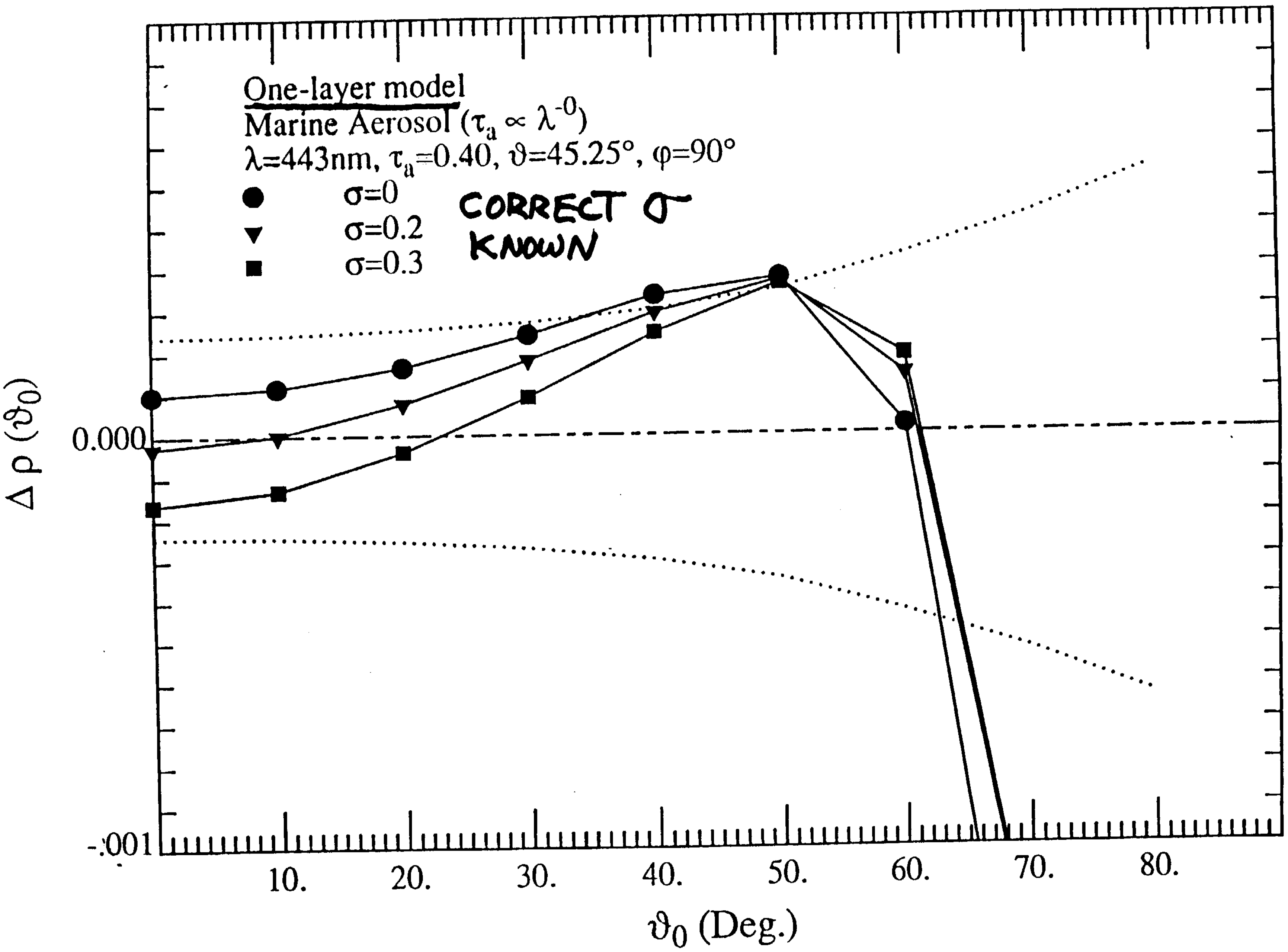

Marine Aerosol ($\tau_a \propto \lambda^{-0}$)
λ=443nm, τ_a=0.40, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
CORRECT σ KNOWN
0.000
-.001
$\Delta\rho(\vartheta_0)$
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0 (Deg.)

Figure 7


One-layer model
Marine Aerosol ($\tau_a \propto \lambda^{-0}$)
λ=443nm, τ_a=0.40, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
CORRECT σ KNOWN
$\Delta\rho(\vartheta_0)$
0.000
-.001
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0 (Deg.)

Figu 2 10.

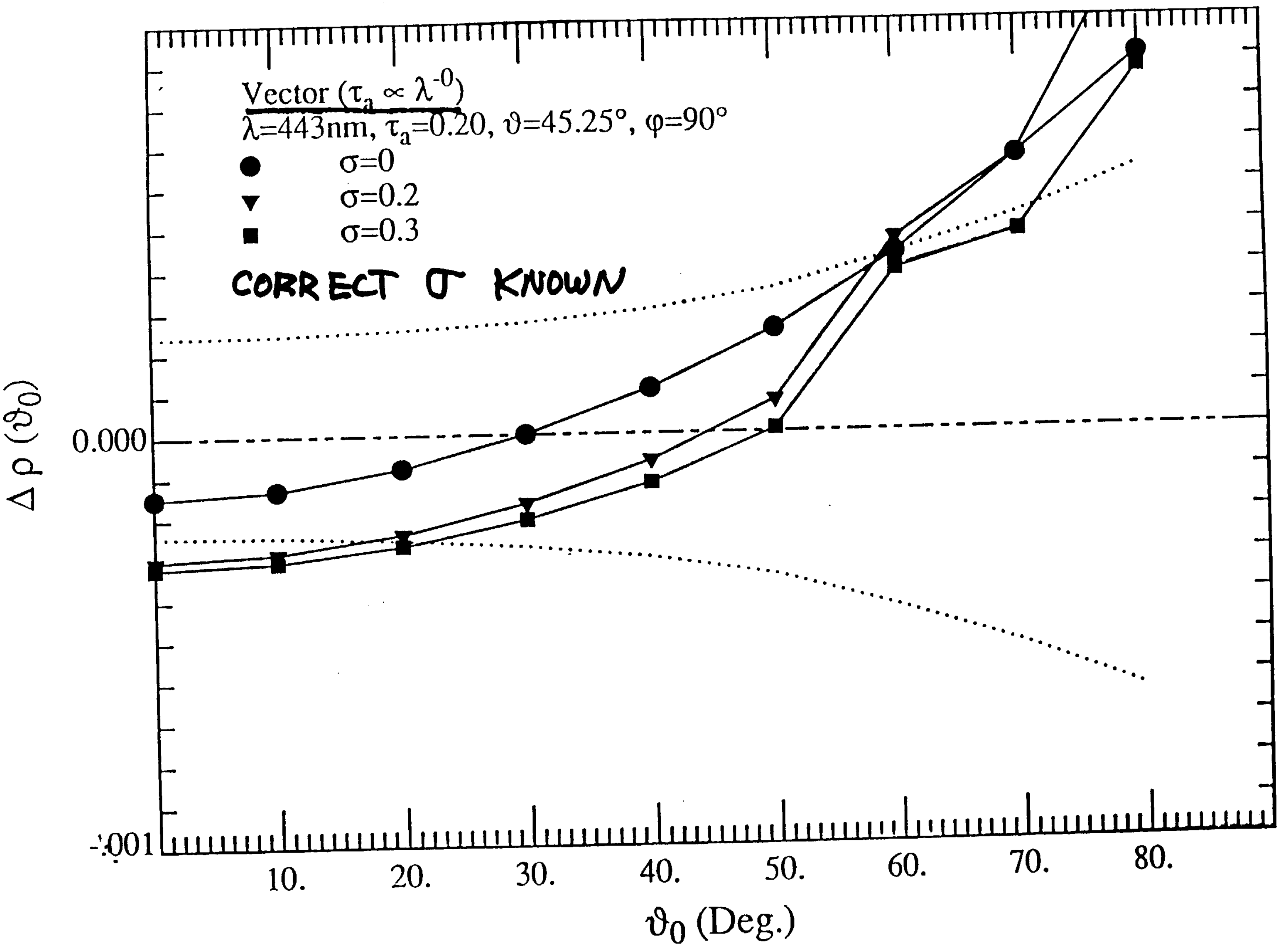

Vector ($\tau_a \propto \lambda^{-0}$)
λ=443nm, τ_a=0.20, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
CORRECT σ KNOWN
$\Delta\rho(\vartheta_0)$
0.000
-.001
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0 (Deg.)

Figure 17

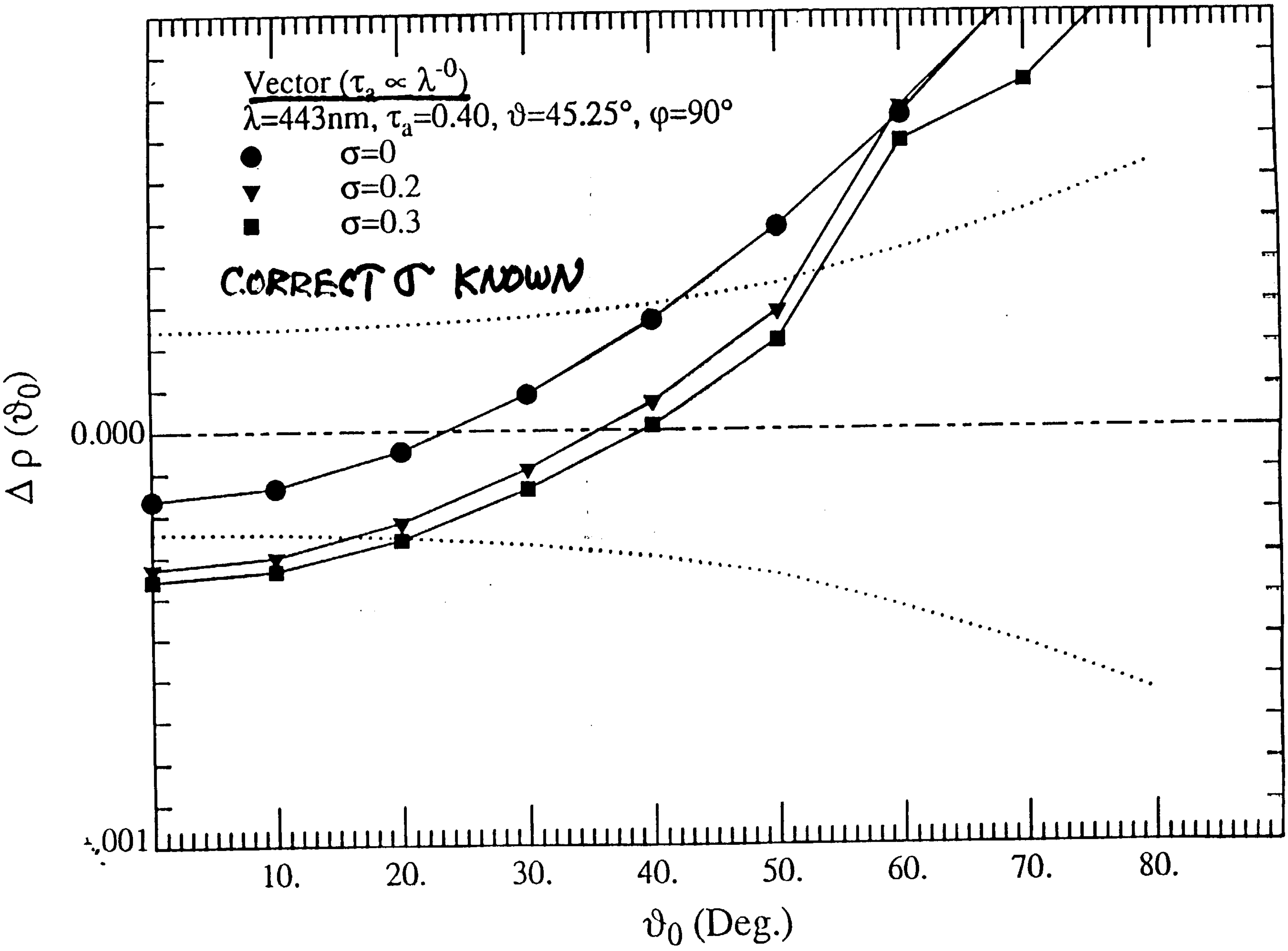
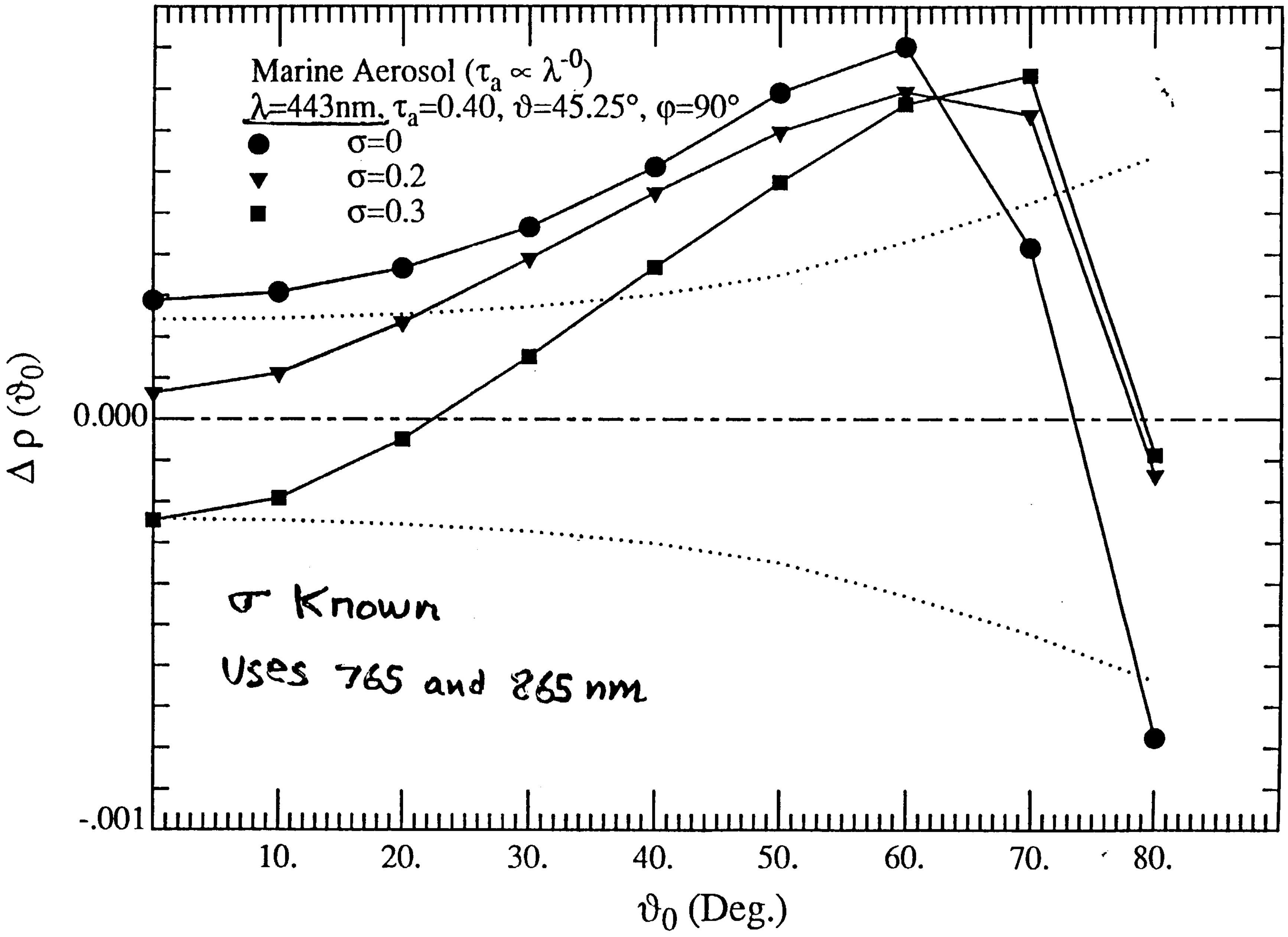
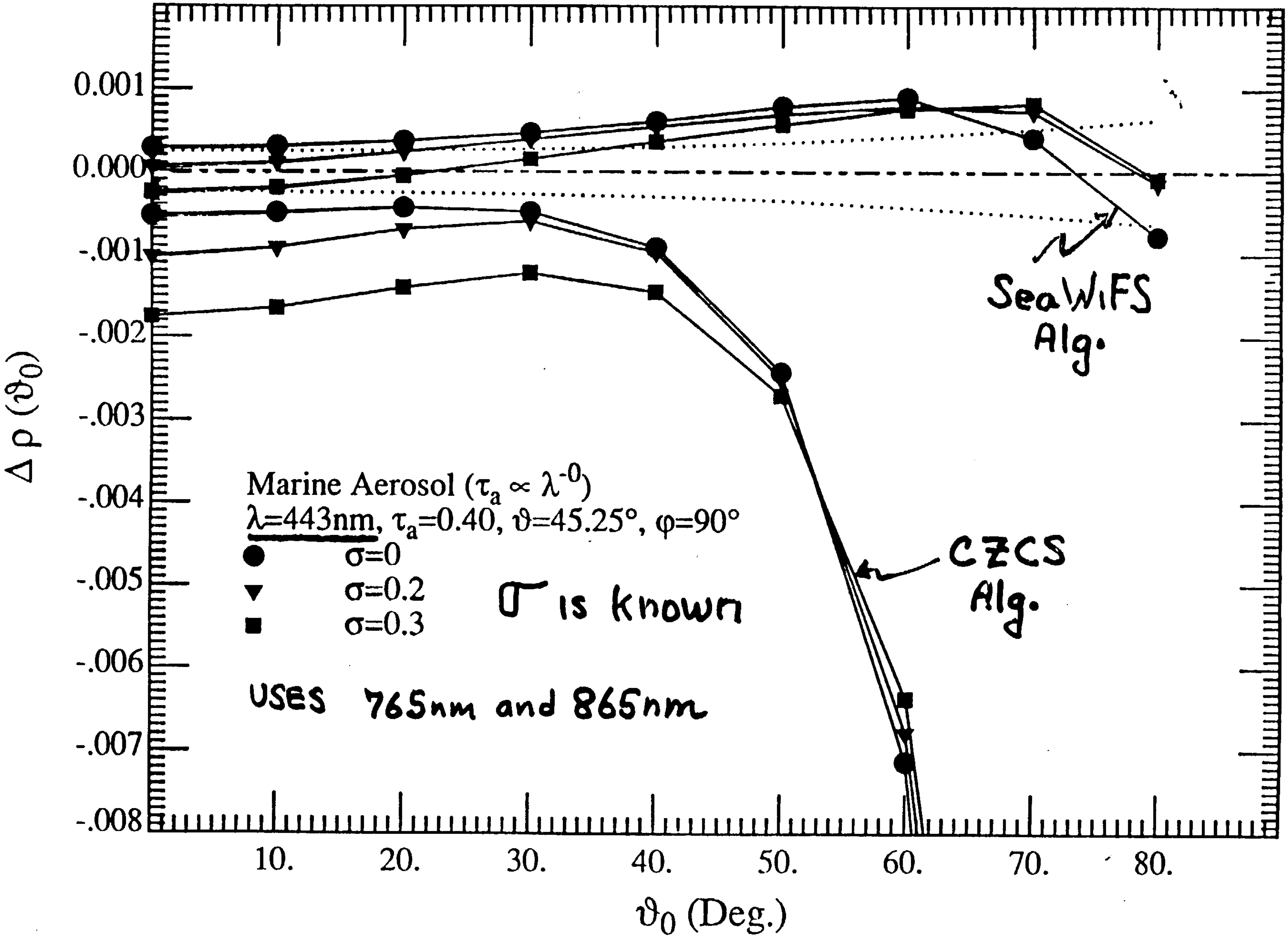

Vector ($\tau_a \propto \lambda^{-0}$)
λ=443nm, τ_a=0.40, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
CORRECT σ KNOWN
$\Delta\rho(\vartheta_0)$
0.000
-.001
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0 (Deg.)

Figure 18


Marine Aerosol ($\tau_a \propto \lambda^{-0}$)
λ=443nm, τ_a=0.40, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
σ Known
Uses 765 and 865 nm
0.000
-.001
$\Delta\rho(\vartheta_0)$
10.
20.
30.
40.
50.
60.
70.
80.
ϑ_0 (Deg.)


0.001
0.000
-.001
-.002
-.003
-.004
-.005
-.006
-.007
-.008
Δ ρ (ϑ0)
10.
20.
30.
40.
50.
60.
70.
80.
ϑ0 (Deg.)
Marine Aerosol (τa ∝ λ-0)
λ=443nm, τa=0.40, ϑ=45.25°, φ=90°
● σ=0
▼ σ=0.2
■ σ=0.3
σ is known
USES 765nm and 865nm
CZCS Alg.
SeaWiFS Alg.

WHAT'S NEXT ?

1. DEVELOP CODE FOR TESTING ON CZCS DATA
    - A. LOW LATITUDE — EXPECT LITTLE DIFFERENCE
    - B. HIGH LATITUDE — EXPECT IMPROVEMENT
    - C. CZCS CALIBRATION COULD BE A PROBLEM

2. IMPLEMENTATION FOR SEAWIFS PROCESSING
    - A. NEED τ_{Oz}, P_0, WINDS (R. EVANS)
    - B. NEED ρ_r FOR VARIOUS WIND SPEEDS
    - C. NEED C_1 AND C_2 FOR ALL SCENARIOS
    - D. NEED TO STUDY ϵ EXTRAPOLATION

3. IS IT VIABLE FOR MODIS?
    - A. INVESTIGATE MORE CASES
    - B. COMPUTE C_1 AND C_2 USING VECTOR THEORY
    - C. SEAWIFS EXPERIENCE

4. WHAT MORE IS REQUIRED FOR MODIS?
    - A. DEVELOP AN ACCURATE WHITECAP MODEL
    - B. LOOK AT VARIATION OF ρ_w WITH VIEW ANGLE
    - C. EARTH CURVATURE AFFECTS
    - D. REMOVE RESIDUAL INSTRUMENT POLARIZATION