ECE 785

Project 2: Vectorizing the Spherical geometry code

Objective:

The main objective of the project is to optimize the execution time of the given spherical geometry code using NEON SIMD operations via compiler intrinsics and various other possible optimizations. The output generated by the optimized version of the code is validated against the output obtained using single precision cos function.

Initial performance analysis:

Output with validation:

```
debian@beaglebone:~/Project1$ ./sg
Vaildation:
Error in distance!Expected:9.588253 Actual:9.837340 Error:-2.597839 for Annapolis , Maryland
Error in distance!Expected:84.079651 Actual:84.108429 Error:-0.034227 for Dover , Delaware
Error in distance!Expected:130.731613 Actual:130.750107 Error:-0.014146 for Hartford , Connecticut
Error in distance!Expected:123.929008 Actual:123.948524 Error:-0.015748 for Juneau , Alaska
Error in distance!Expected:668.489380 Actual:696.772461 Error:-4.230895 for Nashville , Tennessee
Error in bearing!Expected:169.332611 Actual:331.899628 Error:-162.567017 for Nashville , Tennessee
Error in name!Expected:DAUPHIN ISLAND, AL Actual:SOUTH BASS ISLAND, OH for Nashville , Tennessee
Error in distance!Expected:76.643372 Actual:76.674934 Error:-0.041181 for Olympia , Washington
Error in distance!Expected:148.266769 Actual:148.283081 Error:-0.011002 for Sacramento , California
Error in distance!Expected:96.135429 Actual:96.160591 Error:-0.026173 for Tallahassee , Florida
Output:
0.Closest waypoint for Albany , New York is NYC ENTR. 254.716675 km away at bearing 181.550583 degrees
1.Closest waypoint for Annapolis , Maryland is THOMAS POINT, MD. 9.837340 km away at bearing 213.130646 degrees
2.Closest waypoint for Atlanta , Georgia is GRAYS REEF. 421.432037 km away at bearing 232.451050 degrees
3.Closest waypoint for Augusta , Maine is PORTLAND. 93.222275 km away at bearing 161.085648 degrees
4.Closest waypoint for Austin , Texas is PORT ARANSAS, TX. 279.357788 km away at bearing 194.268921 degrees
5.Closest waypoint for Baton Rouge, Louisiana is BILOXI. 231.263412 km away at bearing 260.404968 degrees
6.Closest waypoint for Bismarck , North Dakota is DEVILS ISLAND, WI. 772.233704 km away at bearing 259.330780 degrees
7.Closest waypoint for Boise , Idaho is NEWPORT, OR. 634.778564 km away at bearing 77.240952 degrees
8.Closest waypoint for Boston , Massachusetts is BOSTON. 33.576942 km away at bearing 292.475555 degrees
9.Closest waypoint for Carson City, Nevada is SAN FRANCISCO. 309.820831 km away at bearing 119.219414 degrees
10.Closest waypoint for Charleston , West Virginia is W LK ERIE. 376.048218 km away at bearing 9.754081 degrees
11.Closest waypoint for Cheyenne , Wyoming is DEVILS ISLAND, WI. 1300.067627 km away at bearing 305.208618 degrees
12.Closest waypoint for Columbia , South Carolina is FOLLY ISLAND, SC. 180.381088 km away at bearing 216.451447 degrees
13.Closest waypoint for Columbus , Ohio is SOUTH BASS ISLAND, OH. 185.942719 km away at bearing 355.881439 degrees
14.Closest waypoint for Concord , New Hampshire is ISLE OF SHOALS, NH. 80.402351 km away at bearing 250.083450 degrees
15.Closest waypoint for Denver , Colorado is DEVILS ISLAND, WI. 1407.891968 km away at bearing 310.096191 degrees
16.Closest waypoint for Des Moines, Iowa is SHEBOYGAN, WI. 540.894043 km away at bearing 298.330109 degrees
17.Closest waypoint for Dover , Delaware is THOMAS POINT, MD. 84.108429 km away at bearing 109.976585 degrees
18.Closest waypoint for Frankfort , Kentucky is SOUTH BASS ISLAND, OH. 418.861938 km away at bearing 336.318695 degrees
19.Closest waypoint for Harrisburg , Pennsylvania is THOMAS POINT, MD. 156.847061 km away at bearing 193.910110 degrees
20.Closest waypoint for Hartford , Connecticut is MONTAUK PT. 130.750107 km away at bearing 203.853012 degrees
21.Closest waypoint for Helena , Montana is WEST POINT, WA. 795.983765 km away at bearing 77.659920 degrees
22.Closest waypoint for Honolulu , Hawaii is W HAWAII. 385.118530 km away at bearing 129.342636 degrees
23.Closest waypoint for Indianapolis , Indiana is S LK MICHIGAN. 328.528412 km away at bearing 12.689395 degrees
24.Closest waypoint for Jackson , Mississippi is BILOXI. 283.126831 km away at bearing 209.237030 degrees
25.Closest waypoint for Jefferson City, Missouri is S LK MICHIGAN. 629.953918 km away at bearing 317.949829 degrees
26.Closest waypoint for Juneau , Alaska is FIVE FINGERS, AK. 123.948524 km away at bearing 202.528458 degrees
27.Closest waypoint for Lansing , Michigan is LAKE ST. CLAIR. 149.145386 km away at bearing 259.276031 degrees
28.Closest waypoint for Lincoln , Nebraska is SHEBOYGAN, WI. 807.715393 km away at bearing 296.838989 degrees
```

The initial execution time was **54.447 µs.**

Output without validation:

```
29.Closest waypoint for Little Rock, Arkansas is SABINE, TX. 584.455139 km away at bearing 163.670013 degrees
30.Closest waypoint for Madison , Wisconsin is SHEBOYGAN, WI. 156.120331 km away at bearing 299.329956 degrees
31.Closest waypoint for Montgomery , Alabama is ORANGE BCH. 282.013397 km away at bearing 154.293076 degrees
32.Closest waypoint for Montpelier , Vermont is PORTLAND. 211.352295 km away at bearing 248.053284 degrees
33.Closest waypoint for Nashville , Tennessee is SOUTH BASS ISLAND, OH. 696.772461 km away at bearing 331.899628 degrees
34.Closest waypoint for Oklahoma City, Oklahoma is SABINE, TX. 723.815002 km away at bearing 207.938629 degrees
35.Closest waypoint for Olympia , Washington is WEST POINT, WA. 76.674934 km away at bearing 333.737518 degrees
36.Closest waypoint for Phoenix , Arizona is SAN CLEMENTE. 565.683105 km away at bearing 99.226471 degrees
37.Closest waypoint for Pierre , South Dakota is DEVILS ISLAND, WI. 803.698975 km away at bearing 295.413635 degrees
38.Closest waypoint for Providence , Rhode Island is BUZZARDS BAY,MA. 57.319054 km away at bearing 214.821564 degrees
39.Closest waypoint for Raleigh , North Carolina is ONSLOW BAY. 189.372559 km away at bearing 221.099457 degrees
40.Closest waypoint for Richmond , Virginia is CHESAPEAKE LIGHT, VA. 170.051636 km away at bearing 246.203003 degrees
41.Closest waypoint for Sacramento , California is SAN FRANCISCO. 148.283081 km away at bearing 126.205139 degrees
42.Closest waypoint for Saint Paul, Minnesota is DEVILS ISLAND, WI. 299.008118 km away at bearing 323.221375 degrees
43.Closest waypoint for Salem , Oregon is NEWPORT, OR. 89.569160 km away at bearing 113.121010 degrees
44.Closest waypoint for Salt Lake, Utah is SAN FRANCISCO. 997.999329 km away at bearing 105.949211 degrees
45.Closest waypoint for Santa Fe, New Mexico is SAN CLEMENTE. 1165.089355 km away at bearing 104.183609 degrees
46.Closest waypoint for Springfield , Illinois is S LK MICHIGAN. 388.610229 km away at bearing 326.534698 degrees
47.Closest waypoint for Tallahassee , Florida is KEATON BEACH, FL. 96.160591 km away at bearing 223.236084 degrees
48.Closest waypoint for Topeka , Kansas is S LK MICHIGAN. 832.105530 km away at bearing 301.781250 degrees
49.Closest waypoint for Trenton , New Jersey is NYC ENTR. 91.095810 km away at bearing 280.769745 degrees
Average    54.447 us
Minimum    52.187 us
debian@beaglebone:~/Project1$
```
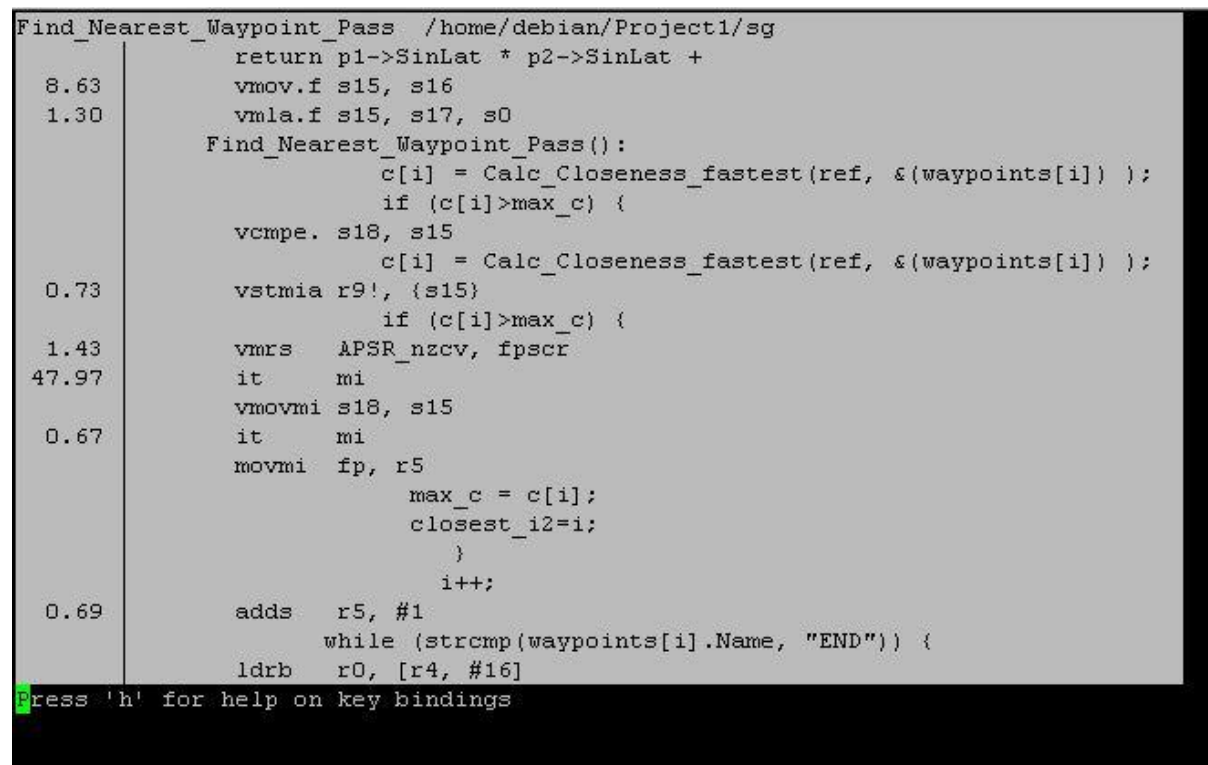
Function-profile:

```
Samples: 116K of event 'cycles:ppp', Event count (approx.): 28525890381
Overhead   Command   Shared Object       Symbol
   45.75%  sg        sg                  [.] Find_Nearest_Waypoint_Pass
   26.24%  sg        sg                  [.] __mcount_internal
   18.20%  sg        sg                  [.] cos_12
    5.03%  sg        sg                  [.] __gnu_mcount_nc
    0.76%  sg        sg                  [.] cos_73
    0.60%  sg        sg                  [.] __sincosf
    0.56%  sg        sg                  [.] __ieee754_sqrtf
    0.50%  sg        sg                  [.] __ieee754_atan2f
    0.38%  sg        sg                  [.] __kernel_cosf
    0.32%  sg        sg                  [.] __atanf
    0.32%  sg        sg                  [.] __ieee754_acosf
    0.27%  sg        [kernel.kallsyms]   [k] _raw_spin_unlock_irqrestore
    0.18%  sg        [kernel.kallsyms]   [k] __softirqentry_text_start
    0.10%  sg        [kernel.kallsyms]   [k] _raw_spin_unlock_irq
    0.08%  sg        sg                  [.] __kernel_sinf
    0.07%  sg        sg                  [.] main
    0.06%  sg        sg                  [.] strcmp
    0.05%  sg        [kernel.kallsyms]   [k] restore_sigframe
    0.05%  sg        [kernel.kallsyms]   [k] setup_sigframe
    0.03%  sg        [kernel.kallsyms]   [k] sys_clock_gettime
    0.03%  sg        [kernel.kallsyms]   [k] rcu_process_callbacks
Tip: Show user configuration overrides: perf config --user --list
```

Run-time profile:

```
Find_Nearest_Waypoint_Pass  /home/debian/Project1/sg
                    return p1->SinLat * p2->SinLat +
  8.63            vmov.f s15, s16
  1.30            vmla.f s15, s17, s0
                Find_Nearest_Waypoint_Pass():
                        c[i] = Calc_Closeness_fastest(ref, &(waypoints[i]) );
                        if (c[i]>max_c) {
                 vcmpe. s18, s15
                        c[i] = Calc_Closeness_fastest(ref, &(waypoints[i]) );
  0.73            vstmia r9!, {s15}
                        if (c[i]>max_c) {
  1.43            vmrs   APSR_nzcv, fpscr
 47.97            it     mi
                 vmovmi s18, s15
  0.67            it     mi
                 movmi  fp, r5
                        max_c = c[i];
                        closest_i2=i;
                            }
                          i++;
  0.69            adds   r5, #1
                 while (strcmp(waypoints[i].Name, "END")) {
                 ldrb   r0, [r4, #16]
Press 'h' for help on key bindings
```

Vectorization 1:

The first vectorization was aimed at vectorizing the version of code involving no passes and which used cos_73 math function for calculating closeness. The main aim of vectorization is to calculate closeness 'c' of a given reference point for 4 waypoints simultaneously within the for loop in Find_Nearest_Waypoint function so as to parallelize the computation within the loop. This can be achieved using SIMD instructions via compiler intrinsics which helps to utilize NEON architecture to improve the performance of the code.

Code before vectorization:

while (strcmp(waypoints[i].Name, "END")) {

    c[i] = ref->SinLat * waypoints[i].SinLat + ref->CosLat * waypoints[i].CosLat*
    cos_73(waypoints[i].Lon - ref->Lon);

    if (c[i]>max_c) {

      max_c = c[i];

      closest_i2=i;

    }

    i++;

}

Code after vectorization:

```
for (int i=0;i<164;i+=4)

    {


        v4_waypoints_SinLat=vld1q_f32(&SinLat[i]);

        v4_waypoints_CosLat=vld1q_f32(&CosLat[i]);

        v4_waypoints_Lon=vld1q_f32(&Lon[i]);

        v4_waypoints_Lon=v_cos_73(v4_waypoints_Lon);

        v4_temp_index=vld1q_u32(&temp_index[i]);

        v4_SinLat=vmulq_n_f32(v4_waypoints_SinLat,ref->SinLat);

        v4_CosLat=vmulq_n_f32(v4_waypoints_CosLat,ref->CosLat);

        v4_Term2=vmulq_f32(v4_waypoints_Lon,v4_CosLat);

        v4_c=vaddq_f32(v4_SinLat,v4_Term2);

        v4_prev_max=v4_max_c;

        v4_max_c=vmaxq_f32(v4_max_c,v4_c);

        v4_temp=vceqq_f32(v4_prev_max,v4_max_c);

        v4_index=vbslq_u32(v4_temp,v4_index,v4_temp_index);

    }
```

Instructions like vmulq_f32, vaddq_f32 are used to perform arithmetic operations on a quad vector while vld1q_f32 is used for loading vector memory. The vector containing maximum values obtained, using vmaxq_f3,2 is compared using vceqq_f32 against its previous value to check if any new maximum value is inserted into the maximum value vector. Based on the compare value, the corresponding index for the newly inserted maximum value is stored in the index vector.

The vector result obtained for index values and maximum closeness is then reduced to obtain the final value for maximum closeness and corresponding index. The following code is used to obtain a vector of two elements for max closeness and index:

v2_u = vget_high_f32(v4_max_c);

v2_l = vget_low_f32(v4_max_c);

v2_index1 = vget_high_u32(v4_index);

v2_index2 = vget_low_u32(v4_index);

The following code is used for obtaining 2 greatest values out of the 4 maximum values obtained along with their indices:

v2_u = vpmax_f32(v2_l, v2_u);

v2_compare=vceq_f32(v2_u,v2_temp_u);

v2_index_rev=vrev64_u32(v2_index1);

v2_index_1=vbsl_u32(v2_compare,v2_index1,v2_index_rev);

First the maximum values are obtained using vpmax_f32 and this vector is then compared with the previous vector v2_u. The compare output value thus obtained is then used along with the vbsl_u32 intrinsic to obtain the index of one of the maximum value. The same is repeated for the second maximum value. The final index for the two maximum values is then stored in a vector register v4_index after processing as follows:

v2_index=vext_u32(v2_index_1,v2_index_2,1);

v2_index_rev=v2_index;

v2_index=vrev64_u32(v2_index);

The same above procedure is repeated for obtaining maximum closeness value and its corresponding value from the vector of two maximum values and its indices as follows:

v2_u = vpmax_f32(v2_u, v2_zero);

v2_compare=vceq_f32(v2_u,v2_temp_u);

v2_index=vbsl_u32(v2_compare,v2_index,v2_index_rev);

max_c= vget_lane_f32(v2_u, 0);

closest_i= vget_lane_u32(v2_index, 0);

Hence max_c and closest_i values are obtained using vectorization.

Vectorization 2:

This is aimed at vectorizing polynomial approximation version cos functions. The cos function is vectorized to generate values for 4 different arguments passed in a vector. To begin with the quadrant for each of the 4 arguments is determined and stored in a vector in the following way:

v4_quad=vcvtq_u32_f32(vmulq_n_f32(v4_x,two_over_pi));

The modified values of each argument according to the quadrant to which it belongs is calculated as follows:

v4_case2=vsubq_f32(vdupq_n_f32(DP_PI),v4_x);   //DP_PI-x

v4_case3=vsubq_f32(v4_x,vdupq_n_f32(DP_PI));   //x-DP_PI

v4_case4=vsubq_f32(vdupq_n_f32(twopi),v4_x);   //twopi-x

The value of quadrant for each argument is then compared against four possible cases using vceqq_f32 and this compare value is used along with vbslq_f32 to select the modified argument value according to the corresponding quadrant value :

v4_compare=vceqq_u32(vld1q_u32(case1),v4_quad);   //for case 1

v4_result=vbslq_f32(v4_compare,v4_x,v4_result);

v4_compare=vceqq_u32(vld1q_u32(case2),v4_quad);   //for case 2

v4_compare_neg1=v4_compare;

v4_result=vbslq_f32(v4_compare,v4_case2,v4_result);

v4_compare=vceqq_u32(vld1q_u32(case3),v4_quad);   //for case 3

v4_compare_neg2=v4_compare;

v4_result=vbslq_f32(v4_compare,v4_case3,v4_result);

v4_compare=vceqq_u32(vld1q_u32(case4),v4_quad);   //for case 4

v4_result=vbslq_f32(v4_compare,v4_case4,v4_result);

The final cos value for each argument stored in the vector is then obtained by multiplying the values in the vector with the appropriate constants depending on the approximation function used. The cos value for cos_12 was obtained as follows:

v4_result=vmulq_f32(v4_result,v4_result);

v4_term=vmulq_n_f32(v4_result,c2);

v4_result=vaddq_f32(vdupq_n_f32(c1),v4_term);

Then the result is multiplied with the -1 and the negative results obtained are selectively selected and stored in result vector using vbslq_f32 and result obtained by ORing the compare results for case 1 and case 2.

v4_result_temp=v4_result;

v4_result_temp=vmulq_n_f32(v4_result,-1);

v4_result=vbslq_f32(v4_compare_neg1,v4_result_temp,v4_result);

Output with validation:

This is the output obtained after implementing vectorization 1 & 2 in Find_Nearest_Waypoint function and for cos_73 function.

```
debian@beaglebone:~/Project2/Test$ ./sg
Vaildation:
Error in distance!Expected:33.504810 Actual:33.648918 Error:-0.430111 for Boston , Massachusetts
Error in distance!Expected:180.354263 Actual:180.381088 Error:-0.014873 for Columbia , South Carolina
Error in distance!Expected:130.731613 Actual:130.750107 Error:-0.014146 for Hartford , Connecticut
Error in distance!Expected:149.129166 Actual:149.161606 Error:-0.021753 for Lansing , Michigan
Error in distance!Expected:76.643372 Actual:76.674934 Error:-0.041181 for Olympia , Washington
Error in distance!Expected:148.266769 Actual:148.283081 Error:-0.011002 for Sacramento , California
Error in distance!Expected:96.135429 Actual:96.185753 Error:-0.052346 for Tallahassee , Florida
Error in distance!Expected:91.069252 Actual:91.122368 Error:-0.058325 for Trenton , New Jersey
Output:
0.Closest waypoint for Albany , New York is NYC ENTR. 254.707184 km away at bearing 181.550583 degrees
1.Closest waypoint for Annapolis , Maryland is THOMAS POINT, MD. 9.837340 km away at bearing 213.130646 degrees
2.Closest waypoint for Atlanta , Georgia is GRAYS REEF. 421.432037 km away at bearing 232.451050 degrees
3.Closest waypoint for Augusta , Maine is PORTLAND. 93.222275 km away at bearing 161.085648 degrees
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9.Closest waypoint for Carson City, Nevada is SAN FRANCISCO. 309.820831 km away at bearing 119.219414 degrees
10.Closest waypoint for Charleston , West Virginia is W LK ERIE. 376.041748 km away at bearing 9.754081 degrees
11.Closest waypoint for Cheyenne , Wyoming is DEVILS ISLAND, WI. 1300.067627 km away at bearing 305.208618 degrees
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23.Closest waypoint for Indianapolis , Indiana is S LK MICHIGAN. 328.521057 km away at bearing 12.689395 degrees
24.Closest waypoint for Jackson , Mississippi is BILOXI. 283.126831 km away at bearing 209.237030 degrees
25.Closest waypoint for Jefferson City, Missouri is S LK MICHIGAN. 629.953918 km away at bearing 317.949829 degrees
26.Closest waypoint for Juneau , Alaska is FIVE FINGERS, AK. 123.929001 km away at bearing 202.528458 degrees
27.Closest waypoint for Lansing , Michigan is LAKE ST. CLAIR. 149.161606 km away at bearing 259.276031 degrees
28.Closest waypoint for Lincoln , Nebraska is SHEBOYGAN, WI. 807.715393 km away at bearing 296.838989 degrees
29.Closest waypoint for Little Rock, Arkansas is SABINE, TX. 584.455139 km away at bearing 163.670013 degrees
30.Closest waypoint for Madison , Wisconsin is SHEBOYGAN, WI. 156.104843 km away at bearing 299.329956 degrees
```

Output without validation:

```
9.Closest waypoint for Carson City, Nevada is SAN FRANCISCO. 309.820831 km away at bearing 119.219414 degrees
10.Closest waypoint for Charleston , West Virginia is W LK ERIE. 376.041748 km away at bearing 9.754081 degrees
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41.Closest waypoint for Sacramento , California is SAN FRANCISCO. 148.283081 km away at bearing 126.205139 degrees
42.Closest waypoint for Saint Paul, Minnesota is DEVILS ISLAND, WI. 299.008118 km away at bearing 323.221375 degrees
43.Closest waypoint for Salem , Oregon is NEWPORT, OR. 89.569160 km away at bearing 113.121010 degrees
44.Closest waypoint for Salt Lake, Utah is SAN FRANCISCO. 997.999329 km away at bearing 105.949211 degrees
45.Closest waypoint for Santa Fe, New Mexico is SAN CLEMENTE. 1165.089355 km away at bearing 104.183609 degrees
46.Closest waypoint for Springfield , Illinois is S LK MICHIGAN. 388.616486 km away at bearing 326.534698 degrees
47.Closest waypoint for Tallahassee , Florida is KEATON BEACH, FL. 96.185753 km away at bearing 223.236084 degrees
48.Closest waypoint for Topeka , Kansas is S LK MICHIGAN. 832.105530 km away at bearing 301.781250 degrees
49.Closest waypoint for Trenton , New Jersey is NYC ENTR. 91.122368 km away at bearing 280.769745 degrees
Average    14.688 us
Minimum    14.358 us
debian@beaglebone:~/Project2/Test$
```

The execution time obtained after vectorization 1 & 2 is **14.608 µs**.

Run-time profile:

```
Find_Nearest_Waypoint  /home/debian/Project2/Test/sg
              {
                  return (float32x4_t)__builtin_neon_vdup_nv4sf ((__builtin_neon_sf
                  mov     sl, r4
  0.02            mov     r0, r8
                  mov     r1, r5
  0.03            str     r3, [sp, #16]
              Find_Nearest_Waypoint():
                  {
                          SinLat[j]=waypoints[j].SinLat;
                          CosLat[j]=waypoints[j].CosLat;
                          Lon[j]=waypoints[j].Lon-ref->Lon;
 28.08            vldr    s15, [r3, #12]
                  adds    r3, #48 ; 0x30
                          SinLat[j]=waypoints[j].SinLat;
  5.77            ldr.w   ip, [r3, #-44]
                          CosLat[j]=waypoints[j].CosLat;
  3.57            ldr.w   lr, [r3, #-40]
                          temp_index[j]=j;
  2.39            str.w   r2, [fp, #4]!
                  for (int j=0;j<164;j++)
                  adds    r2, #1
                          Lon[j]=waypoints[j].Lon-ref->Lon;
Press 'h' for help on key bindings
```

Function-profile:

```
Samples: 31K of event 'cycles:ppp', Event count (approx.): 7688075920
Overhead  Command  Shared Object      Symbol
  38.32%  sg       sg                 [.] Find_Nearest_Waypoint
  25.32%  sg       sg                 [.] __mcount_internal
  19.54%  sg       sg                 [.] v_cos_73
   4.62%  sg       sg                 [.] __gnu_mcount_nc
   2.24%  sg       sg                 [.] __sincosf
   2.03%  sg       sg                 [.] __ieee754_sqrtf
   1.80%  sg       sg                 [.] __ieee754_atan2f
   1.42%  sg       sg                 [.] __kernel_cosf
   1.38%  sg       sg                 [.] __atanf
   0.99%  sg       sg                 [.] __ieee754_acosf
   0.53%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irqrestore
   0.26%  sg       sg                 [.] main
   0.26%  sg       [kernel.kallsyms]  [k] __softirqentry_text_start
   0.24%  sg       sg                 [.] __kernel_sinf
   0.10%  sg       sg                 [.] strcmp
   0.09%  sg       [kernel.kallsyms]  [k] sys_clock_gettime
   0.08%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irq
   0.05%  sg       [kernel.kallsyms]  [k] vector_swi
   0.05%  sg       sg                 [.] __libc_do_syscall
   0.04%  sg       [kernel.kallsyms]  [k] setup_sigframe
   0.04%  sg       [kernel.kallsyms]  [k] restore_sigframe
Tip: Customize output of perf script with: perf script -F event,ip,sym
```

Vectorization 3:

This is aimed at vectorizing the first pass of Find_Nearest_Waypoint_Pass function in the code. In this approach the SinLat, CosLat and Lon values are stored as the members of array of structure values. These values are then loaded into 3 quad vectors segregating SinLat, CosLat and Lon values into 3 different vectors using vld3q_f32 intrinsic.

// Storing SinLat, CosLat and Lon values in array of structure

for (int j=0;j<164;j++)

{

       values[j].SinLat=waypoints[j].SinLat;

       values[j].CosLat=waypoints[j].CosLat;

       values[j].Lon=waypoints[j].Lon;

}

//Loading the values in 3 vectors

v4_waypoints=vld3q_f32(&values[i]);

The value of closeness obtained is stored in array c as follows:

vst1q_f32(&c[i],v4_c);

Output with validation:

This output was obtained after implementing vectorization 3.

```
debian@beaglebone:~/Project2/Test$ ./sg
Vaildation:
Error in distance!Expected:33.504810 Actual:33.648918 Error:-0.430111 for Boston , Massachusetts
Error in distance!Expected:180.354263 Actual:180.381088 Error:-0.014873 for Columbia , South Carolina
Error in distance!Expected:130.731613 Actual:130.750107 Error:-0.014146 for Hartford , Connecticut
Error in distance!Expected:149.129166 Actual:149.161606 Error:-0.021753 for Lansing , Michigan
Error in distance!Expected:76.643372 Actual:76.674934 Error:-0.041181 for Olympia , Washington
Error in distance!Expected:148.266769 Actual:148.283081 Error:-0.011002 for Sacramento , California
Error in distance!Expected:96.135429 Actual:96.185753 Error:-0.052346 for Tallahassee , Florida
Error in distance!Expected:91.069252 Actual:91.122368 Error:-0.058325 for Trenton , New Jersey
Output:
0.Closest waypoint for Albany , New York is NYC ENTR. 254.707184 km away at bearing 181.550583 degrees
1.Closest waypoint for Annapolis , Maryland is THOMAS POINT, MD. 9.837340 km away at bearing 213.130646 degrees
2.Closest waypoint for Atlanta , Georgia is GRAYS REEF. 421.432037 km away at bearing 232.451050 degrees
3.Closest waypoint for Augusta , Maine is PORTLAND. 93.222275 km away at bearing 161.085648 degrees
4.Closest waypoint for Austin , Texas is PORT ARANSAS, TX. 279.357788 km away at bearing 194.268921 degrees
5.Closest waypoint for Baton Rouge, Louisiana is BILOXI. 231.263412 km away at bearing 260.404968 degrees
6.Closest waypoint for Bismarck , North Dakota is DEVILS ISLAND, WI. 772.233704 km away at bearing 259.330780 degrees
7.Closest waypoint for Boise , Idaho is NEWPORT, OR. 634.778564 km away at bearing 77.240952 degrees
8.Closest waypoint for Boston , Massachusetts is BOSTON. 33.648918 km away at bearing 292.475555 degrees
9.Closest waypoint for Carson City, Nevada is SAN FRANCISCO. 309.820831 km away at bearing 119.219414 degrees
10.Closest waypoint for Charleston , West Virginia is W LK ERIE. 376.041748 km away at bearing 9.754081 degrees
11.Closest waypoint for Cheyenne , Wyoming is DEVILS ISLAND, WI. 1300.067627 km away at bearing 305.208618 degrees
12.Closest waypoint for Columbia , South Carolina is FOLLY ISLAND, SC. 180.381088 km away at bearing 216.451447 degrees
13.Closest waypoint for Columbus , Ohio is SOUTH BASS ISLAND, OH. 185.942719 km away at bearing 355.881439 degrees
14.Closest waypoint for Concord , New Hampshire is ISLE OF SHOALS, NH. 80.402351 km away at bearing 250.083450 degrees
15.Closest waypoint for Denver , Colorado is DEVILS ISLAND, WI. 1407.891968 km away at bearing 310.096191 degrees
16.Closest waypoint for Des Moines, Iowa is SHEBOYGAN, WI. 540.894043 km away at bearing 298.330109 degrees
17.Closest waypoint for Dover , Delaware is THOMAS POINT, MD. 84.108429 km away at bearing 109.976585 degrees
18.Closest waypoint for Frankfort , Kentucky is SOUTH BASS ISLAND, OH. 418.861938 km away at bearing 336.318695 degrees
19.Closest waypoint for Harrisburg , Pennsylvania is THOMAS POINT, MD. 156.847061 km away at bearing 193.910110 degrees
20.Closest waypoint for Hartford , Connecticut is MONTAUK PT. 130.750107 km away at bearing 203.853012 degrees
21.Closest waypoint for Helena , Montana is WEST POINT, WA. 795.983765 km away at bearing 77.659920 degrees
22.Closest waypoint for Honolulu , Hawaii is W HAWAII. 385.118530 km away at bearing 129.342636 degrees
23.Closest waypoint for Indianapolis , Indiana is S LK MICHIGAN. 328.521057 km away at bearing 12.689395 degrees
24.Closest waypoint for Jackson , Mississippi is BILOXI. 283.126831 km away at bearing 209.237030 degrees
25.Closest waypoint for Jefferson City, Missouri is S LK MICHIGAN. 629.953918 km away at bearing 317.949829 degrees
26.Closest waypoint for Juneau , Alaska is FIVE FINGERS, AK. 123.929001 km away at bearing 202.528458 degrees
27.Closest waypoint for Lansing , Michigan is LAKE ST. CLAIR. 149.161606 km away at bearing 259.276031 degrees
28.Closest waypoint for Lincoln , Nebraska is SHEBOYGAN, WI. 807.715393 km away at bearing 296.838989 degrees
```

Output without validation:

```
29.Closest waypoint for Little Rock, Arkansas is SABINE, TX. 584.455139 km away at bearing 163.670013 degrees
30.Closest waypoint for Madison , Wisconsin is SHEBOYGAN, WI. 156.104843 km away at bearing 299.329956 degrees
31.Closest waypoint for Montgomery , Alabama is ORANGE BCH. 282.013397 km away at bearing 154.293076 degrees
32.Closest waypoint for Montpelier , Vermont is PORTLAND. 211.352295 km away at bearing 248.053284 degrees
33.Closest waypoint for Nashville , Tennessee is DAUPHIN ISLAND, AL. 668.493042 km away at bearing 169.332596 degrees
34.Closest waypoint for Oklahoma City, Oklahoma is SABINE, TX. 723.811646 km away at bearing 207.938629 degrees
35.Closest waypoint for Olympia , Washington is WEST POINT, WA. 76.674934 km away at bearing 333.737518 degrees
36.Closest waypoint for Phoenix , Arizona is SAN CLEMENTE. 565.683105 km away at bearing 99.226471 degrees
37.Closest waypoint for Pierre , South Dakota is DEVILS ISLAND, WI. 803.698975 km away at bearing 295.413635 degrees
38.Closest waypoint for Providence , Rhode Island is BUZZARDS BAY,MA. 57.319054 km away at bearing 214.821564 degrees
39.Closest waypoint for Raleigh , North Carolina is ONSLOW BAY. 189.372559 km away at bearing 221.099457 degrees
40.Closest waypoint for Richmond , Virginia is CHESAPEAKE LIGHT, VA. 170.051636 km away at bearing 246.203003 degrees
41.Closest waypoint for Sacramento , California is SAN FRANCISCO. 148.283081 km away at bearing 126.205139 degrees
42.Closest waypoint for Saint Paul, Minnesota is DEVILS ISLAND, WI. 299.008118 km away at bearing 323.221375 degrees
43.Closest waypoint for Salem , Oregon is NEWPORT, OR. 89.569160 km away at bearing 113.121010 degrees
44.Closest waypoint for Salt Lake, Utah is SAN FRANCISCO. 997.999329 km away at bearing 105.949211 degrees
45.Closest waypoint for Santa Fe, New Mexico is SAN CLEMENTE. 1165.089355 km away at bearing 104.183609 degrees
46.Closest waypoint for Springfield , Illinois is S LK MICHIGAN. 388.616486 km away at bearing 326.534698 degrees
47.Closest waypoint for Tallahassee , Florida is KEATON BEACH, FL. 96.185753 km away at bearing 223.236084 degrees
48.Closest waypoint for Topeka , Kansas is S LK MICHIGAN. 832.105530 km away at bearing 301.781250 degrees
49.Closest waypoint for Trenton , New Jersey is NYC ENTR. 91.122368 km away at bearing 280.769745 degrees
Average    14.692 us
Minimum    14.331 us
debian@beaglebone:~/Project2/Test$ █
```

The execution time obtained after vectorization 3 is **14.692 μs**.

Run-time profile:

```
Find_Nearest_Waypoint   /home/debian/Project2/Test/sg
                {
                    return (float32x4_t)__builtin_neon_vdup_nv4sf ((__builtin_neon_sf
   0.01           mov     s1, r4
   0.05           mov     r0, r8
                  mov     r1, r5
   0.01           str     r3, [sp, #16]
                Find_Nearest_Waypoint():
                    {
                        SinLat[j]=waypoints[j].SinLat;
                        CosLat[j]=waypoints[j].CosLat;
                        Lon[j]=waypoints[j].Lon-ref->Lon;
  28.05           vldr    s15, [r3, #12]
                  adds    r3, #48 ; 0x30
                        SinLat[j]=waypoints[j].SinLat;
   6.01           ldr.w   ip, [r3, #-44]
                        CosLat[j]=waypoints[j].CosLat;
   3.62           ldr.w   lr, [r3, #-40]
                        temp_index[j]=j;
   2.68           str.w   r2, [fp, #4]!
                        for (int j=0;j<164;j++)
                  adds    r2, #1
                        Lon[j]=waypoints[j].Lon-ref->Lon;
Press 'h' for help on key bindings
```

Function-profile:

```
Samples: 31K of event 'cycles:ppp', Event count (approx.): 7727751822
Overhead  Command  Shared Object      Symbol
  37.13%  sg       sg                 [.] Find_Nearest_Waypoint
  25.35%  sg       sg                 [.] __mcount_internal
  20.48%  sg       sg                 [.] v_cos_73
   4.64%  sg       sg                 [.] __gnu_mcount_nc
   2.22%  sg       sg                 [.] __sincosf
   2.01%  sg       sg                 [.] __ieee754_sqrtf
   1.72%  sg       sg                 [.] __ieee754_atan2f
   1.56%  sg       sg                 [.] __kernel_cosf
   1.34%  sg       sg                 [.] __atanf
   1.12%  sg       sg                 [.] __ieee754_acosf
   0.51%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irqrestore
   0.29%  sg       sg                 [.] __kernel_sinf
   0.28%  sg       [kernel.kallsyms]  [k] __softirqentry_text_start
   0.25%  sg       sg                 [.] main
   0.11%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irq
   0.08%  sg       sg                 [.] strcmp
   0.08%  sg       [kernel.kallsyms]  [k] sys_clock_gettime
   0.06%  sg       [kernel.kallsyms]  [k] vector_swi
   0.06%  sg       [kernel.kallsyms]  [k] setup_sigframe
   0.04%  sg       [kernel.kallsyms]  [k] restore_sigframe
   0.04%  sg       sg                 [.] __libc_do_syscall
Tip: Save output of perf stat using: perf stat record <target workload>
```

Optimization:

Intially the for loop to store the values of SinLat, CosLat and Lon into array of structure was placed in the Find_Nearest_Waypoint_Pass function. This for loop was shifted and placed in the main function before the for loop in main function was executed for 10000 test cases. This improved the execution time by 1µs.

Output with validation:

```
debian@beaglebone:~/Project2/Test$ ./sg
Vaildation:
Error in distance!Expected:33.504810 Actual:33.648918 Error:-0.430111 for Boston , Massachusetts
Error in distance!Expected:180.354263 Actual:180.381088 Error:-0.014873 for Columbia , South Carolina
Error in distance!Expected:130.731613 Actual:130.750107 Error:-0.014146 for Hartford , Connecticut
Error in distance!Expected:149.129166 Actual:149.161606 Error:-0.021753 for Lansing , Michigan
Error in distance!Expected:76.643372 Actual:76.674934 Error:-0.041181 for Olympia , Washington
Error in distance!Expected:148.266769 Actual:148.283081 Error:-0.011002 for Sacramento , California
Error in distance!Expected:96.135429 Actual:96.185753 Error:-0.052346 for Tallahassee , Florida
Error in distance!Expected:91.069252 Actual:91.122368 Error:-0.058325 for Trenton , New Jersey
Output:
0.Closest waypoint for Albany , New York is NYC ENTR. 254.707184 km away at bearing 181.550583 degrees
1.Closest waypoint for Annapolis , Maryland is THOMAS POINT, MD. 9.837340 km away at bearing 213.130646 degrees
2.Closest waypoint for Atlanta , Georgia is GRAYS REEF. 421.432037 km away at bearing 232.451050 degrees
3.Closest waypoint for Augusta , Maine is PORTLAND. 93.222275 km away at bearing 161.085648 degrees
4.Closest waypoint for Austin , Texas is PORT ARANSAS, TX. 279.357788 km away at bearing 194.268921 degrees
5.Closest waypoint for Baton Rouge, Louisiana is BILOXI. 231.263412 km away at bearing 260.404968 degrees
6.Closest waypoint for Bismarck , North Dakota is DEVILS ISLAND, WI. 772.233704 km away at bearing 259.330780 degrees
7.Closest waypoint for Boise , Idaho is NEWPORT, OR. 634.778564 km away at bearing 77.240952 degrees
8.Closest waypoint for Boston , Massachusetts is BOSTON. 33.648918 km away at bearing 292.475555 degrees
9.Closest waypoint for Carson City, Nevada is SAN FRANCISCO. 309.820831 km away at bearing 119.219414 degrees
10.Closest waypoint for Charleston , West Virginia is W LK ERIE. 376.041748 km away at bearing 9.754081 degrees
11.Closest waypoint for Cheyenne , Wyoming is DEVILS ISLAND, WI. 1300.067627 km away at bearing 305.208618 degrees
12.Closest waypoint for Columbia , South Carolina is FOLLY ISLAND, SC. 180.381088 km away at bearing 216.451447 degrees
13.Closest waypoint for Columbus , Ohio is SOUTH BASS ISLAND, OH. 185.942719 km away at bearing 355.881439 degrees
14.Closest waypoint for Concord , New Hampshire is ISLE OF SHOALS, NH. 80.402351 km away at bearing 250.083450 degrees
15.Closest waypoint for Denver , Colorado is DEVILS ISLAND, WI. 1407.891968 km away at bearing 310.096191 degrees
16.Closest waypoint for Des Moines, Iowa is SHEBOYGAN, WI. 540.894043 km away at bearing 298.330109 degrees
17.Closest waypoint for Dover , Delaware is THOMAS POINT, MD. 84.108429 km away at bearing 109.976585 degrees
18.Closest waypoint for Frankfort , Kentucky is SOUTH BASS ISLAND, OH. 418.861938 km away at bearing 336.318695 degrees
19.Closest waypoint for Harrisburg , Pennsylvania is THOMAS POINT, MD. 156.847061 km away at bearing 193.910110 degrees
20.Closest waypoint for Hartford , Connecticut is MONTAUK PT. 130.750107 km away at bearing 203.853012 degrees
21.Closest waypoint for Helena , Montana is WEST POINT, WA. 795.983765 km away at bearing 77.659920 degrees
22.Closest waypoint for Honolulu , Hawaii is W HAWAII. 385.118530 km away at bearing 129.342636 degrees
23.Closest waypoint for Indianapolis , Indiana is S LK MICHIGAN. 328.521057 km away at bearing 12.689395 degrees
24.Closest waypoint for Jackson , Mississippi is BILOXI. 283.126831 km away at bearing 209.237030 degrees
25.Closest waypoint for Jefferson City, Missouri is S LK MICHIGAN. 629.953918 km away at bearing 317.949829 degrees
26.Closest waypoint for Juneau , Alaska is FIVE FINGERS, AK. 123.929001 km away at bearing 202.528458 degrees
27.Closest waypoint for Lansing , Michigan is LAKE ST. CLAIR. 149.161606 km away at bearing 259.276031 degrees
28.Closest waypoint for Lincoln , Nebraska is SHEBOYGAN, WI. 807.715393 km away at bearing 296.838989 degrees
```

Output without validation:

```
29.Closest waypoint for Little Rock, Arkansas is SABINE, TX. 584.455139 km away at bearing 163.670013 degrees
30.Closest waypoint for Madison , Wisconsin is SHEBOYGAN, WI. 156.104843 km away at bearing 299.329956 degrees
31.Closest waypoint for Montgomery , Alabama is ORANGE BCH. 282.013397 km away at bearing 154.293076 degrees
32.Closest waypoint for Montpelier , Vermont is PORTLAND. 211.352295 km away at bearing 248.053284 degrees
33.Closest waypoint for Nashville , Tennessee is DAUPHIN ISLAND, AL. 668.493042 km away at bearing 169.332596 degrees
34.Closest waypoint for Oklahoma City, Oklahoma is SABINE, TX. 723.811646 km away at bearing 207.938629 degrees
35.Closest waypoint for Olympia , Washington is WEST POINT, WA. 76.674934 km away at bearing 333.737518 degrees
36.Closest waypoint for Phoenix , Arizona is SAN CLEMENTE. 565.683105 km away at bearing 99.226471 degrees
37.Closest waypoint for Pierre , South Dakota is DEVILS ISLAND, WI. 803.698975 km away at bearing 295.413635 degrees
38.Closest waypoint for Providence , Rhode Island is BUZZARDS BAY,MA. 57.319054 km away at bearing 214.821564 degrees
39.Closest waypoint for Raleigh , North Carolina is ONSLOW BAY. 189.372559 km away at bearing 221.099457 degrees
40.Closest waypoint for Richmond , Virginia is CHESAPEAKE LIGHT, VA. 170.051636 km away at bearing 246.203003 degrees
41.Closest waypoint for Sacramento , California is SAN FRANCISCO. 148.283081 km away at bearing 126.205139 degrees
42.Closest waypoint for Saint Paul, Minnesota is DEVILS ISLAND, WI. 299.008118 km away at bearing 323.221375 degrees
43.Closest waypoint for Salem , Oregon is NEWPORT, OR. 89.569160 km away at bearing 113.121010 degrees
44.Closest waypoint for Salt Lake, Utah is SAN FRANCISCO. 997.999329 km away at bearing 105.949211 degrees
45.Closest waypoint for Santa Fe, New Mexico is SAN CLEMENTE. 1165.089355 km away at bearing 104.183609 degrees
46.Closest waypoint for Springfield , Illinois is S LK MICHIGAN. 388.616486 km away at bearing 326.534698 degrees
47.Closest waypoint for Tallahassee , Florida is KEATON BEACH, FL. 96.185753 km away at bearing 223.236084 degrees
48.Closest waypoint for Topeka , Kansas is S LK MICHIGAN. 832.105530 km away at bearing 301.781250 degrees
49.Closest waypoint for Trenton , New Jersey is NYC ENTR. 91.122368 km away at bearing 280.769745 degrees
Average    14.930 us
Minimum    14.448 us
debian@beaglebone:~/Project2/Test$
```

Run-time profile:

```
Find_Nearest_Waypoint   /home/debian/Project2/Test/sg
            {
                return (float32x4_t)__builtin_neon_vdup_nv4sf ((__builtin_neon_sf
   0.02            mov     sl, r4
   0.02            mov     r0, r8
                   mov     r1, r5
   0.03            str     r3, [sp, #16]
                Find_Nearest_Waypoint():
                {
                        SinLat[j]=waypoints[j].SinLat;
                        CosLat[j]=waypoints[j].CosLat;
                        Lon[j]=waypoints[j].Lon-ref->Lon;
  28.60            vldr    s15, [r3, #12]
                   adds    r3, #48 ; 0x30
                        SinLat[j]=waypoints[j].SinLat;
   6.10            ldr.w   ip, [r3, #-44]
                        CosLat[j]=waypoints[j].CosLat;
   3.66            ldr.w   lr, [r3, #-40]
                        temp_index[j]=j;
   2.50            str.w   r2, [fp, #4]!
                   for (int j=0;j<164;j++)
                   adds    r2, #1
                        Lon[j]=waypoints[j].Lon-ref->Lon;
Press 'h' for help on key bindings
```

Function-profile:

```
Samples: 31K of event 'cycles:ppp', Event count (approx.): 7761412473
Overhead  Command  Shared Object      Symbol
  37.24%  sg       sg                 [.] Find_Nearest_Waypoint
  25.52%  sg       sg                 [.] __mcount_internal
  20.39%  sg       sg                 [.] v_cos_73
   4.50%  sg       sg                 [.] __gnu_mcount_nc
   2.20%  sg       sg                 [.] __sincosf
   2.15%  sg       sg                 [.] __ieee754_sqrtf
   1.65%  sg       sg                 [.] __ieee754_atan2f
   1.58%  sg       sg                 [.] __kernel_cosf
   1.23%  sg       sg                 [.] __atanf
   1.05%  sg       sg                 [.] __ieee754_acosf
   0.61%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irqrestore
   0.26%  sg       sg                 [.] __kernel_sinf
   0.23%  sg       sg                 [.] main
   0.23%  sg       [kernel.kallsyms]  [k] __softirqentry_text_start
   0.12%  sg       sg                 [.] strcmp
   0.11%  sg       [kernel.kallsyms]  [k] sys_clock_gettime
   0.09%  sg       [kernel.kallsyms]  [k] vector_swi
   0.08%  sg       [kernel.kallsyms]  [k] setup_sigframe
   0.07%  sg       [kernel.kallsyms]  [k] _raw_spin_unlock_irq
   0.06%  sg       [kernel.kallsyms]  [k] restore_sigframe
   0.04%  sg       [kernel.kallsyms]  [k] arm_copy_to_user
Tip: Save output of perf stat using: perf stat record <target workload>
```

Conclusion:

Hence by utilizing SIMD instructions via compiler intrinsics to implement vectorization we were able to reduce the execution time from **54.447 µs** to **14.930 µs**. A speedup of almost **3.646** was obtained by implementing vectorization.