POINT SPREAD

Okulo Multi-Camera Synchronization User's Guide

Release 1.0

Point Spread Technology Co., Ltd.

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ONE

INTRODUCTION

Okulo ™ P1 series cameras produced by Point Spread use RGB and ToF sensors to capture the RGB and Depth images for 3D applications. However, when capturing the image of objects from one perspective, the Okulo ™ camera cannot obtain the color and depth information from the other perspectives due to objects' occlusions and the camera's limited field of view. One solution to this problem is to take sequential images from multiple locations and perspectives by moving the camera or the object. This trivial solution works well on static and rigid objects but usually fails on dynamic or flexible ones. To this end, Point Spread provides a solution that drives multiple Okulo ™ cameras to capture images of an object from multiple locations and perspectives simultaneously, and use interleaved exposure time for these cameras to avoid mutual interference.

For a quick overview of the maximum number of cameras that can be arranged to be synchronized, we present the following tables under 15, 30 and 60 frame-per-second configurations. In general, with 15fps setting, the maximum number of cameras to synchronize is between 10 and 48; with 30 fps setting, the maximum number of cameras to synchronize is between 4 and 24; and with 60 fps setting, the maximum number of cameras to synchronize is between 2 and 12. In the following sections, we provide the algorithms and calculation steps to correctly set the time divisions for those cameras.

Table 1.1: Max number of cameras to synchronize for 15fps frame rate

Frame rate / *fps*	ToF sub-frame exposure time / *milli-second*	Max No. of Cameras to Sync
15	1.2	10
15	1.1	10
15	1.0	10
15	0.9	12
15	0.8	12
15	0.7	12
15	0.6	12
15	0.5	21
15	0.4	21
15	0.3	28
15	0.2	32
15	0.1	48

Table 1.2: Max number of cameras to synchronize for 30fps frame rate

Frame rate / *fps*	ToF sub-frame exposure time / *milli-second*	Max No. of Cameras to Sync
30	1.2	4
30	1.1	4
30	1.0	4
30	0.9	6
30	0.8	6
30	0.7	6
30	0.6	6
30	0.5	9
30	0.4	9
30	0.3	12
30	0.2	16
30	0.1	24

Table 1.3: Max number of cameras to synchronize for 60fps frame rate

Frame rate / *fps*	ToF sub-frame exposure time / *milli-second*	Max No. of Cameras to Sync
60	1.2	2
60	1.1	2
60	1.0	2
60	0.9	2
60	0.8	2
60	0.7	2
60	0.6	2
60	0.5	3
60	0.4	3
60	0.3	4
60	0.2	8
60	0.1	12

CHAPTER

TWO

MULTI-CAMERA SYNCHRONIZATION

2.1 Overview

When there are multiple Okulo ™ cameras in the same scenario, each of them needs to first emit infrared optical waves and then receive the reflected waves to measure object depth. If one camera's emitted wave is received by another, the latter one's depth measurement will be disturbed. And this can happen the other way around, which we refer to as mutual interference.

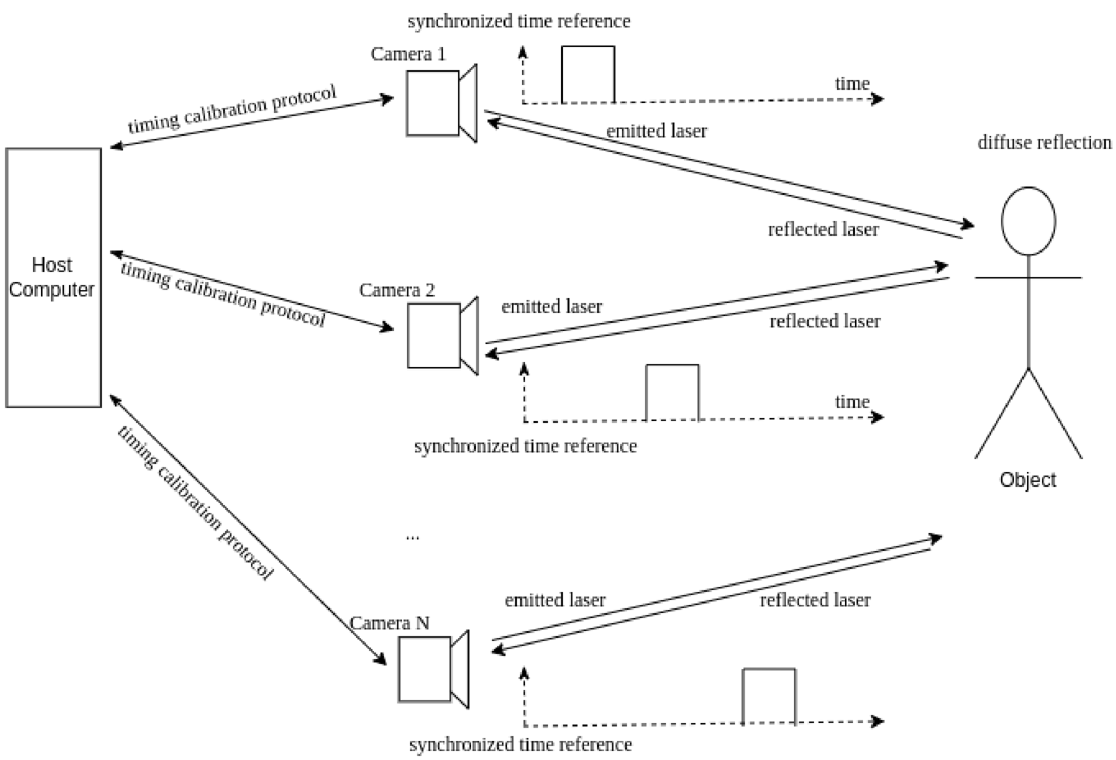

Fig. 2.1: Overview of a multiple camera capturing system

To build a multi-camera capturing system free from mutual interference as in Fig. 2.1, a USB transaction-based timing calibration protocol is first developed to help multiple cameras synchronize with each other. The protocol has high synchronization accuracy of down to 200 µs jitter. Once multiple cameras are synchronized, we can assign non-overlapped time slots as the exposure time for them to measure distance. These Okulo ™ cameras will no longer interfere with each other, thus achieving the cooperation of multiple cameras.

2.2 iToF Exposure Timing

The iToF sensor in an Okulo ™ P1 camera needs to acquire 4 sub-frames to compose a single depth frame, and after exposure for each sub-frame, the sensor will take about 1.75ms to transmit the sub-frame data to the processor. After the exposure and data transmission, there will be an idle stage until starting to expose for a new depth frame. The stages, including 4 exposures, 4 sub-frame data transmissions and idle, will periodically iterate at the depth frame rate such as 30fps, or 100fps. The exposure timing of an iToF is shown in Fig. 2.2. Note that the exposure time we refer to is the sub-frame's exposure time.

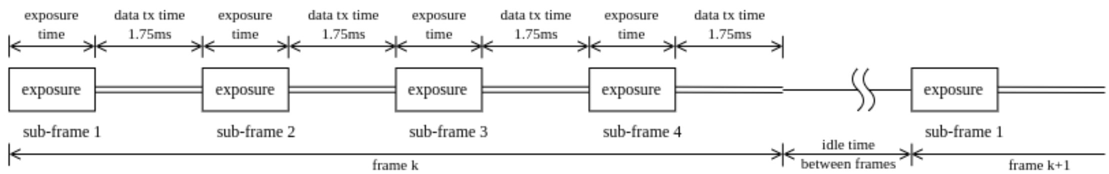

Fig. 2.2: iToF exposure timing

We define the **frame time** as the sum of the 4 exposures and 4 data transmission time:

$$t_\mathrm{f} = 4 \cdot t_\mathrm{e} + 7\mathrm{ms}, \tag{2.1}$$

in which t_e is the exposure time.

Thus the **idle time** can be derived as:

$$t_\mathrm{i} = 1/f - 4 \cdot t_\mathrm{e} - 7\mathrm{ms}, \tag{2.2}$$

in which f is the frame rate.

2.3 Frame Interleave Mode

To use multiple cameras in the same scenario, different cameras should expose at different time slots. Other than that, there must be a safe interval between any two cameras' exposure times due to the 200 µs jitter. For example, in a two-camera system, if the second camera's frame time is less than the first camera's idle time and there are sufficient synchronization safe intervals between the two cameras, they can work well in an interleaved manner and are free from mutual interference, as shown in Fig. 2.3. We call this synchronization mode as **Frame Interleave** mode. We use $t_\mathrm{s} = 200$ µs to denote the **safe interval**.

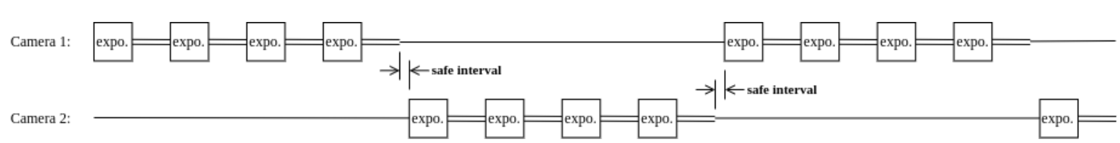

Fig. 2.3: Frame Interleave Mode

In a more generalized case that we want to interleave n cameras, the following constraints must be assured:

$$(n-1) \cdot t_\mathrm{f} + n \cdot t_\mathrm{s} \leq t_\mathrm{i} \tag{2.3}$$

By combining the above equations, we can derive:

$$
\begin{aligned}
n &\le \frac{t_\mathrm{f} + t_\mathrm{i}}{t_\mathrm{f} + t_\mathrm{s}}, \\
n_\mathrm{max} &= \left\lfloor \frac{t_\mathrm{f} + t_\mathrm{i}}{t_\mathrm{f} + t_\mathrm{s}} \right\rfloor = \left\lfloor \frac{1/f}{4 \cdot t_\mathrm{e} + t_\mathrm{s} + 7\mathrm{ms}} \right\rfloor,
\end{aligned}
\tag{2.4}
$$

in which $\lfloor \cdot \rfloor$ is the floor operator.

2.4 Sub-Frame Interleave Mode

If sub-frame time, namely the exposure time is less than the data transmission time and a safe interval can be guaranteed, two cameras can work interleavely, as shown in Fig. 2.4. We call this synchronization mode as **Sub-Frame Interleave Mode**.

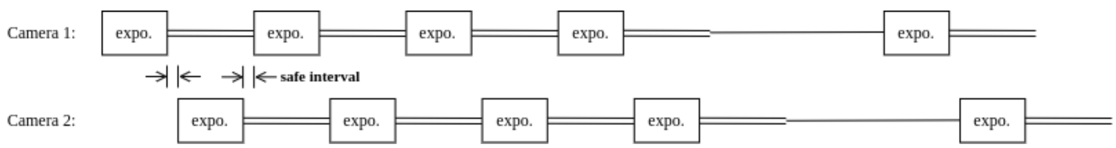

Fig. 2.4: Sub-Frame Frame Interleave Mode

If we want to interleave k cameras in this Sub-Frame Interleave Mode, the following constraints must be satisfied:

$$
(k-1) \cdot t_\mathrm{e} + k \cdot t_\mathrm{s} \le 1.75\mathrm{ms}. \tag{2.5}
$$

Thus, we have:

$$
\begin{aligned}
k &\le \frac{t_\mathrm{e} + 1.75\mathrm{ms}}{t_\mathrm{e} + t_\mathrm{s}}, \\
k_\mathrm{max} &= \left\lfloor \frac{t_\mathrm{e} + 1.75\mathrm{ms}}{t_\mathrm{e} + t_\mathrm{s}} \right\rfloor.
\end{aligned}
\tag{2.6}
$$

CHAPTER

THREE

AUTOMATIC CALCULATION OF EXPOSURE TIME DIVISION

3.1 Okulo Viewer

The okulo_viewer program has been developed with an automatic exposure time division calculation function for synchronizing multiple devices. If you connect two or more Okulo cameras to your host computer and open the okulo_viewer on the host, the `Multi-Device` module will show up. The `Multi-Device` module will check the frame rates, exposure times and parameter limitations of these connected cameras. For those cameras with the same frame rate, the module will calculate the start and stop exposure time points in one exposure period. The occupied time slots by each camera's four sub-frames will be displayed as segments in a ring. Different colors are used to highlight different cameras except that the red color is used to represent conflicts of exposure time. As shown in Fig. 3.1, two cameras with serial numbers `SOKL130002` and `SOKL130004` are working in 60 frame-per-second. Their exposure times are represented with four orange segments and four yellow segments, and no conflict happens between them. Another case with exposure time conflicts is shown in Fig. 3.2. The `SOKL130004`'s first, second and third sub-frames are conflicted with `SOKL130004`'s second, third and fourth sub-frame. These conflicts are marked with red colors. If there exist conflicts, click the radio button beside `ExpoTime` in the `Multi-Device` interface. Then the program will automatically calculate a setting to avoid conflicts. The strategy behind the automatic exposure time division obeys the following rules:

1) Use Sub-Frame Interleave Mode as a preference, otherwise use Frame Interleave Mode;
2) Adjust exposure phases as a preference. If conflicts still exist, then adjust exposure times at the same frame rate.

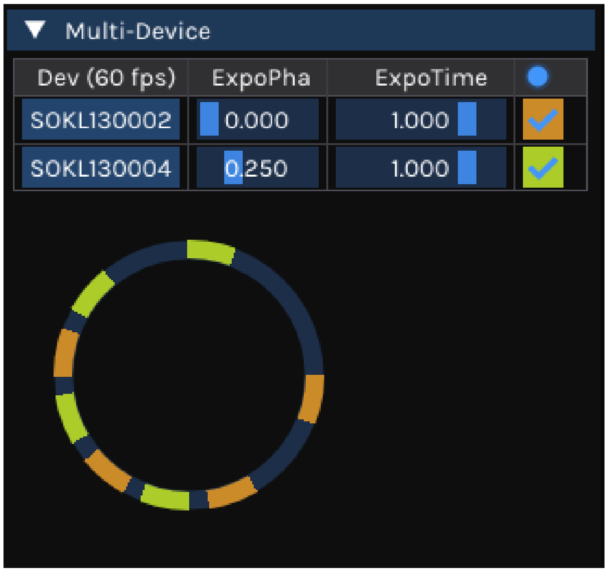

Fig. 3.1: Exposure settings with no conflict

Fig. 3.2: Exposure settings with conflict

3.2 SDK API

The Aurora SDK provides APIs to set the exposure times and phases of cameras. It's ensured by the parameters you set that cameras with active encoded lighting won't interfere with each other. A multi-device example in OkuloSdk/example/multiDevice is given to demonstrate two cameras working at the same time. We list the core function of the example in Listing 3.1. In Line 21-22 of Listing 3.1, we set the two cameras to the same frame rate of 60fps. In Line 24-25, we set both cameras to use 1.0 milli-second sub-frame exposure time. In Line 27-28, we set the two cameras to use 0.0 and 0.5 normalized exposure phase (see *Normalized Exposure Phase* definition), which means that the two cameras will work in the **Frame Interleave Mode** and they are conflict-free.

Listing 3.1: multiDevice in Frame Interleave Mode

```
1  int multiDeviceDemo()
2  {
3      auto devSNlist = getDeviceSerialsNumberList();
4      if (devSNlist.size() >= 2)
5      {
6          PDdevice devInst1(devSNlist[0]);
7          PDdevice devInst2(devSNlist[1]);
8
9          if (devInst1 && devInst2)
10         {
11             auto tofStream1 = PDstream(devInst1, "ToF");
12             auto tofStream2 = PDstream(devInst2, "ToF");
13
14             if (tofStream1 && tofStream2)
15             {
16                 tofStream1.set("Distance", 7.5f);
17                 tofStream2.set("Distance", 7.5f);
18
19                 // Please refer to the Automatic Exposure Time Division section
```

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```
                //   to set StreamFps, Exposure and ExpoNpha
                tofStream1.set("StreamFps", 60);
                tofStream2.set("StreamFps", 60);

                tofStream1.set("Exposure", 1.0f);
                tofStream2.set("Exposure", 1.0f);

                tofStream1.set("ExpoNpha", 0.0f);
                tofStream2.set("ExpoNpha", 0.5f);

                while (1)
                {
                    auto frame1 = tofStream1.waitFrames();
                    auto frame2 = tofStream2.waitFrames();
                    char key = cv::waitKey(1);
                    if (key == 'q')
                        break;
                    showFrame(frame1, 1, key == 'c');
                    showFrame(frame2, 2, key == 'c');

                    std::this_thread::sleep_for(std::chrono::milliseconds(1));
                }
                return true;
            }
        }
    }
    return false;
}
```

Alternatively, a developer may use other settings to synchronize two cameras. For example, according to the settings in Fig. 3.1, the second camera’s `ExpoNpha` can be set to 0.25. As shown in Listing 3.2, the two cameras are working in the **Sub-Frame Interleave Mode**. We encourage developers to use the settings calculated by the okulo_viewer to configure their multiple cameras without conflicts.

Listing 3.2: multiDevice in Sub-Frame Interleave Mode

```
   tofStream1.set("StreamFps", 60);
   tofStream2.set("StreamFps", 60);

   tofStream1.set("Exposure", 1.0f);
   tofStream2.set("Exposure", 1.0f);

   tofStream1.set("ExpoNpha", 0.0f);
   tofStream2.set("ExpoNpha", 0.25f);
```

CHAPTER

FOUR

MANUAL CALCULATION OF EXPOSURE TIME DIVISION

The calculation will become complex when setting cameras with different exposure times. We provide a manual calculation method when cameras are set to the same exposure time. Below we first introduce the concept of normalized exposure phase and show the calculation steps on how to divide the time slots for multiple cameras using the above Frame Interleave Mode and Sub-Frame Interleave Mode.

4.1 Normalized Exposure Phase

Once a camera's first sub-frame's starting time is given, its full exposure timing can be determined. Therefore, to obtain the time division plan in a multi-camera system, we only have to decide the first sub-frame's starting time of each camera. For the convenience of calculating time division, we define the normalized phase Φ as below to describe the exposure starting time point of the **first sub-frame**:

$$\Phi = \frac{t_{\text{start}}}{T} = f t_{\text{start}}, \tag{4.1}$$

where T is the period of capturing a depth frame. Fig. 4.1 shows the timing of 4 cameras working in mixed Frame Interleave Mode and Sub-Frame Interleave Mode, the normalized exposure phase of these cameras are:

$$\begin{aligned} \Phi_0 &\overset{\text{def}}{=} 0 \\ \Phi_1 &= t_1/T = t_1 f \\ \Phi_2 &= t_2/T = t_2 f \\ \Phi_3 &= t_3/T = t_3 f \end{aligned} \tag{4.2}$$

4.2 Calculation Steps

Now we can calculate of time division plan for a multi-camera system. What's known:

1. Frame rate f;
2. Exposure time t_{e};
3. Safe interval time $t_{\text{s}} = 0.2\text{ms}$;
4. Number of cameras to co-operate N.

Calculation Steps:

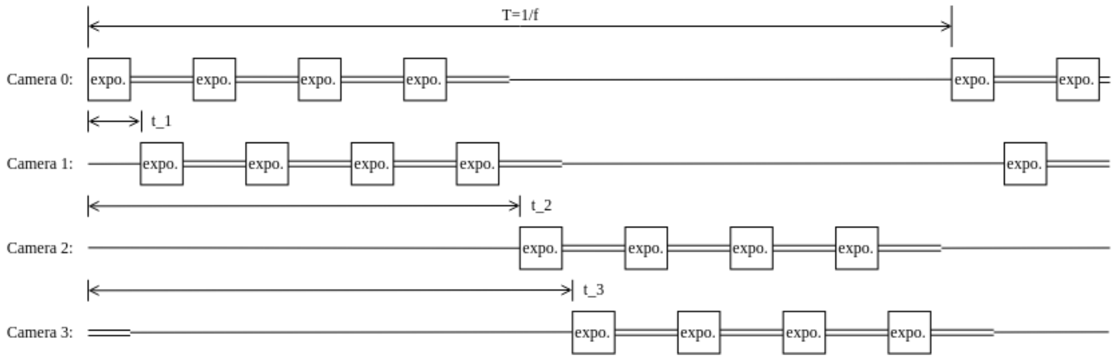

Fig. 4.1: Mixed Frame Interleave and Sub-Frame Interleave Modes

1. Calculate max Sub-Frame Interleave number by Eq. (2.6):

$$k_{\text{max}} = \left\lfloor \frac{t_{\text{e}} + 1.75\text{ms}}{t_{\text{e}} + t_{\text{s}}} \right\rfloor \tag{4.3}$$

1. Calculate max Frame Interleave number by Eq. (2.4):

$$n_{\text{max}} = \left\lfloor \frac{1/f}{4 \cdot t_{\text{e}} + t_{\text{s}} + 7\text{ms}} \right\rfloor \tag{4.4}$$

3. If $k_{\text{max}} \cdot n_{\text{max}} < N$, reduce f or/and t_{e}, and try step 1 - 2 again.
4. Select proper k and n to make $k \leq k_{\text{max}},\ n \leq n_{\text{max}}$ and $nk \geq N$, it's recommended that:

$$\begin{aligned} k &= \left\lceil \sqrt{N k_{\text{max}} / n_{\text{max}}} \right\rceil \\ n &= \lceil N/k \rceil \end{aligned} \tag{4.5}$$

And nk may be larger than N, meaning that more than N interleave slots can be arranged and some slots can be left unused.

5. Calculate normalized phases:

   k normalized phases $\Phi_i,\ i = 0, 1, \cdots, k-1$:

$$\Phi_i = \frac{if(t_{\text{e}} + 1.75\text{ms})}{k} \tag{4.6}$$

n normalized phases $\Phi_j,\ j = 0, 1, \cdots, n-1$

$$\Phi_j = \frac{j}{n} \tag{4.7}$$

6. nk normalized phases for cameras:

$$\Phi_{j,i} = \Phi_i + \Phi_j \tag{4.8}$$

4.3 Calculation Example

What's known:

1. Frame rate $f = 30\text{Hz}$;
2. Exposure time $t_\text{e} = 0.7\text{ms}$;
3. Safe interval time t_s, normally $t_\text{s} = 0.2\text{ms}$;
4. Number of cameras co-operation $N = 4$.

Calculation Steps:

1. Calculate max Sub-Frame Interleave number by Eq. (2.6):

$$k_\text{max} = \left\lfloor \frac{t_\text{e} + 1.75\text{ms}}{t_\text{e} + t_\text{s}} \right\rfloor = 2$$

1. Calculate max Frame Interleave number by Eq. (2.4):

$$n_\text{max} = \left\lfloor \frac{1/f}{4 \cdot t_\text{e} + t_\text{s} + 7\text{ms}} \right\rfloor = 3$$

3. It's true $k_\text{max} \cdot n_\text{max} \geq N$.
4. Select proper k and n to make $k \leq k_\text{max},\ n \leq n_\text{max}$ and $nk \geq N$, and use the recommended formula:

$$k = \left\lceil \sqrt{N k_\text{max} / n_\text{max}} \right\rceil = 2$$
$$n = \lceil N/k \rceil = 2$$

5. Calculate normalized phases:

k normalized phases $\Phi_i,\ i = 0, 1, \cdots, k-1$:

$$\{\Phi_i\} = \{0, 0.03675\}$$

n normalized phases $\Phi_j,\ j = 0, 1, \cdots, n-1$:

$$\{\Phi_j\} = \{0, 0.5\}$$

6. Normalized phases for cameras:

$$\Phi_{0,0} = 0$$
$$\Phi_{0,1} = 0.03675$$
$$\Phi_{1,0} = 0.5$$
$$\Phi_{1,1} = 0.53675$$

Therefore we can set the 4 cameras with these 4 normalized phases.

4.4 Spreadsheet for Calculation

We implemented the above calculation steps in LibreOffice Calc (http://dev.pointspread.cn:82/idle_time_calc.ods) for Linux users and Microsoft Excel (http://dev.pointspread.cn:82/idle_time_calc.xlsx) for Windows users.

Fig. 4.2 shows the contents in LibreOffice Calc calculation spreadsheet, users can input frame rate, exposure time, safe interval and number of cameras in the yellow cells, and the recommended k, n and normalized phases for camera settings will show in blue and red cells.

User Input			
frame rate	f_frame	30	fps
exposure time	t_expo	0.70	ms
safe interval	t_safe	0.20	ms
number of cameras	N	4	
Calculated number of interleaved cameras			
frame time	t_frame	9.8	ms
idle time between frame	t_idle	23.533	ms
Max number of inner-frame interleave	k_max	2	
Max number of inter-frame interleave	n_max	3	
Arrangeable?		YES	
number of inner-frame interleave	k	2	
number of inter-frame interleave	n	2	

		Inter-frame interleave							
		J	0	1	2	3	4	5	6
Inner-frame interleave	I	Phi	0.0000	0.5000	1.0000	1.5000	2.0000	2.5000	3.0000
	0	0.0000	0.0000	0.5000	1.0000	1.5000	2.0000	2.5000	3.0000
	1	0.0368	0.0368	0.5368	1.0368	1.5368	2.0368	2.5368	3.0368
	2	0.0735	0.0735	0.5735	1.0735	1.5735	2.0735	2.5735	3.0735
	3	0.1103	0.1103	0.6103	1.1103	1.6103	2.1103	2.6103	3.1103
	4	0.1470	0.1470	0.6470	1.1470	1.6470	2.1470	2.6470	3.1470
	5	0.1838	0.1838	0.6838	1.1838	1.6838	2.1838	2.6838	3.1838
	6	0.2205	0.2205	0.7205	1.2205	1.7205	2.2205	2.7205	3.2205

Fig. 4.2: Spreadsheet of time division calculation

CHAPTER

FIVE

ABOUT US

Point Spread Technology Co., Ltd. is committed to revolutionize computational photography, computational optics with its world-leading computational imaging technology. We vow to push forward imaging in the consumer electronics, vehicle-mounted and other related industrial fields, to initiate the automotive optimization era in optics design and the joint-optimization for optics and image signal processing.

Point Spread Technology Co., Ltd. is located in China and have multiple branches in Shenzhen and Nantong. Please feel free to get help by contacting support@pointspread.cn.