Working Document for A Fast Topological Trigger for Real Time Analysis of Nanosecond Time Scale Phenomena: The Design

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1. Parallaxwidth Array Trigger: Concept

The overall structure of a Parallax-Trigger is shown in Figure 1. The system consists of 2 main components, the camera trigger providing information about the image pattern in the focal plane of each individual telescope and the central array unit that combines the camera patterns and analyzes the parallax of the pattern in real time. In the following we first discuss the design considerations of a camera trigger and then we explain the array trigger.

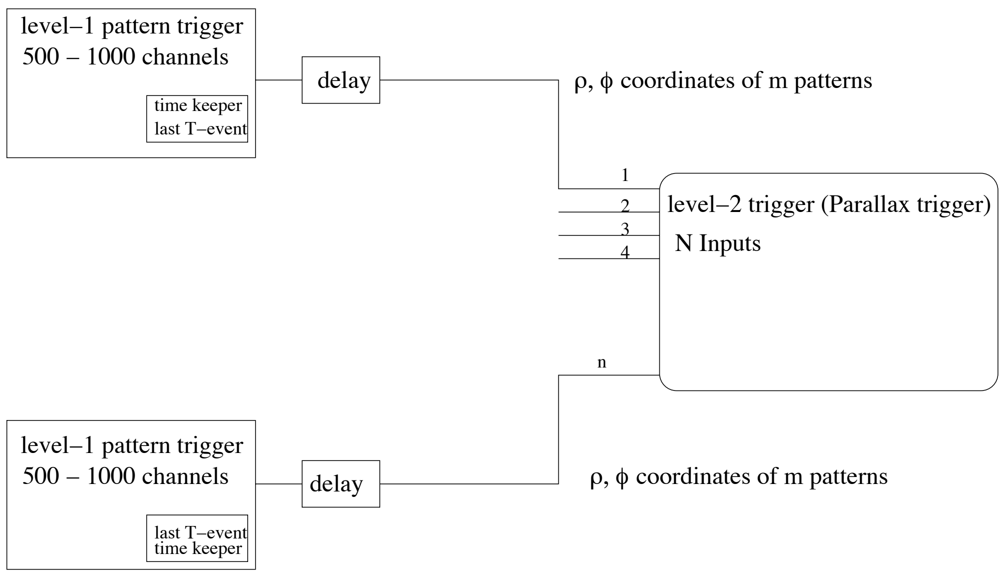

Fig. 1.— The basic structure of a Parallax Trigger/Camera trigger for an IACT array is shown. The level-1 and the level-2 stages of the trigger could be used in any other application using multiple imaging systems and the combined information for stereoscopic pattern recognition.

2. Design Specifications for overall trigger system:

The Parallax-Trigger concept we discuss here consists of 4 identical camera trigger units, one at each telescope, and a centrally located array parallax trigger unit receiving information from each telescope camera trigger.

The following specifications are a guideline for the requirements of the camera and array trigger units:

• maximum rate of the array trigger with ≥ 3 telescopes participating in the trigger: 10 kHz. This specification is likely high and it is with respect to a future array allowing the possibility of running deeply into the noise to lower the energy threshold. The prototype to be tested in VERITAS-4 could certainly do with 1 kHz as a maximum rate. After all, we are trying to reduce the cosmic ray background with this system and furthermore the data acquisition of VERITAS is limited to a design spec of 1 kHz. The maximum rate of the array trigger will be limited by the trigger latencies of all elements involved.

• Data Processing Bandwidth of FPGA logic: $\geq$ 400 MHz. A Cherenkov light flash from an air shower has a typical pulse width of 4-8 ns and depends on primary energy and shower core location. Modern IACT arrays achieve better than 2 ns absolute timing resolution, which should be matched by the Parallax-trigger. Such high timing accuracy is useful at the camera trigger level for forming fast coincidences of neighbor pixels and is likely going to be the most difficult part. At the array trigger level one would still like to maintain this accuracy, however, the air shower physics suggests that array coincidences will be more likely in the 10-15 ns regime.

• The maximum output rate of the camera trigger should be around 100 MHz. This would allow to run deeply into the noise and let the array trigger do its work in looking for meaningful coincidences. For example the rate for a VERITAS type telescope with a coincidence of 2 neighbor PMTs is approximatley 60 MHz at a 4 photoelectron trigger threshold. This is not far from the 400 MHz processing speed which poses the absolute resolution limit.

3. Design Specifications for the camera trigger:

With the general guidelines as mentioned above we now turn to the specifications for the camera trigger.

• Maximum background input rate per channel: 10-100 MHz. This is motivated due to the fact that a photomultiplier in a typical modern large Cherenkov telescope (100 m^2 mirror and pixel size 0.15°) has a singles rate from the night sky fluctuations of 1 MHz (4 MHz) at a threshold of 5 (4) photoelectrons. The number of 4-5 photoelectrons is the typical trigger threshold that could be achieved with a sophisticated array trigger electronics proposed here. This is based on a night sky as is found in a dark location, e.g., at major observatories for optical astronomy (N.S.B $= 2 \times 10^{12}$ photons $m^{-2}\,sr^{-1}\,s^{-1}$ (Mirzoyan et al. 1994).

The VERITAS CFDs can handle a singles rate of 100 MHz. It may be possible that we may be able to trigger lower than 4 photoelectrons and then the maximum input rate could go up substantially. A target number of 100 MHz may be useful for exploring the full potential of the array trigger to reduce chance coincidences from to the night sky.

A high input rate capability would allow us to consider a special low energy trigger for part of the camera (using lower CFD settings), e.g., for the central 0.6° around a point source.

• 500 - 1000 input channels: It would be good to have a design that can handle in the order of 10^3 inputs. This is with view towards "Beyond VERITAS", it is not really a requirement for the prototype. It depends bit on how challenging it will be to feed 100 channels into the board and we may or may not want to do this for the prototype, which will depend on the engineering challenge and its implications for the board design.

• ECL inputs for compatibility with the VERITAS CFD outputs

• pulse width of ECL input signals are between 3-5 ns

• jitter of CFD pulses $\leq$1 ns: It is important that the camera trigger module conserves the timing jitter specification, 2 ns maybe acceptable, however, it is best to not deteriote the timing by more than that.

• For a possible test of the trigger in VERITAS-4 we will need a Connector splitter/transition box required to go from a 26-pin ribbon cable connector (as provided by the CFD/FADC module) to higher density connector to allow 500 - 1000 input channels for trigger module. The splitter is also necessary to minimize interference with the standard VERITAS operation.

• Trigger Decision time $1 - 10\,\mu$s. This is a non-critical specification and must be tuned for a specific application. Modern IACT arrays have trigger latencies on the order of several microseconds. The basic data processing of the trigger will be pipelined, and require some minimum time, depending on the nature and sophistication of the algorithm. This specification sets an upper limit on the processing time.

• Timing precision of the individual camera trigger decision: 1-2 clock periods (2 ns). This is important so that the coincidences can be properly superimposed in subsequent image analysis at the array level.

• Coincidence gate width for array trigger decision: adjustable between 4-60 ns. Since the shower front of the Cherenkov light is conical and the arrival direction not known a priory, the coincidences from several telescopes require flexible time windows. For example, if the arrival time of Cherenkov light as a function of shower core distance is shifted by 10 - 15 ns (Karle 1994).

4. Camera Trigger Algorithm

The philosophy of the algorithm is to put the local telescope trigger into a position that it can already make sophisticated trigger decisions based on the image pattern and location. This requires some basic image analysis. To save processing time, it would be most beneficial to process the following calculations in parallel, whenever possible. This is likely going to increase the timing requirements for each individual process and hence it is important to synchronize those. Synchronizing could mean that all processes have a fixed amount of time to come to a decision making it necessary to built in delays for the processes that take the least amount of time.

1. One step for the camera trigger is to calculate the position of the image centroid in the camera from the hit pattern that is received in parallel from the CFDs. It is perhaps useful to express the hit pattern as a vector $\vec{p}(499)$ for further discussion and processing since it enters the FPGA in parallel. For example, if just pixel 1, 2 and 3 have fired, $\vec{p}(499) = (1, 1, 1, 0, ...0)$.

The calculation of the pattern's mean x-position $\bar{x}$ and the y-position $\bar{y}$ can be performed using adders and multipliers effectively forming the dot product of the vector of the x-positions of the individual pixels $\vec{x}(499)$ (supplied in appendix B) and the vector containing the hit pattern $\vec{p}$. The resulting sum has to be divided by $\vec{p} \cdot \vec{p}$ for normalization. This also provides us with the number of CFDs triggered, hence the pixel number in the image. The vectors $\vec{x}$ and $\vec{y}$ are given in Appendix A.

$\bar{x} = \frac{\vec{p} \cdot \vec{x}}{\vec{p} \cdot \vec{p}}$

$\bar{y} = \frac{\vec{p} \cdot \vec{y}}{\vec{p} \cdot \vec{p}}$

n_{hit} = number of pixels fired: $n_{hit} = \vec{p} \cdot \vec{p}$

The actual operation could be achieved by loading the contents of the x-coordinate/y-coordinate into an 8-bit stack for each channel and form a sum of all the channels that have a hit using a digital summing operation. Normalization can be achieved by having a separate branch counting the number of hits.

The result from these two operations should be $\bar{x}$, $\bar{y}$ and n_{hit}. These two operations could be done in parallel.

2. To make a decision for issueing a local telescope trigger we need two characteristics of the event: number of pixels fired n_{hit}, in the following denoted by j, and the number of neighbor pixels, in the following denoted as m.

Therefore, we need to calculate the number of neighbor pixels in the hit pattern vector. This can be achieved by the following algorithm using a lookup-table that contains the following information:

1	2	3	4	5	6	7
2	1	3	7	8	9	19
3	1	2	4	9	10	11
....						
499	....					

Each row contains the pixel number i, element 2 to 7 contain the neighbors of pixel i. The algorithm goes as follows (for complete table see Appendix A). First we form a logical AND between the hit pattern vector $\vec{p}(499)$ and column 1. This gives the pixel numbers that have a hit and that should be evaluated for neighbor counts.

The next step is to compare $\vec{p}(499)$ with the neighbor vector $\vec{n}_i(499)$ for each fired pixel in increasing order. The maximum number of steps here is j (given by n_{hit}) Again this is a simple dot product and the result gives the number of neighbors also hit for a particular pixel i. The next steps are going through each fired pixel and compare the neighbor vector with the hit vector $\vec{p}(499) - (0, 0, 1_j, 0, 0, ...0)$, to avoid double counting of neighbors.

By counting the number of matches we get the total number of pixels that have a neighbor $n_{neighbor}$. This algorithm could be fast for small single island images, which are most of the events close to threshold.

Obviously there could be images (hit patterns) that have a large number of n_{hit} and consequently one would count a large number of neighbors. However, once n_{hit} reaches a number between 5 - 10 we are no longer interested in the total amount of neighbors, since the requirement for a low n-fold coincidence is met. This means that we could limit the counting of neighbors to the neighbor coincidence criterion and issue a flag indicating that a camera trigger is present.

3. The centroid positions are most useful in polar coordinates, allowing a straightforward trigger criteria first at the camera level and subsequently for the array trigger level. The following formulas provide the coordinates r and ϕ.

$r = \sqrt{\bar{x}^2 + \bar{y}^2}$

$\phi = \arcsin \frac{\bar{y}}{r}$

4. Now a local telescope trigger can be issued based on the following criteria:

r, n_{hit}, $n_{neighbor}$

The detailed criteria will be determined from simulations that we are currently starting. Here we need a Look Up Table (LUT) that uses for example an algorithm making a trigger decision that has different requirements for different radial distances from the source alowing to maximize the collection area at low energies while maintaining sanity for the trigger rate.

5. Time stamp: it is important that each telescope trigger gets a time stamp attached to its image parameter list. There may be different ways to keep track of the time of the CFD hit pattern causing a local array trigger. One would be to have a constant processing time for each hit pattern. This means that the algorithm has to go through the same number of steps (clock ticks) to make a trigger decision. The time stamp could then be determined by subtracting a constant amount (trigger fomation time $t_{trigger}$) from the time stamp recorded when a trigger is issued. This is likely to lead to a slightly inflated trigger formation time $t_{trigger}$. If $t_{trigger}$ is less than about 10μs this may be acceptable.

6. Each camera trigger should get an event number and event type. Those data should be send together with the image pattern information. We should foresee injected events and special events that can initiate a camera trigger.

7. Each camera trigger should get a calibration input to test the absolute timing precision of the trigger modules from the various cameras.

5. Other Considerations for a Camera Trigger:

In this approach, it is assumed that the front-end electronics of the IACT array would provide a fast discriminated output, where the threshold is set to the 4-5 photoelectron level per channel. Because of the fast timing requirements, it is desirable for this to be implemented using Constant Fraction Discriminators (CFDs.) It is desirable to have the capability to set the CFD thresholds separately for individual channels so that selected parts of the camera could be run at a lower discriminator threshold as a means to study the performance of the low energy threshold trigger. The VERITAS CFDs can be set to different thresholds, the ones corresponding to the inner pixels can have a lower threshold than the outer pixels.

For a "Beyond VERITAS" design it may be useful to have even more flexibility: having a single threshold per channel means that the resolution in determining the x-y-position of an image pattern would not make use of pulse-height information, and hence will limit the gamma/hadron separation capability somewhat for larger images consisting of many pixels. Simulations are required to estimate the loss in resolution and gamma/hadron separation when using only a single trigger threshold, and this is part of the scope of this proposal. However, preliminary simulations indicate that the loss in resolution will be small, given the goal of achieving a low energy threshold using images with only few pixels.

The individual camera of 500-1000 pixels would be read into a single FPGA. The algorithm in the FPGA would use a look-up table (LUT) to search for pattern matches in the input bit stream, evaluating all possible n-fold multiplicity patterns within a selected time window. The size of the LUT is estimated to require 150,000 logic cells, which is achievable with modern high-performance FPGAs. The output would be the multiplicity and position of all patterns found. For the case where there are multiple patterns in a given time window in different parts of the camera, perhaps due to night sky noise fluctuations or a large hadronic shower, additional processing would be needed. Multiple patterns produced by a single telescope trigger could be compared with the stereo view from the other telescopes, and an array trigger issued only when the geometry is correct. The best way to handle multiple patterns would be studied in simulations as part of the scope of this proposal.

6. Considerations of the Array Trigger (Parallax Trigger):

A parallax array trigger requires primarily the knowledge of the image pattern positions in the cameras of the individual telescopes in the array, expressed in polar coordinates, ϕ and r. This would allow to use phi only when using the trigger solely for the purpose of gamma/hadron separation, and use the combination of both if a lower energy threshold and fewer chance coincidences due to the night sky are desired. Again, an LUT could be used for estimating the position. The n-fold coincidence will provide n values for ϕ and r. The LUT could also be used on different patterns to apply a position dependent correction if needed. This LUT will be provided by Monte Carlo simulations to come, since the fluctuations of air showers are a key determinent for the trigger criteria.

The transfer of *phi* and r values to other telescopes or central location must be achieved so that the data is aligned in time. Since the IACT arrays might be distal, it is desirable to have each camera trigger append a ”timestamp” onto the data. This would be used by the Parallax Trigger to align data fragements as they arrive, without needing to have crisp timing over great distances. The problem of data alignment then reduces to synchronizing the timestamp circuits on each camera trigger. Modern techniques for achieving timing synchronization use Global Positioning Systems (GPS), which are commercially available, low cost, and have the needed timing accuracy.

The data from the different telescopes would be sent to the Parallax Trigger serially. The fast serial transfer between telescopes with approximately 64 bits of data per telescope and can be done via commercially available optical fiber receivers and transceivers (1 bit for valid trigger, 4 bit for n-fold coincidence, 13 bits for geometry information, 32 bits of timestamp.) At this stage it would be sensible to introduce the necessary timing correction (zenith angle dependent) to account for the different arrival times of the Cherenkov front at the different telescopes. By using digital delay units to delay the bitstreams between the telescope trigger and the Parallax Trigger array trigger, it would be possible to correct for the timing of the individual telescope triggers before reaching the Parallax Trigger unit.

The array algorithm requires simulations which is work in progress.

7. Simulations of Trigger Algorithm

TBD

8. List of all inputs and outputs of Camera trigger, Array trigger

TBD

9. Programmable Digital Delays

TBD

10. Appendix A: next neighbor list

The first column shows the pixel numbers in increasing order, column 2 - 7 show the neighbor pixel numbers. Note that the outer pixels do have less than 6 neighbors.

1 6 2 3 4 5 6 7

2 6 1 3 7 8 9 19

3 6 1 2 4 9 10 11

4 6 1 3 5 11 12 13

5 6 1 4 6 13 14 15

6 6 1 5 7 15 16 17

7 6 1 2 6 17 18 19

8 6 2 9 19 20 21 37

9 6 2 3 8 10 21 22

10 6 3 9 11 22 23 24

11 6 3 4 10 12 24 25

12 6 4 11 13 25 26 27

13 6 4 5 12 14 27 28

14 6 5 13 15 28 29 30

15 6 5 6 14 16 30 31

16 6 6 15 17 31 32 33

17 6 6 7 16 18 33 34

18 6 7 17 19 34 35 36

19 6 2 7 8 18 36 37

20 6 8 21 37 38 39 61

21 6 8 9 20 22 39 40

22 6 9 10 21 23 40 41

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414 6 348 349 413 415 472 473

415 6 349 350 414 416 473 474

416 6 350 351 415 417 474 475

417 5 351 352 416 418 475

418 4 352 353 417 419

419 3 353 354 418

420 3 354 355 421

421 4 355 356 420 422

422 5 356 357 421 423 476

423 6 357 358 422 424 476 477

424 6 358 359 423 425 477 478

425 6 359 360 424 426 478 479

426 6 360 361 425 427 479 480

427 6 361 362 426 428 480 481

428 5 362 363 427 429 481

429 4 363 364 428 430

430 3 364 365 429

431 3 365 366 432

432 4 366 367 431 433

433 5 367 368 432 434 482

434 6 368 369 433 435 482 483

435 6 369 370 434 436 483 484

436 6 370 371 435 437 484 485

437 6 371 372 436 438 485 486

438 6 372 373 437 439 486 487

439 5 373 374 438 440 487

440 4 374 375 439 441

441 3 375 376 440

442 3 376 377 443

443 4 377 378 442 444

444 5 378 379 443 445 488

445 6 379 380 444 446 488 489

446 6 380 381 445 447 489 490

447 6 381 382 446 448 490 491

448 6 382 383 447 449 491 492

449 6 383 384 448 450 492 493

450 5 384 385 449 451 493

451 4 385 386 450 452

452 3 386 387 451

453 3 387 388 454

454 4 388 389 453 455

455 5 389 390 454 456 494

456 6 390 391 455 457 494 495

457 6 391 392 456 458 495 496

458 6 392 393 457 459 496 497

459 6 393 394 458 460 497 498

460 6 394 395 459 461 498 499

461 5 395 396 460 462 499

462 4 396 397 461 463

463 3 332 397 462

464 3 400 401 465

465 4 401 402 464 466

466 4 402 403 465 467

467 4 403 404 466 468

468 4 404 405 467 469

469 3 405 406 468

470 3 411 412 471

471 4 412 413 470 472

472 4 413 414 471 473

473 4 414 415 472 474

474 4 415 416 473 475

475 3 416 417 474

476 3 422 423 477

477 4 423 424 476 478

478 4 424 425 477 479

479 4 425 426 478 480

480 4 426 427 479 481

481 3 427 428 480

482 3 433 434 483

483 4 434 435 482 484

484 4 435 436 483 485

485 4 436 437 484 486

486 4 437 438 485 487

487 3 438 439 486

488 3 444 445 489

489 4 445 446 488 490

490 4 446 447 489 491

491 4 447 448 490 492

492 4 448 449 491 493

493 3 449 450 492

494 3 455 456 495

495 4 456 457 494 496

496 4 457 458 495 497

497 4 458 459 496 498

498 4 459 460 497 499

499 3 460 461 498

11. Appendix B: x-coordinate list

- the X position coordinate in the focal plane in mm

- Camera coordinates are such that increasing X corresponds to going WEST when telescope is pointing SOUTH. Increasing Y corresponds to increasing elevation

- the accuracy to which we know the position of a pixel is defined by the lightconcentrators which have a mechanical specification of better than 0.5 mm. It is sufficient to carry an accuracy of 3 mm which corresponds to an accuracy of 0.015 degree in angular scale.

1 0.000000

2 30.997116

3 15.498533

4 -15.498533

5 -30.997116

6 -15.498533

7 15.498533

8 61.994644

9 46.495804

10 30.997116

11 0.000000

12 -30.997116

13 -46.495804

14 -61.994644

15 -46.495804

16 -30.997116

17 0.000000

18 30.997116

19 46.495804

20 92.993011

21 77.493698

22 61.994644

23 46.495804

24 15.498533

25 -15.498533

26 -46.495804

27 -61.994644

28 -77.493698

29 -92.993011

30 -77.493698

31 -61.994644

32 -46.495804

33 -15.498533

34 15.498533

35 46.495804

36 61.994644

37 77.493698

38 123.992599

39 108.492630

40 92.993011

41 77.493698

42 61.994644

43 30.997116

44 0.000000

45 -30.997116

46 -61.994644

47 -77.493698

48 -92.993011

49 -108.492630

50 -123.992599

51 -108.492630

52 -92.993011

53 -77.493698

54 -61.994644

55 -30.997116

56 0.000000

57 30.997116

58 61.994644

59 77.493698

60 92.993011

61 108.492630

62 154.993866

63 139.492996

64 123.992599

65 108.492630

66 92.993011

67 77.493698

68 46.495804

69 15.498533

70 -15.498533

71 -46.495804

72 -77.493698

73 -92.993011

74 -108.492630

75 -123.992599

76 -139.492996

77 -154.993866

78 -139.492996

79 -123.992599

80 -108.492630

81 -92.993011

82 -77.493698

83 -46.495804

84 -15.498533

85 15.498533

86 46.495804

87 77.493698

88 92.993011

89 108.492630

90 123.992599

91 139.492996

92 185.997177

93 170.495224

94 154.993866

95 139.492996

96 123.992599

97 108.492630

98 92.993011

99 61.994644

100 30.997116

101 0.000000

102 -30.997116

103 -61.994644

104 -92.993011

105 -108.492630

106 -123.992599

107 -139.492996

108 -154.993866

109 -170.495224

110 -185.997177

111 -170.495224

112 -154.993866

113 -139.492996

114 -123.992599

115 -108.492630

116 -92.993011

117 -61.994644

118 -30.997116

119 0.000000

120 30.997116

121 61.994644

122 92.993011

123 108.492630

124 123.992599

125 139.492996

126 154.993866

127 170.495224

128 217.002975

129 201.499741

130 185.997177

131 170.495224

132 154.993866

133 139.492996

134 123.992599

135 108.492630

136 77.493698

137 46.495804

138 15.498533

139 -15.498533

140 -46.495804

141 -77.493698

142 -108.492630

143 -123.992599

144 -139.492996

145 -154.993866

146 -170.495224

147 -185.997177

148 -201.499741

149 -217.002975

150 -201.499741

151 -185.997177

152 -170.495224

153 -154.993866

154 -139.492996

155 -123.992599

156 -108.492630

157 -77.493698

158 -46.495804

159 -15.498533

160 15.498533

161 46.495804

162 77.493698

163 108.492630

164 123.992599

165 139.492996

166 154.993866

167 170.495224

168 185.997177

169 201.499741

170 248.011688

171 232.506958

172 217.002975

173 201.499741

174 185.997177

175 170.495224

176 154.993866

177 139.492996

178 123.992599

179 92.993011

180 61.994644

181 30.997116

182 0.000000

183 -30.997116

184 -61.994644

185 -92.993011

186 -123.992599

187 -139.492996

188 -154.993866

189 -170.495224

190 -185.997177

191 -201.499741

192 -217.002975

193 -232.506958

194 -248.011688

195 -232.506958

196 -217.002975

197 -201.499741

198 -185.997177

199 -170.495224

200 -154.993866

201 -139.492996

202 -123.992599

203 -92.993011

204 -61.994644

205 -30.997116

206 0.000000

207 30.997116

208 61.994644

209 92.993011

210 123.992599

211 139.492996

212 154.993866

213 170.495224

214 185.997177

215 201.499741

216 217.002975

217 232.506958

218 279.023712

219 263.517242

220 248.011688

221 232.506958

222 217.002975

223 201.499741

224 185.997177

225 170.495224

226 154.993866

227 139.492996

228 108.492630

229 77.493698

230 46.495804

231 15.498533

232 -15.498533

233 -46.495804

234 -77.493698

235 -108.492630

236 -139.492996

237 -154.993866

238 -170.495224

239 -185.997177

240 -201.499741

241 -217.002975

242 -232.506958

243 -248.011688

244 -263.517242

245 -279.023712

246 -263.517242

247 -248.011688

248 -232.506958

249 -217.002975

250 -201.499741

251 -185.997177

252 -170.495224

253 -154.993866

254 -139.492996

255 -108.492630

256 -77.493698

257 -46.495804

258 -15.498533

259 15.498533

260 46.495804

261 77.493698

262 108.492630

263 139.492996

264 154.993866

265 170.495224

266 185.997177

267 201.499741

268 217.002975

269 232.506958

270 248.011688

271 263.517242

272 310.039459

273 294.531067

274 279.023712

275 263.517242

276 248.011688

277 232.506958

278 217.002975

279 201.499741

280 185.997177

281 170.495224

282 154.993866

283 123.992599

284 92.993011

285 61.994644

286 30.997116

287 0.000000

288 -30.997116

289 -61.994644

290 -92.993011

291 -123.992599

292 -154.993866

293 -170.495224

294 -185.997177

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302 -310.039459

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304 -279.023712

305 -263.517242

306 -248.011688

307 -232.506958

308 -217.002975

309 -201.499741

310 -185.997177

311 -170.495224

312 -154.993866

313 -123.992599

314 -92.993011

315 -61.994644

316 -30.997116

317 0.000000

318 30.997116

319 61.994644

320 92.993011

321 123.992599

322 154.993866

323 170.495224

324 185.997177

325 201.499741

326 217.002975

327 232.506958

328 248.011688

329 263.517242

330 279.023712

331 294.531067

332 341.059326

333 325.548828

334 310.039459

335 294.531067

336 279.023712

337 263.517242

338 248.011688

339 232.506958

340 217.002975

341 201.499741

342 185.997177

343 170.495224

344 139.492996

345 108.492630

346 77.493698

347 46.495804

348 15.498533

349 -15.498533

350 -46.495804

351 -77.493698

352 -108.492630

353 -139.492996

354 -170.495224

355 -185.997177

356 -201.499741

357 -217.002975

358 -232.506958

359 -248.011688

360 -263.517242

361 -279.023712

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363 -310.039459

364 -325.548828

365 -341.059326

366 -325.548828

367 -310.039459

368 -294.531067

369 -279.023712

370 -263.517242

371 -248.011688

372 -232.506958

373 -217.002975

374 -201.499741

375 -185.997177

376 -170.495224

377 -139.492996

378 -108.492630

379 -77.493698

380 -46.495804

381 -15.498533

382 15.498533

383 46.495804

384 77.493698

385 108.492630

386 139.492996

387 170.495224

388 185.997177

389 201.499741

390 217.002975

391 232.506958

392 248.011688

393 263.517242

394 279.023712

395 294.531067

396 310.039459

397 325.548828

398 356.570953

399 341.059326

400 325.548828

401 310.039459

402 294.531067

403 279.023712

404 263.517242

405 248.011688

406 232.506958

407 217.002975

408 201.499741

409 154.993866

410 123.992599

411 92.993011

412 61.994644

413 30.997116

414 0.000000

415 -30.997116

416 -61.994644

417 -92.993011

418 -123.992599

419 -154.993866

420 -201.499741

421 -217.002975

422 -232.506958

423 -248.011688

424 -263.517242

425 -279.023712

426 -294.531067

427 -310.039459

428 -325.548828

429 -341.059326

430 -356.570953

431 -356.570953

432 -341.059326

433 -325.548828

434 -310.039459

435 -294.531067

436 -279.023712

437 -263.517242

438 -248.011688

439 -232.506958

440 -217.002975

441 -201.499741

442 -154.993866

443 -123.992599

444 -92.993011

445 -61.994644

446 -30.997116

447 0.000000

448 30.997116

449 61.994644

450 92.993011

451 123.992599

452 154.993866

453 201.499741

454 217.002975

455 232.506958

456 248.011688

457 263.517242

458 279.023712

459 294.531067

460 310.039459

461 325.548828

462 341.059326

463 356.570953

464 341.059326

465 325.548828

466 310.039459

467 294.531067

468 279.023712

469 263.517242

470 77.493698

471 46.495804

472 15.498533

473 -15.498533

474 -46.495804

475 -77.493698

476 -263.517242

477 -279.023712

478 -294.531067

479 -310.039459

480 -325.548828

481 -341.059326

482 -341.059326

483 -325.548828

484 -310.039459

485 -294.531067

486 -279.023712

487 -263.517242

488 -77.493698

489 -46.495804

490 -15.498533

491 15.498533

492 46.495804

493 77.493698

494 263.517242

495 279.023712

496 294.531067

497 310.039459

498 325.548828

499 341.059326

12. Appendix C: y-coordinate list

1 0.000000

2 0.000000

3 -26.808302

4 -26.808302

5 0.000000

6 26.808302

7 26.808302

8 0.000000

9 -26.808302

10 -53.616871

11 -53.616871

12 -53.616871

13 -26.808302

14 0.000000

15 26.808302

16 53.616871

17 53.616871

18 53.616871

19 26.808302

20 0.000000

21 -26.808302

22 -53.616871

23 -80.425980

24 -80.425980

25 -80.425980

26 -80.425980

27 -53.616871

28 -26.808302

29 0.000000

30 26.808302

31 53.616871

32 80.425980

33 80.425980

34 80.425980

35 80.425980

36 53.616871

37 26.808302

38 0.000000

39 -26.808302

40 -53.616871

41 -80.425980

42 -107.445335

43 -107.445335

44 -107.445335

45 -107.445335

46 -107.445335

47 -80.425980

48 -53.616871

49 -26.808302

50 0.000000

51 26.808302

52 53.616871

53 80.425980

54 107.445335

55 107.445335

56 107.445335

57 107.445335

58 107.445335

59 80.425980

60 53.616871

61 26.808302

62 0.000000

63 -26.808302

64 -53.616871

65 -80.425980

66 -107.445335

67 -134.256317

68 -134.256317

69 -134.256317

70 -134.256317

71 -134.256317

72 -134.256317

73 -107.445335

74 -80.425980

75 -53.616871

76 -26.808302

77 0.000000

78 26.808302

79 53.616871

80 80.425980

81 107.445335

82 134.256317

83 134.256317

84 134.256317

85 134.256317

86 134.256317

87 134.256317

88 107.445335

89 80.425980

90 53.616871

91 26.808302

92 0.000000

93 -26.808302

94 -53.616871

95 -80.425980

96 -107.445335

97 -134.256317

98 -161.068649

99 -161.068649

100 -161.068649

101 -161.068649

102 -161.068649

103 -161.068649

104 -161.068649

105 -134.256317

106 -107.445335

107 -80.425980

108 -53.616871

109 -26.808302

110 0.000000

111 26.808302

112 53.616871

113 80.425980

114 107.445335

115 134.256317

116 161.068649

117 161.068649

118 161.068649

119 161.068649

120 161.068649

121 161.068649

122 161.068649

123 134.256317

124 107.445335

125 80.425980

126 53.616871

127 26.808302

128 0.000000

129 -26.808302

130 -53.616871

131 -80.425980

132 -107.445335

133 -134.256317

134 -161.068649

135 -187.882599

136 -187.882599

137 -187.882599

138 -187.882599

139 -187.882599

140 -187.882599

141 -187.882599

142 -187.882599

143 -161.068649

144 -134.256317

145 -107.445335

146 -80.425980

147 -53.616871

148 -26.808302

149 0.000000

150 26.808302

151 53.616871

152 80.425980

153 107.445335

154 134.256317

155 161.068649

156 187.882599

157 187.882599

158 187.882599

159 187.882599

160 187.882599

161 187.882599

162 187.882599

163 187.882599

164 161.068649

165 134.256317

166 107.445335

167 80.425980

168 53.616871

169 26.808302

170 0.000000

171 -26.808302

172 -53.616871

173 -80.425980

174 -107.445335

175 -134.256317

176 -161.068649

177 -187.882599

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179 -214.698410

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185 -214.698410

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187 -187.882599

188 -161.068649

189 -134.256317

190 -107.445335

191 -80.425980

192 -53.616871

193 -26.808302

194 0.000000

195 26.808302

196 53.616871

197 80.425980

198 107.445335

199 134.256317

200 161.068649

201 187.882599

202 214.698410

203 214.698410

204 214.698410

205 214.698410

206 214.698410

207 214.698410

208 214.698410

209 214.698410

210 214.698410

211 187.882599

212 161.068649

213 134.256317

214 107.445335

215 80.425980

216 53.616871

217 26.808302

218 0.000000

219 -26.808302

220 -53.616871

221 -80.425980

222 -107.445335

223 -134.256317

224 -161.068649

225 -187.882599

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237 -214.698410

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239 -161.068649

240 -134.256317

241 -107.445335

242 -80.425980

243 -53.616871

244 -26.808302

245 0.000000

246 26.808302

247 53.616871

248 80.425980

249 107.445335

250 134.256317

251 161.068649

252 187.882599

253 214.698410

254 241.516357

255 241.516357

256 241.516357

257 241.516357

258 241.516357

259 241.516357

260 241.516357

261 241.516357

262 241.516357

263 241.516357

264 214.698410

265 187.882599

266 161.068649

267 134.256317

268 107.445335

269 80.425980

270 53.616871

271 26.808302

272 0.000000

273 -26.808302

274 -53.616871

275 -80.425980

276 -107.445335

277 -134.256317

278 -161.068649

279 -187.882599

280 -214.698410

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284 -268.336731

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301 -26.808302

302 0.000000

303 26.808302

304 53.616871

305 80.425980

306 107.445335

307 134.256317

308 161.068649

309 187.882599

310 214.698410

311 241.516357

312 268.336731

313 268.336731

314 268.336731

315 268.336731

316 268.336731

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319 268.336731

320 268.336731

321 268.336731

322 268.336731

323 241.516357

324 214.698410

325 187.882599

326 161.068649

327 134.256317

328 107.445335

329 80.425980

330 53.616871

331 26.808302

332 0.000000

333 -26.808302

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335 -80.425980

336 -107.445335

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366 26.808302

367 53.616871

368 80.425980

369 107.445335

370 134.256317

371 161.068649

372 187.882599

373 214.698410

374 241.516357

375 268.336731

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377 295.159790

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386 295.159790

387 295.159790

388 268.336731

389 241.516357

390 214.698410

391 187.882599

392 161.068649

393 134.256317

394 107.445335

395 80.425980

396 53.616871

397 26.808302

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419 -322.195343

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