Modal Excitation of Optical Fibers

Initial Results: Calculation of Modal Power Distribution

J.S. Abbott *TIA 2.2tg DRAFT NOTES* June 25, 1998

1. Summary/Outline

This note is a continuation for the June 15,1998 note [1] which summarized the derivation of the method. It summarizes initial results showing the calculation of the mode power distribution P_m in a multimode fiber from the measured near field intensity $I(r)$, measured at the end of a length L. The calculations use the modal functions $\psi_m(r)$ and assume that the near field intensity can be expressed as the sum

$$I(r) = \sum_m P_m \psi_m^2(r)$$

The results included here include two theoretical examples and two examples using actual data. The examples are:

1. (Figures 3, 4) Calculation of P_m if $I(r)$ is simply the fundamental mode ($P_m = 1$ for mode 1) and looks like a Gaussian. The method works perfectly.

2. (Figures 5, 6) Calculaton of P_m if $I(r)$ is due to equal excitation of all modes ($P_m = 1$ for all modes) and looks like a parabola. The method works perfectly.

3. (Figures 7, 8) Calculation of P_m if $I(r)$ has a narrow multipeaked shape (possibly a 780nm CD-laser). The method has problems and this example warrants further discussion.

4. (Figures 9, 10) Calculation of P_m if $I(r)$ has a slightly broader, also multilobed shape (possibly a 850nm VCSEL). The method works but this example also warrants further discussion.

Recall that the MPD calculation method being used is a modified least squares procedure, which calculates the MPD which minimizes a function χ^2_{tot} which includes both a term forcing agreement between the predicted and measured $I(r)$ and a term forcing some sort of smoothness on the P_m's. The parameter controlling this smoothness is denoted by λ_a and the larger λ_a is, the smoother the P_m's will be at the expense (in general) of the agreement between predicted and measured $I(r)$.

2. Results

In these examples the 850nm modes are modeled using 32 mode groups (setting P_m for the 33rd to zero), and we use data at 1um increments for $I(r)$ which also gives 32 points. Conceptually this gives a 32x32 matrix which could be inverted, but the results below with $\lambda_a = 0$ show that this matrix is ill-conditioned.

Figure 3 shows the calculated P_m for the case of a Gaussian input beam optimized for the fundamental mode so that $P_m = 1$ for mode 1 and $P_m = 0$ otherwise. When $\lambda_a = 0$ there is noise but with a very small value of $\lambda_a = 0.0001$ it gives nearly the exact result. If λ_a gets too large the smoothness criterion tries to reduce the abrupt change in P_m from 1 to 0 and hence for this case a smaller λ_a is better. **Figure 4** shows that the recalculated $I_{pred}(r)$ for each λ_a agrees with the original (theoretical) $I(r)$, except for the largest value ($\lambda_a = 0.1$)

Figure 5 shows the calculated P_m for the case of uniform modal excitation so that $P_m = 1$ for all modes (the mode groups have been scaled to account for different groups having a different number of modes). Again when $\lambda_a = 0$ the deconvolving of P_m gives a noisy result but only a small value of λ_a is needed to give the exact result. Note that since the *answer* is P_m = a constant, there is no degradation of the solution as λ_a gets larger and larger. This is a special case. **Figure 6** shows the corresponding $I(r)$, which should be identical to the $I(r)$ curve in figure 2 of the previous note [1], except figure 6 is sampled at 1um intervals. (Figure 6 seems to show a dip at $r = 0$ while figures 1 and 2 show a peak, and this point needs to be explained)

Figure 7 shows the recalculated $I(r)$ for an experimentally measured nearfield and **figure 8** shows the corresponding modal powers P_m. In this case $I(r)$ has a multi-lobed, narrow shape which decays to zero at the outer radii. Figure 7 shows that as λ_a is increased the agreement between prediction and experimental data becomes worse. This is to be expected to some extent with any measured data (the previous examples used theoretically generated data which can be inverted perfectly and the only obstacle is numerical round-off error). However, figure 8 shows that the predicted modal power for mode groups 2 and 3 is *negative* and that increasing λ_a does not fix the problem. What this means is that the modal functions being used do not fit the data. This could be caused by (among other reasons)

1. Bad data (the first choice of theoreticians!)
2. Measurement may be at 780nm (CD-laser?) or there may be some other reason that the 850nm modal functions are a poor fit.
3. The 289 modes have been organized into 32 mode groups assuming uniform power within a group. This may be incorrect; for example, different fractions may be going into radial modes and azimuthal modes or higher order azimuthal modes may not have much power. Only every other mode group has a radial mode.
4. The actual intensity distribution $I(r)$ may have to be analyzed as a two-dimensional distribution $I(x, y)$ or $I(r, \theta)$ (this is related to explanation 3).

Figure 9 shows a second experimentally measured $I(r)$ distribution and the recalculated $I(r)$ for different values of λ_a. Here the agreement is reasonable. **Figure 10** shows the calculated modal powers and in this model the modal powers drop out for certain groups. There isn't a good explanation for why this would happen but with $\lambda_a = 0.016$ all the P_m's are positive or only slightly negative, and there is still reasonable agreement in figure 9. The experimental data in figure 9 does not drop completely to zero at the core radius $r = a$, which causes fitting problems at the outside particularly with P_{32}.

3. Additional Discussion

The shape of $I(r)$ in Figure 9 should be noted. There are obvious waves and the lack of power in the 15-20um region compared to figure 6 suggests the hypothesis that power might be missing from higher order azimuthal modes but not the radial modes.

The modal fitting procedure used here can be extended by separating out the 16 radial modal functions and allowing them to have a weight independent of the azimuthal modes. The procedure can be conceptually be carried to estimates of the power in individual modes although small amounts of noise in the experimental data may be amplified, requiring an improved smoothing procedure.

The experimental data being fitted needs to have been transmitted through a sufficiently long length of fiber so that $I(r)$ has dropped to zero at the outside. Otherwise, the procedure won't work. However, the same point applies to analysis of overfilled launches on short lengths. One solution is to force $P_m = 0$ in the outer mode groups or to force an exponential decrease in P_m in the outer mode groups.

The example in figures 7 and 8 was not satisfactorily fit by the model, because figure 8 shows $P_m < 0$ for groups 2 and 3, which is unphysical. Because the data shows $P_m \approx 0$ for $m > 15$, it may be feasible to refit the $I(r)$ data with a subset of the individual modes and see if there is an improvement. Alternatively, if the data was taken at 780nm, the mode groups can be recalculated for 780nm to see if the fit improves.

Finally, the idea has been raised in the 2.2tg group that lobed or wavy $I(r)$ distributions like Figures 7 and 9 are *prima facie* proof that there is not equal modal power within the mode groups. This is related to but not the same as saying there is at best weak coupling within groups and that the assumption of modal degeneracy is not valid. Much of the nearfield data is taken on extremely short lengths of fiber (20m or less) where coupling cannot have been complete, and hence the interpretation of $I(r)$ data on short lengths needs to take that into account. The question of whether coupling occurs on the $100 - 500m$ lengths corresponding to LANs is a separate issue. For short lengths, there has always been incomplete coupling, and the question is more one of whether the radial and angular (near field and far field) extents of the launch are balanced. This can be checked by measuring the far field power as well as the near field power and comparing the power vs. radius and the power vs. angle. The limit of near field / far field mismatch is the so-called *radial overfill launch* (ROFL) [2] which puts power only into the radial modes. The ROFL launches appear to be among the least desirable for maximizing the worst-case performance of potential problem fibers. The extension of the current procedure described above, which breaks out the radial modes separately, would theoretically be able to identify the ROFL-like character of some launches.

6. References

[1] Abbott, J.S., "Modal Excitation of Optical Fibers: Estimating the Modal Power Distribution", *TIA 2.2tg Draft Notes* June 15, 1998.

[2] The ROFL launch was discussed in detail in the IEEE 802.3z MBI group meetings chaired by David Cunningham of HP Laboratories, Bristol England and is reviewed in the minutes of that group.

Figure 3
Modes calculated from $I_{data}(r)$
$I_{data}(r)$ for P_m=1 mode 1 only
λ_a = 0., .0001, .001, .01, .1
see Figure 4 for corresponding $I_{pred}(r)$
λ_a=0.0001 gives correct P_m (dots)
λ_a=0.0 noisy (squares), =0.1 oversmooths (line)

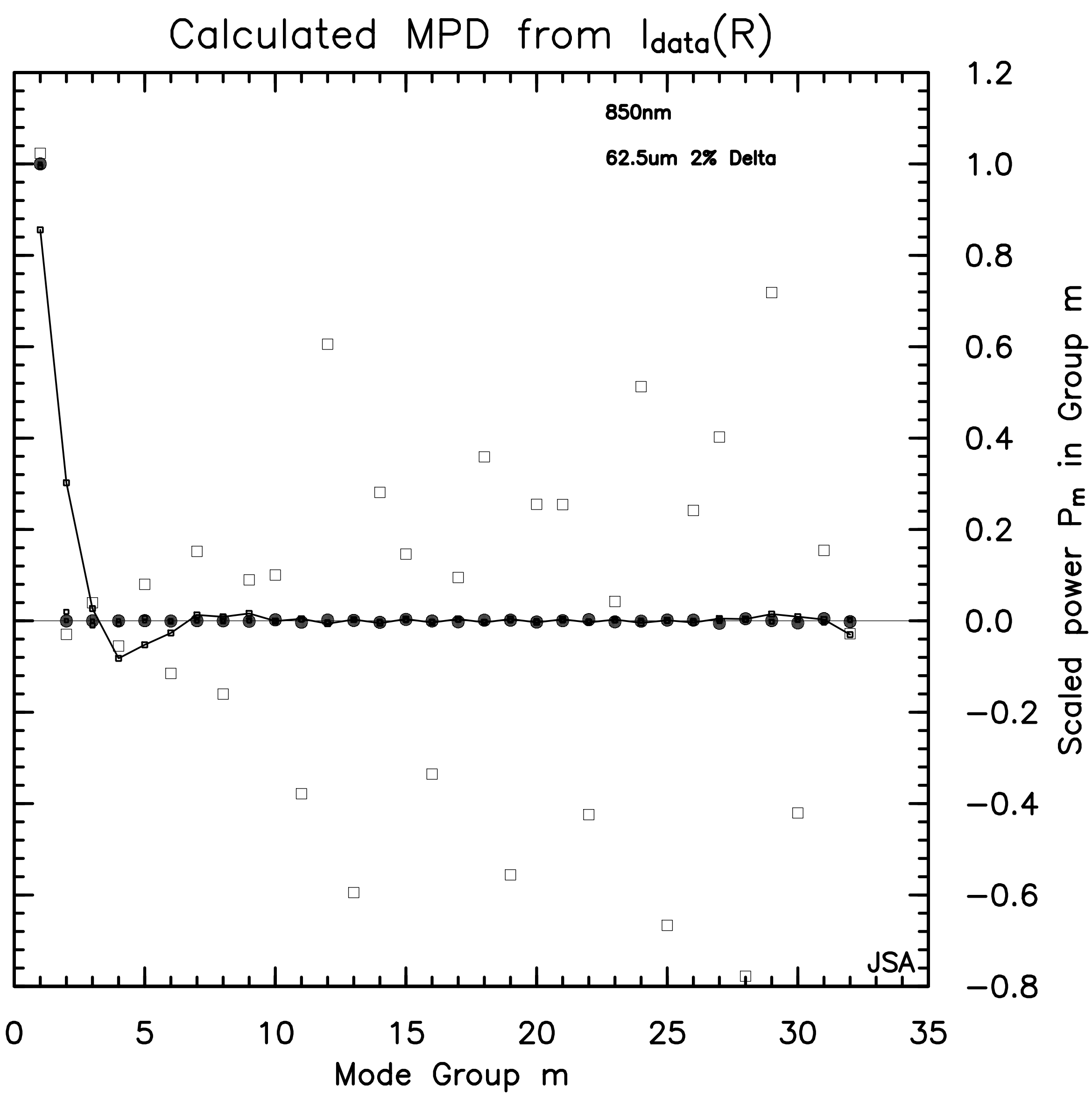

Figure 4

$I_{data}(r)$ and $I_{pred}(r,\lambda_a)$

λ_a = 0.0, 0.0001, 0.001, 0.01, 0.1

$I_{data}(r) = I_{pred}(r)$ except for λ_a=0.1

Hence λ_a up to 0.01 suggested

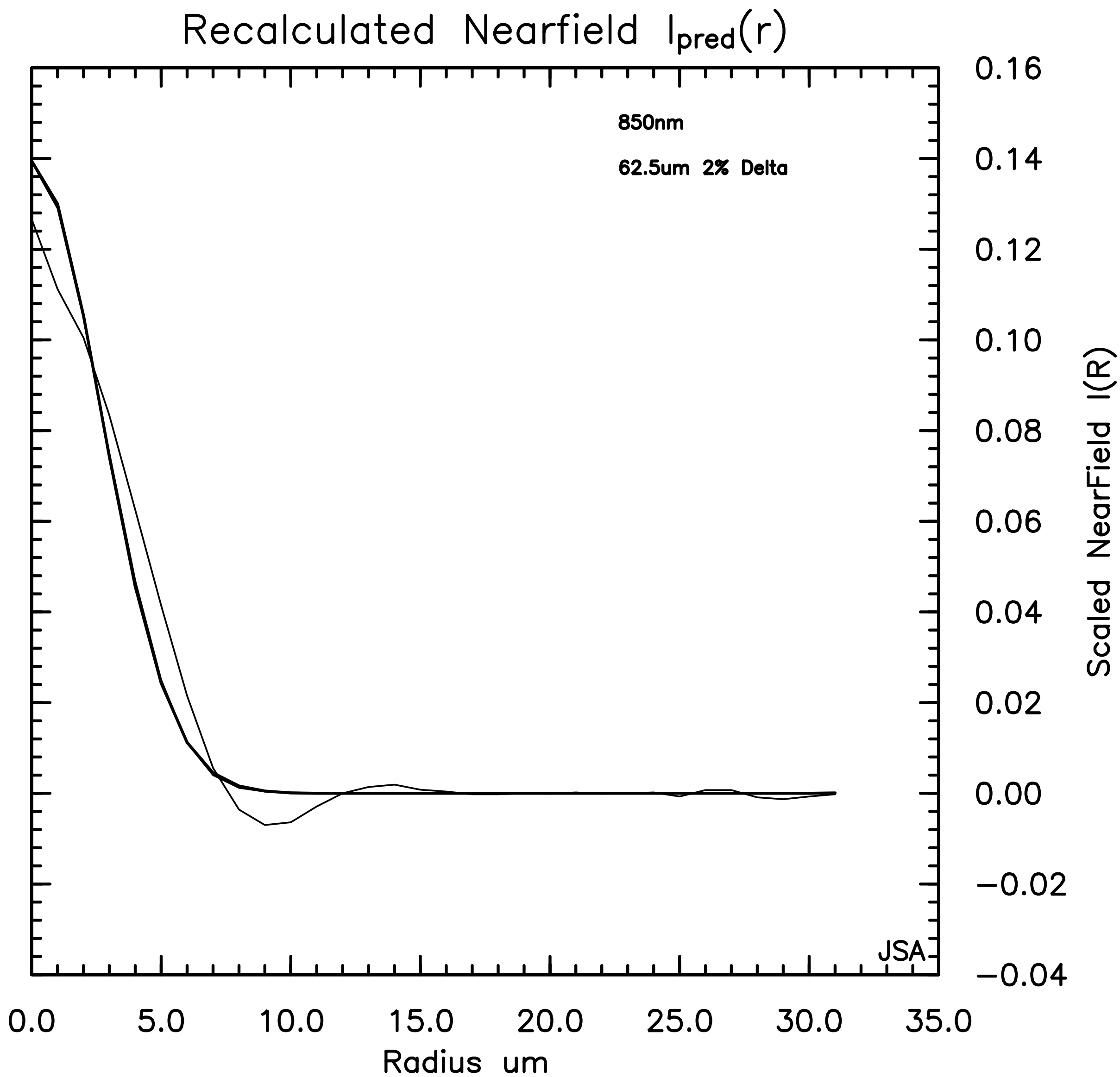

Figure 5
Modes calculated from $I_{data}(r)$
$I_{data}(r)$ for P_m=1 all m
λ_a = 0., .00001, .0001, .001, .01
see Figure 6 for corresponding $I_{pred}(r)$
λ_a=0.0, 0.00001 noisy (squares)
λ_a=0.0001, 0.001 okay (dots/circles)

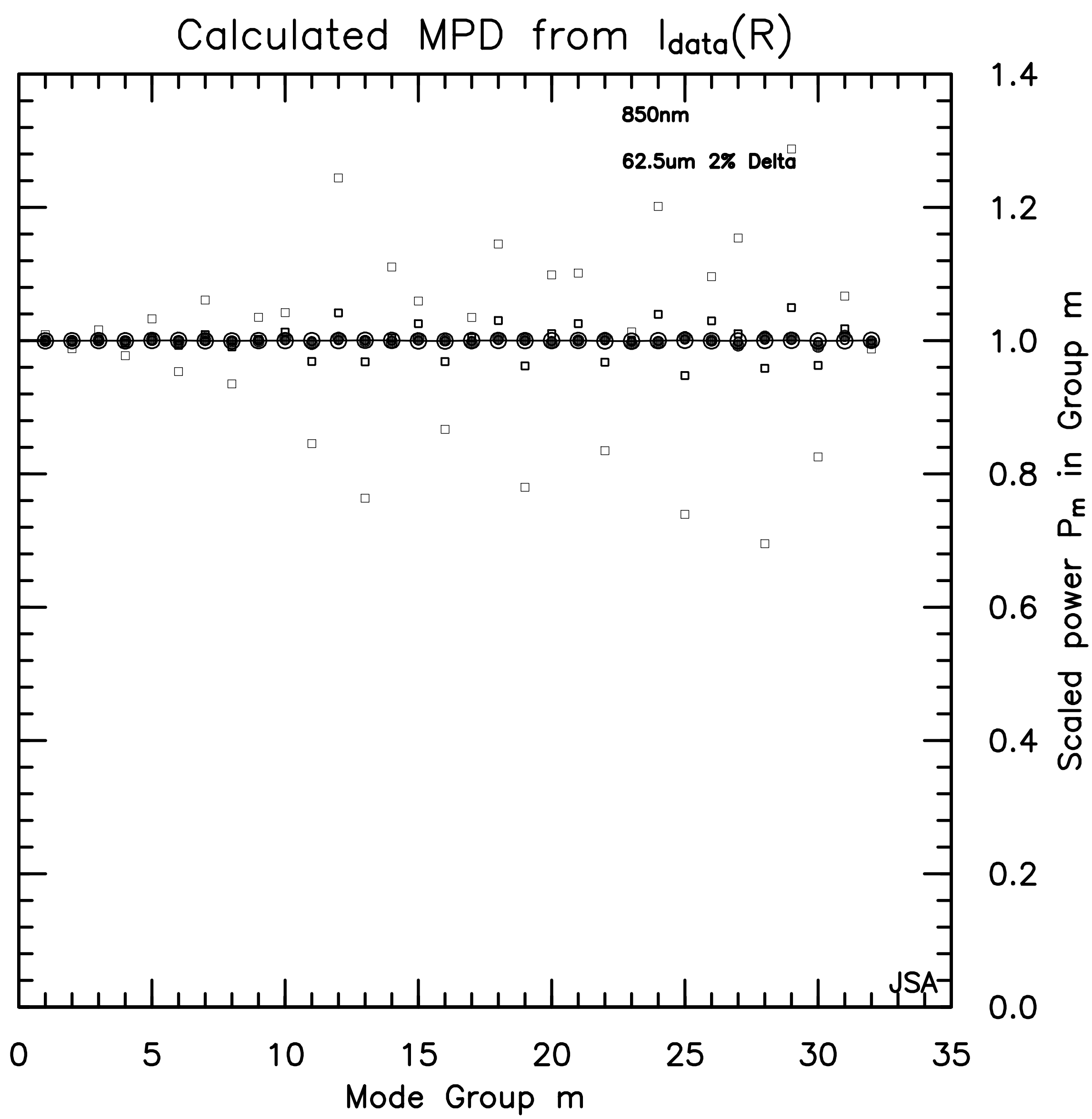

Figure 6
$I_{data}(r)$ (P_m=1 all m) and $I_{pred}(r,\lambda_a)$
For this case $I_{data}(r)$ and $I_{pred}(r)$ are indistinguishable
This is because actual solution is P_m = constant

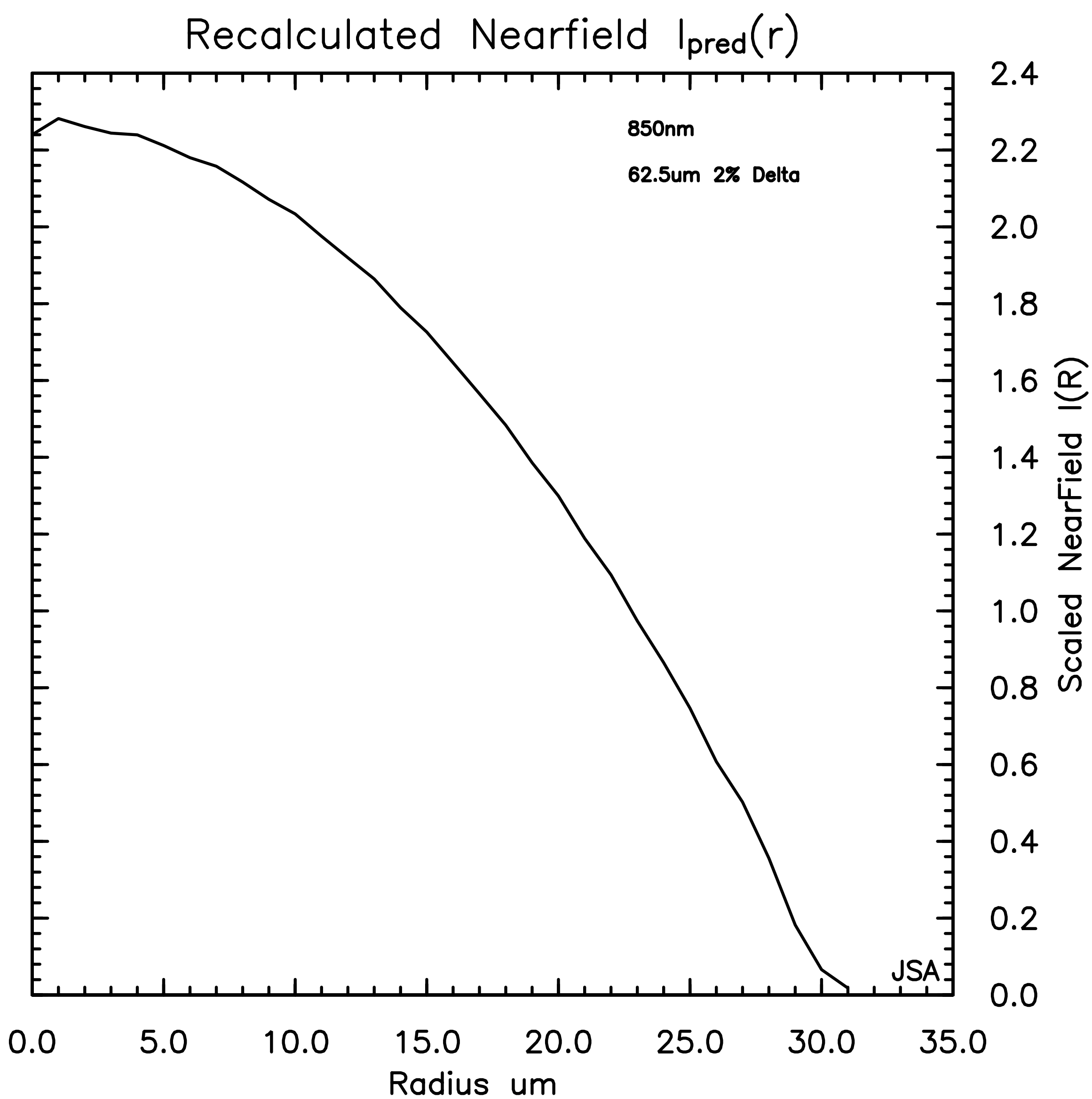

Figure 7

$I_{data}(r)$ (probably taken at 780nm) and $I_{pred}(r,\lambda_a)$

$I_{data}(r)$ and $I_{pred}(r)$ do not agree exactly

See Figure 8:

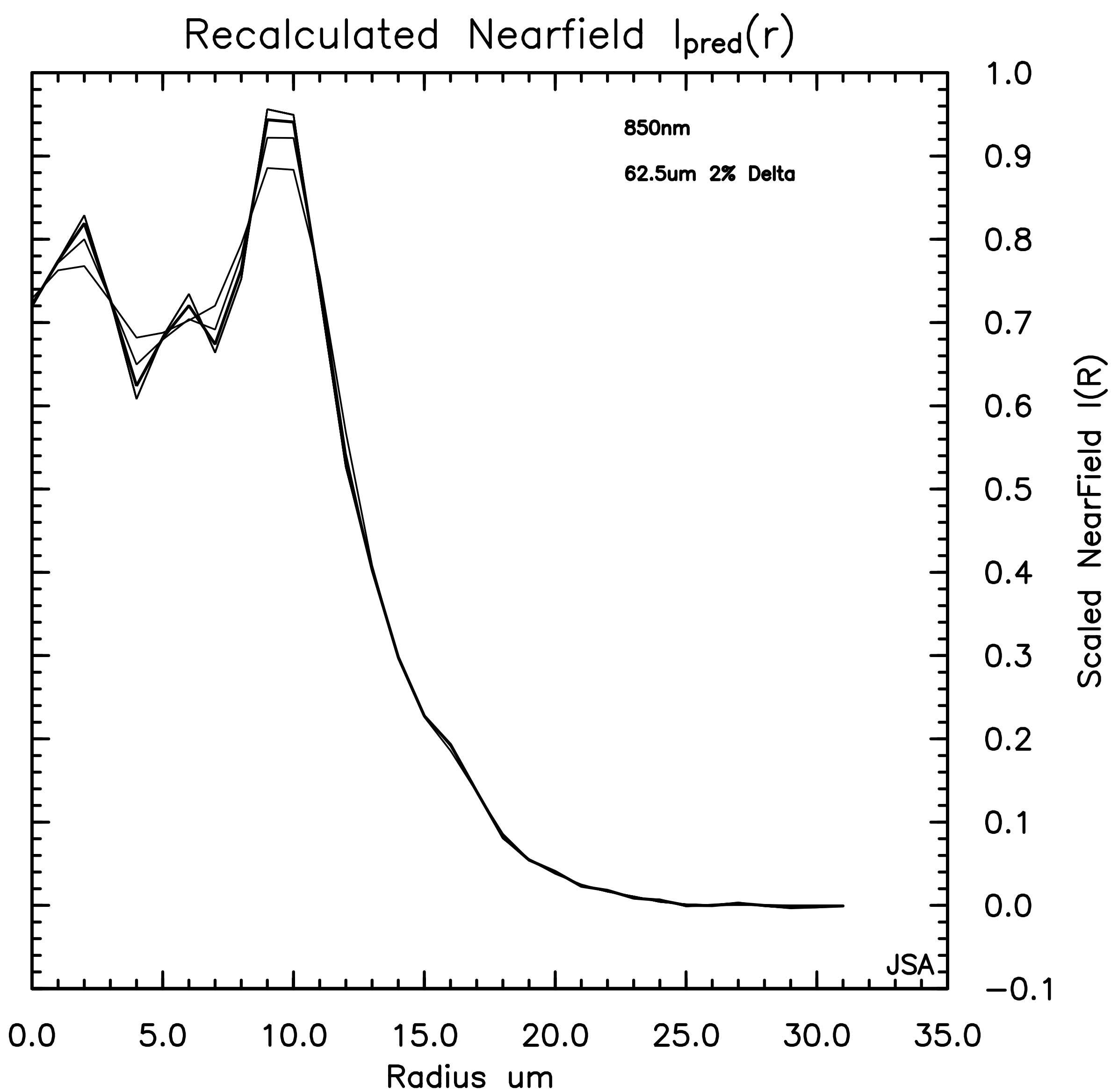

Figure 8
Modes calculated from $I_{data}(r)$
$I_{data}(r)$ measured data (780nm?)
λ_a = 0.0001, .001, .01, .02, .04
P_m<0 for m=2,3 -- model doesn't fit

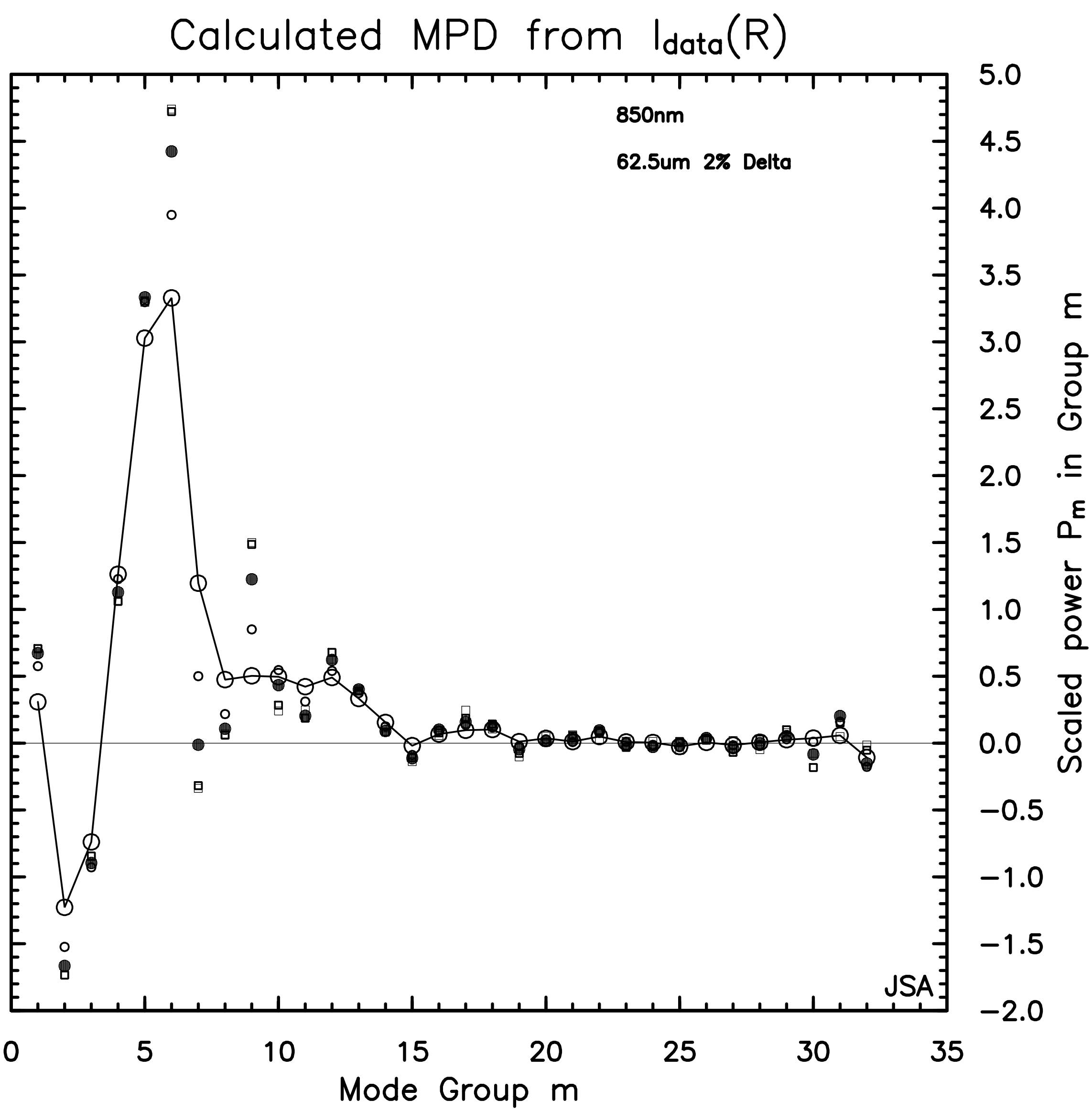

Figure 9

$I_{data}(r)$ (?) and $I_{pred}(r,\lambda_a)$

$I_{data}(r)$ and $I_{pred}(r)$ agree fairly well.

See Figure 10: modal powers are 〉 0 which suggests good agreement

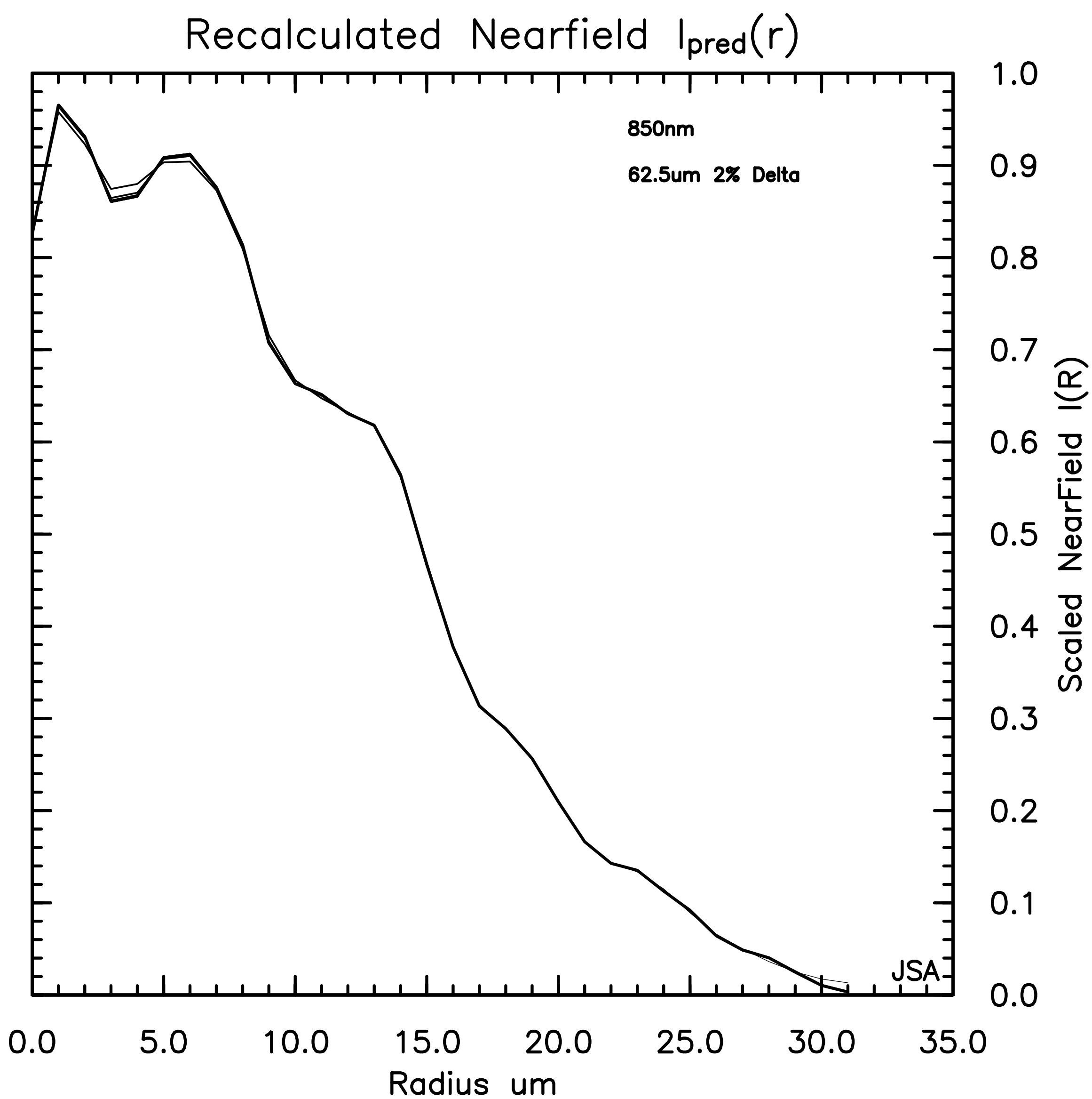

Figure 10
Modes calculated from $I_{data}(r)$
$I_{data}(r)$ measured data (850nm?)
λ_a = 0.001, .002, .004, .008, .016
P_m)0 for -- model fits okay
note that P_{32} is large because $I_{data}(r)$ didn't go to zero