Some fitting results for the DUMAND Dec '93 data

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1 Introduction

This note is to describe the data we got from the DUMAND string # 1 installed into the ocean in Dec '93 and the result of muon track fitting to the selected data, including the most interesting event Shinji found. These data were recorded after the junction box had touched down to the bottom of the ocean. At this moment the string was still attached to the sacrificial anchor through the sacrificial rope. So, the shape of the string was like a bow, as one can see on the module positions listed below.

I have been working on the conversion of the pulse width to photo-electron (PE) number and the event reconstruction on the events decoded and selected by others. Those who should get credit for decoding all the data and eventually finding these events are Shinji Kondo, Bob Svoboda, Dennis Nicklaus, and Russell Clark. Also, Peter Gorham should get credit for reconstructing the string shape and calculating the module position. Of course, I acknowledge the work of the entire DUMAND collaboration, without which we could not have any data at all.

2 Description of "the event"

The list of all the hits involved in the most interesting event ("the event") taken in Dec '93 is shown in Table 1. In this list, all suspected Q pulses of JOM's had been removed. Also the timing diagram of this event is shown in Figure 1. In this diagram, hit ID. is included in each hit. Also, a timing diagram of a muon perpendicular to the string and passing through the string between modules # 4 and 5 is shown as an example.

The PE numbers in Table 1 are calculated based on the module calibration result in the test tank. Due to the longer than normal TOT pulses which start to show up in the data for $\geq$ 100 PE for JOM's and skew the relation between pulse width and PE, the PE conversion is limited up to 100 PE. The results for JOM's are multiplied by a factor of 2 after the conversion to take the difference in the PMT gain between the calibration data and the ocean data into account. This is the reason why hits e, g, and i have $\geq$ 200 PE indicated.

In Table 2, the suspected Q pulses for the hits in Table 1 are listed. Common conversion factors from the Q pulse width to PE were used to calculate PE number, so that the difference in the modules have not been taken into account.

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hit	mod.	pw(ns)	PE ± err.	time(ns)	x(m)	y(m)	z(m)	comment
a.	2	12	0.7± 1.2	7133822	−289.13	0.	150.78	
b.	3	1900	42.± 18.	7133777	−279.26	0.	147.92	EOM(40 ns added)
c.	4	18	2.3± 1.6	7133799	−269.58	0.	144.92	
d.	4	28	14.± 7.0	7133825				
e.	5	56	≥ 200.	7133769	−260.08	0.	141.64	
f.	5	17	1.8± 1.3	7133840				
g.	6	157	≥ 200.0	7133715	−250.59	0.	138.01	
h.	6	6	0.2± 1.7	7133885				might be noise
i.	7	55	≥200	7133732	−241.28	0.	133.89	
j.	7	18	2.3± 1.6	7133804				
k.	7	23	5.7± 3.5	7133855				
l.	8	32	28.± 11.	7133761	−232.16	0.	129.42	
m.	8	18	2.3± 1.6	7133821				

Table 1: TOT pulse list of "the event"

```
   mod #
     ^
     |
     |                            *           ___
 # 2 |                       __*_____| a |_____
     |                        *    _____
 # 3 |              _____*_____| b                              --> 1.9 us
     |                *
     |              *          _____      _____
 # 4 |        *        _____| c  |__| d   |_____
     | *                _____       _____
 # 5 |        *       _____| e          |_____| f  |_____
     |       _____*_____    _
 # 6 | __| g           *                                 |___|h|___
     |        _____*_____      _____       _____
 # 7 |     ____| i            *|____| j  |_____| k      |_____
     |            _____       _____      _____
 # 8 |        _____| l        |_____*| m  |_____
     |                              *
     ++---------+---------+---------+---------+---------+---------+-----> time

      710       740       770       800       830       860       890    (ns)
```
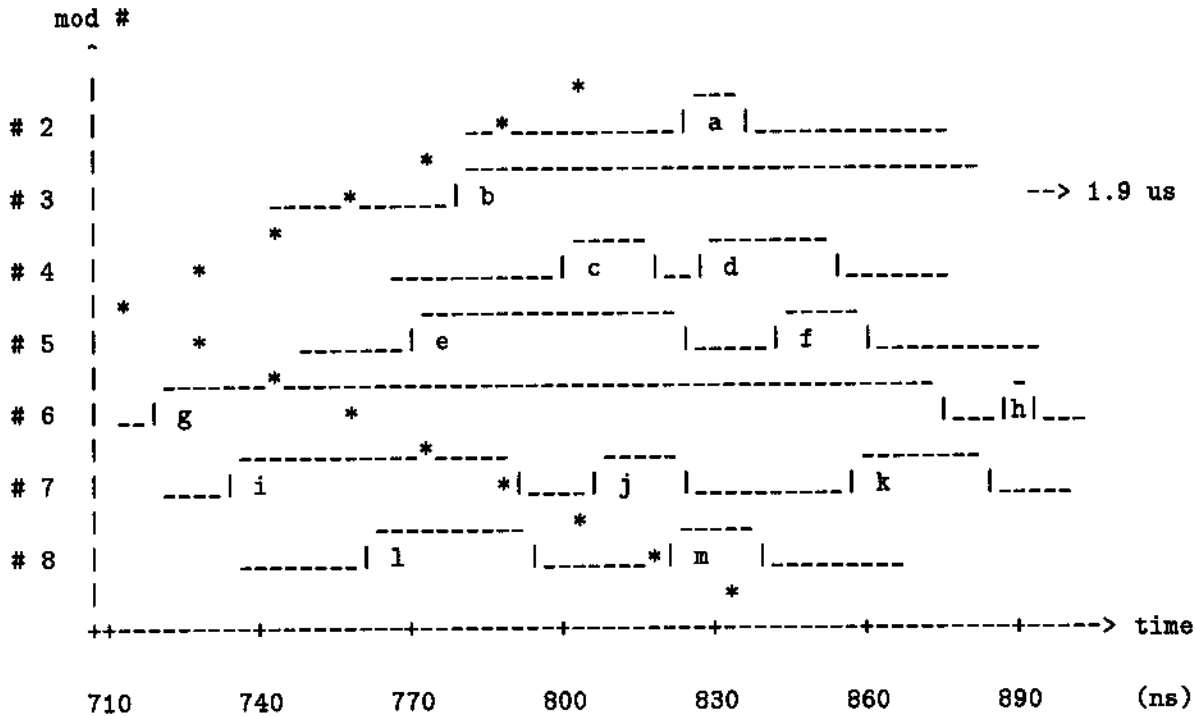
Figure 1: timing chart of "the event". * shows timing diagram for a muon track perpendicular to the string and crossing the string between modules # 4 and 5, as an example.

hit	mod #	pw(ns)	PE ± err(est.)	time(ns)	comment
A.	2	10	7.5± 6.0	7134022	Q pulse of hit a. or just another TOT
B.	4	26	7.9± 6.0	7133982	Q pulse ??
C.	4	201	18.7± 6.8	7134040	Q pulse of hit d. ($T_{diff} = 215$)
D.	5	455	115.± 49.	7133996	Q pulse of hit e. ($T_{diff} = 227$)
E.	6	498	290.± 240.	7133931	Q pulse of hit g. ($T_{diff} = 216$)
F.	7	426	93.± 36.	7133951	Q pulse of hit i. ($T_{diff} = 219$)
G.	8	321	38.3± 13.2	7133971	Q pulse of hit l. ($T_{diff} = 210$)

Table 2: suspected Q pulse list

The result for C and G seem to be consistent with the PE estimated from TOT pulse width, but not for the hits D, E, and F. The hits D and F show smaller PE estimates than their respective TOT counterparts. This is rather peculiar because the Q pulse should give an overestimated PE value if there is more than one TOT pulse before itself due to the circuit we are using in the JOM. So, there should be a rather high possibility of overestimating the PE number calculated from TOT pulses, especially on hits e and i. The source of possible overestimate are,

1) prepulsing
2) afterpulsing
3) multiple light paths or sources

Let me discuss these things before getting to the fitting result.

1) prepulsing The JOM is known to generate prepulses when it is illuminated by the bright light from the head-on direction. This is because of the increased possibility of creating a photo-electron on the first dynode instead of on the photo-cathode. Because the photo-electron created at the first dynode does not have to travel through the space between the photo-cathode and the dynode, it generates an electric pulse about 30 ns earlier than the normal pulse.

The pulse height of prepulse usually is rather small compared to the pulse generated by a photo-electron from the photo-cathode, because it lacks the electron amplification at the first dynode. But, this prepulse starts to become important at around 100 PE equivalent light, because of the higher possibility of creating multiple photo-electrons at the dynode. If the TOT pulse generated by this prepulse becomes longer than the 30 ns interval between it and the normal pulse, we will get an overlapped TOT pulse and this causes an overestimation of the PE number.

If we have prepulse, we will not only overestimate the PE number, but also get incorrect pulse arrival time. Unfortunately there is no way to tell which one had been affected by this prepulse, if any.

2) afterpulsing The afterpulse which affects the TOT pulse width is the one comes out within 100 ns from the normal pulse. This is presumably caused by light emitted from the later stage of the PMT's dynode structure instead of an ion which causes an afterpulse about a few μs later. According to the measurement done by Hamamatsu with very low light level, the probability of generating an afterpulse within 100 ns is much less than 1 %. But, this probability should increase as the input light level increases.

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3) multiple light path or source If there is more than one light source or light path which causes a light arrival timing difference of 10-20 ns, there is a high possibility that the JOM can't separate these two pulses. This can be caused by multiple muons or something reflecting light efficiently. If this happens, we will get much longer TOT pulses than we should have, which causes an overestimation of the PE number.

One other thing we have to discuss before going into the fitting is the module timing data. Because we do not have reliable timing calibration data of the string, we did not try to compensate the arrival time difference of the modules in Table 1 above. The only correction we made was that to the EOM, which is known to have shorter propagation delay of about 40 ns compared to the JOM's. To take the arrival time differences into account, we have to use a slightly larger timing error than that derived from the OM propagation time jitter. We used 5 ns as the tentative uncertainty of the arrival time. We are not sure how reliable this value is, though it should not be larger than 10 ns.

3 Fitting with $z \rightarrow$ up coordinate

First, fitting was tried using the coordinate whose x-axis is pointing east, y-axis pointing north, and z-axis pointing up. To make the numbers less confusing, 7133700ns had been subtracted from the all timing data and the origin of x-axis had been shifted -250m. The fitting was done to find the most probable values of the parameters listed below,

θ ; zenith angle of the muon track

ϕ ; azimuthal angle of muon track (0 = track pointing north)

b ; closest approach distance of muon track to the string

Z_0 ; closest approach height of muon track to the string

t_0 ; time of the muon passing through the closest approach point

α ; muon track brightness factor (1 = minimum ionizing muon)

Also, the following parameters are used in the fit result tables.

ν ; degrees of freedom in fitting

χ^2/ν ; reduced χ^2 of the fitting result

The combination of the hits tried and the results on these combination are shown in Table 3.

As you can see in Table 4, only cases 7) and 8) are on the border line of the muon track criteria, provided that our error estimate is reasonable. The number shown in the parenthesis in χ^2/ν column is the result using an 8 ns timing uncertainty instead of 6 ns. This seems to improve χ^2 value 15-30 %, but resulting fit parameters stay the same within their error.

Some of the resulting angular error listed in Table 4 are rather small. This is mainly because of the selection of the coordinate system, not because of the detector resolution. We will discuss this in the next section.

case	hits included
1)	a, b, c, e, g, i, l
2)	same as 1) without using p.w. information of hit b.
3)	a, b, c, e, g, i
4)	a, c, e, g, i, l
5)	d, e, g, i, l
6)	same as 5) without using p.w. of hit d.
7)	a, b, c, f, h
8)	same as 7) without using p.w. of hit b.

Table 3: hit combinations for "the event"

case	θ (rad)	ϕ (rad)	b	Z_0	t_0	α	χ^2/ν	ν
1)	0.38±0.81	−0.1±0.49	17.	123	11.4	16.5±2.2	18.0(15.4)	8
2)	0.38±0.8	−0.1±0.48	17.	114	11.8	16.2±2.2	16.3(12.9)	7
3)	2.4±0.2	1.0±0.47	7.7	111	−32.	7.2±2.0	21.3(18.3)	6
	I have tried other 6 module combinations of 1). none has $\chi^2/\nu \leq 16$.							
4)	0.42±1.09	−2.9±0.97	−17.	119	26.	16.0±2.4	16.2(13.6)	6
5)	0.62±0.07	−1.57±2.5	0	111	68.	32.±3.6	13.2(10.7)	4
6)	0.75±0.08	−1.6±0.15	3.4	117	50.	50.±6.7	7.1 (4.5)	3
7)	0.35±0.03	−1.16±0.03	−9.5	195	−125.	0.20±0.2	3.45 (2.4)	4
8)	0.19±0.14	4.6±2.4	1.8	245	−289	0.31±0.3	3.9 (2.7)	3

Table 4: fitting result 1. for "the event" using the cases shown in Table 3

mod #	x'	y'	z'	mod #	x'	y'	z'
2	−6.84	0.	326.09	17	5.77	0.	172.73
3	−4.60	0.	316.06	18	6.65	0.	162.62
4	−2.57	0.	306.13	19	7.19	0.	151.57
5	−0.88	0.	296.22	20	7.41	0.	141.66
6	0.50	0.	286.15	21	7.31	0.	131.39
7	1.37	0.	276.00	22	7.13	0.	121.26
8	1.83	0.	265.86	23	6.72	0.	111.17
				24	6.06	0.	100.96

Table 5: rotated coordinate (x' y' and z'), z' axis nearly parallel to the string

case	θ' (rad)	ϕ' (rad)	b	Z_0	t_0	α	χ^2/ν	ν
5)	1.67±0.04	−1.6 ± 1.5	0.	280.	19.5	16±5.4	7.4	4
6)	1.76±0.08	−1.5±1.3	0.	283.	20.1	8.5±3.7	6.7	3
7)	1.38±0.06	4.7±1.2	−2.2	317.	67.2	0.26±0.18	3.7	4
8)	1.21±0.11	4.7±1.50	−0.02	315.	65.7	2.4±1.0	3.0	3

Table 6: fitting result 2. for "the event" using some of the combinations listed in Table 3

4   Fitting with z-axis parallel to the string

A new coordinate system whose z-axis is aligned to the string has been tried in fitting "the event". For simplicity, the x and z-axis were rotated in the x-z plane such a way that the z-axis goes through the string close to the module # 6. The new x', y', and z' coordinate of modules which were turned on is listed in Table 5.

The z-axis is not quite parallel to the string, mainly due to the fact that the junction box is used as an origin of the rotation and that the string is bowing due to the sacrificial anchor. But, all the modules are well within 10 m from the z-axis.

The result of fitting using this new coordinate system is listed in Table 6. Only the cases 5) through 8) have been tried with this coordinate system.

There is not much difference in the fitting result shown in the Table 4 and 6 other than the error on the parameter ϕ. One has to be cautious on comparing θ in these two tables. Because it is measured from z-axis, it is no longer the actual zenith angle of the muon track in the result listed in the Table 6. Actually θ' in this table happened to show the zenith angle of the fitted muon track plus that of the z-axis, which is ~ 1.07 rad.

One noticeable difference by using the new coordinate system is that the contour map of χ^2 in $\theta - \phi$ space tends to be more circular (see Figure 2), whereas that in the previous system tends to be more inclined elliptical shape. Namely the two parameters, θ and ϕ, tend to be correlated in the previous coordinate system more than in this new coordinate system. This is the reason why some of the angular errors in Table 4 are rather small. One expects a better determination in θ' in the new coordinate system, and poor determination in ϕ'.
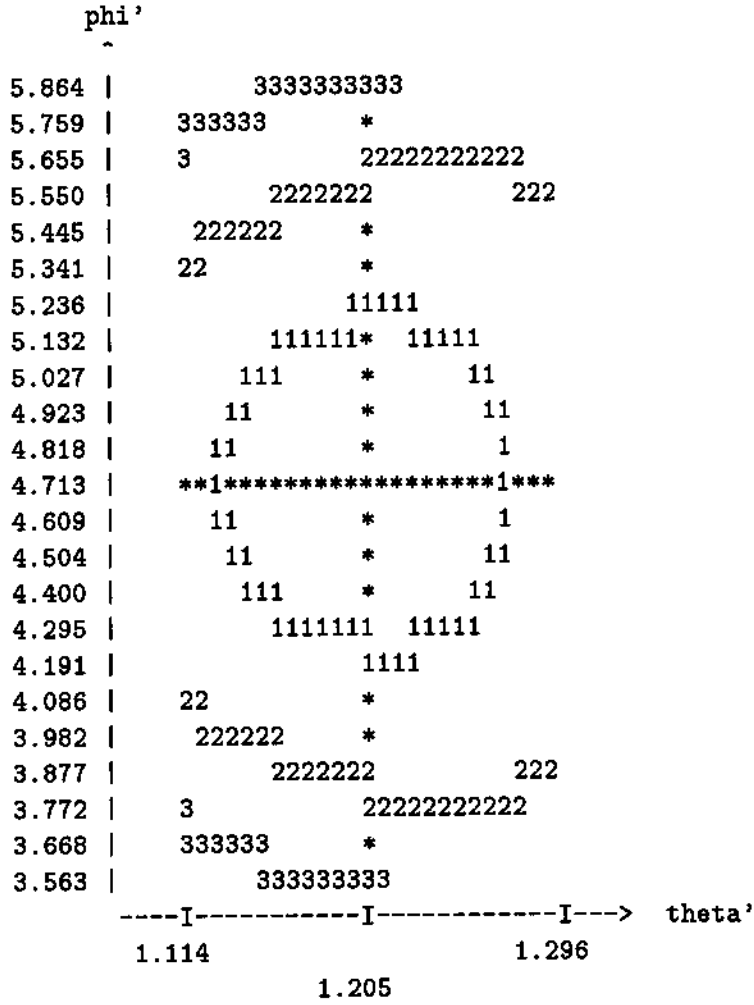
```
        phi'
         ^
5.864 |            3333333333
5.759 |         333333       *
5.655 |         3               22222222222
5.550 |             2222222            222
5.445 |           222222       *
5.341 |         22             *
5.236 |                   11111
5.132 |            111111*  11111
5.027 |            111      *      11
4.923 |           11        *      11
4.818 |           11        *       1
4.713 |         **1*****************1***
4.609 |           11        *       1
4.504 |           11        *      11
4.400 |           111       *     11
4.295 |            1111111  11111
4.191 |                 1111
4.086 |         22             *
3.982 |           222222       *
3.877 |             2222222            222
3.772 |         3               22222222222
3.668 |         333333       *
3.563 |            333333333
        ----I-----------I------------I---> theta'
          1.114                   1.296
                   1.205
```

Figure 2: contour map of χ^2 in $\theta' - \phi'$ plane for the case 8) with rotated coordinate.

case	ev. id	θ (rad)	ϕ (rad)	b	Z_0	t_0	α	χ^2/ν	ν	direct.
1)	16003	1.24±0.10	−1.6±1.4	0.	277.	89.	0.10±0.26	4.6	4	↓
2)	163001	1.44±0.10	−1.5±0.7	0.4	150.	120.	0.01±0.01	9.3	4	↓
3)	167002	0.54±0.01	2.3±0.9	514.	−264.	−223.	22±773	6.9	2	←
4)	235001	2.1±0.2	−4.7±4.0	0.	134.	24.	0.02±0.03	4.4	2	↑
5)	266002	2.2±0.1	−4.7±2.9	0.	323.	134.	0.07±0.03	1.7	2	↑
6)	295001	1.3±0.06	1.6±4.4	0.	284.	72.	0.03±0.04	1.2	4	↑
7)	360001	0.86±0.01	4.7±1.5	0.	290.	91.	1.14±0.7	4.0	2	↓
8)	499004	2.0±0.15	−1.6±1.6	0.	162.	226.	0.02±0.04	4.0	2	↓

Table 7: fitting result 3. for "Svoboda sample"

5 Svoboda data

We have received a list of multiple-fold coincidence from Bob Svoboda. The list was scanned by eye and 10 more than 4-fold candidate muon events including "the event" which has been described above were found. The muon track fitting has been tried on these selected events. The fitting result are listed in Table 7 along with the direction of the resulting muon track. Because the rotated coordinate system listed in Table 5 is used for the fitting, θ' in this system is not the zenith angle of the muon track.

As you can see in this list, some fitting result show quite low reduced χ^2 value, especially for the cases 5 and 6. But, at the same time their result show rather small α. This happened because these events does not have as high PE hit on the modules closest to the fitted track as they should. This might indicate that these events are accidental coincidence of noise hits or that the conversion between pulse width and PE is not correct. Judging from the fact that "the event" fit results tend to show reasonable α value, the former interpretation may be the favorable one.

6 Summary

As a summary,

- Fitting of "the event" had been tried and found that some combinations of the hits can produce fitting results border line of an acceptability as the muon track candidates.

- In particular, the case 8) whose fitting result indicates a muon travelling within a few meter of the module # 3 gives a plausible fit with a muon zenith angle of 0.14 ± 0.11.

- The χ^2 of these fit are not be quite as good as one should expect, but this might be due to the effect of the things listed below,

  – underestimate of timing error

  – problem on the timing correction

  – improper pulse width conversion to PE

  – prepulsing effect on one or more of the modules

incorrect module position (calculation based upon buoyancy model).

- other event fit listed in Table 7 result to either too high χ^2 or too low α.

- this indicate either they are accidental coincidence of noise hits, the PE conversion is improper, or again incorrect module position.