ATS-GPU-NUFFT

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ONE

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CHAPTER

TWO

INTRODUCTION

ATS-GPU-NUFFT provides a framework to allow real-time, non-uniform Fourier transform processing from AlazarTech PCIe digitizers on a CUDA-compatible GPU.

ATS-GPU-NUFFT internally calls ATS-CUDA-NUFFT, which is a low-level library that performs all the necessary operations to perform the non-uniform Fourier Transform. ATS-CUDA-NUFFT is described later in this guide in the section *ATS-CUDA-NUFFT*.

This document assumes that the reader is familiar with ATS-SDK, the standard interface for programming AlazarTech digitizers. Having a copy of the ATS-SDK manual available can be helpful, since many references to ATSApi functions are done here. The latest version of the ATS-SDK manual can be downloaded free of charge from AlazarTech's website.

CHAPTER

THREE

PREREQUISITES

3.1 System requirements

This software requires a PC with a CUDA-enabled GPU, and sufficient CPU resources to supply data to the GPU at the desired data acquisition rate. It also requires a working installation of the same version of ATS-GPU-BASE and ATS-GPU-OCT. It was tested with a GeForce RTX 2080 Ti and a Quadro P5000. DDR4 memory and a modern chipset (X99, X299) will greatly improve transfer speed and overall performance.

Supported operating systems Windows and Linux operating systems are supported. Please verify that your Linux distribution is supported by NVIDIA which supplies the CUDA toolkit required to use ATS-GPU.

Compiler support The C++ code was written with Microsoft Visual C++ 2015, and requires Microsoft Visual C++ 2015 or later. Please note that a Community Edition of Visual Studio is available for free. It is fully compatible with our code samples. CMake can be used to build C++ code. CMake files are provided. On Linux, a C++11 compiler is required to build the library. On older Red Hat distributions, a devtoolset can be obtained to use a more recent version of gcc that supports C++11. NVCC is required to compile the example code, this compiler is included with CUDA toolkit.

CUDA driver requirements In order to use ATS-GPU, you must install the appropriate driver for your CUDA-enabled GPU. Drivers can be downloaded at https://www.nvidia.com/Download/index.aspx.

CHAPTER

FOUR

ATS-GPU-NUFFT

ATS-GPU-NUFFT leverages ATS-GPU-BASE to transfer data from an ATS PCIe digitizer to a GPU in a highly efficient manner. It then takes care of doing NUFFT processing on the data before sending it back to the host computer's RAM. ATS-GPU-NUFFT also relies on ATS-GPU-OCT for standard FFT processing stages.

4.1 Usage

Note: Installation of ATS-GPU-NUFFT generates a Dynamic Link Library (.dll) in ../nufft/library/${arch_type}. In order to link ATS-GPU-NUFFT.dll to your application, you must copy it to /Windows/System32.

ATS-GPU-NUFFT acquisitions are very similar to standard ATSApi acquisitions. Only the differences are listed here for brevity.

The central function of the ATS-GPU-NUFFT interface is `ATS_GPU_NUFFT_Setup()`. This function calls its ATS-GPU-BASE counterpart `ATS_GPU_Setup()` internally, which in turns calls `AlazarBeforeAsyncRead()`. It takes a few extra parameters:

- `OCTFlags`: Used to define which data type, such as amplitude and phase, to obtain from the acquisition.
- `FFTLength`: This is used to select the length of the Fourier transform done on the GPU. This value should be a power of two for efficiency, and it also must be equal to or larger than the record length.
- `NUFFTFlags`: Used to define the source of the linearization function. Linearization can either be user defined by selecting `ATS_GPU_NUFFT_PRESET_LINEARIZATION` or be determined from a K-clock signal when `ATS_GPU_NUFFT_KCLOCK_LINEARIZATION` is used.

```
rc = ATS_GPU_NUFFT_Setup(
         boardHandle, channelMask, -(int) preTriggerSamples,
         samplesPerRecordPerChannel, recordsPerBuffer,
         buffersPerAcquisition * recordsPerBuffer, autoDMAFlags,
         OCTOptions, FFTLength, NUFFTFlags, NULL, &fftBytesPerBuffer);
// Error handling
```

If NUFFTFlags is setup with ATS_GPU_NUFFT_KCLOCK_LINEARIZATION, the channelMask must contain CHANNEL_A and at least one other active channel. With this flag, ATS-GPU-NUFFT will determine the linearization function for each record from the k-clock signal acquired on CHANNEL_A and use it to perform non-uniform FFT on every other active channel.

If NUFFTFlags was setup with ATS_GPU_NUFFT_PRESET_LINEARIZATION, the user is required to specify a precalibrated linearization function. This linearization function will be used to perform non-uniform FFT on every record of every active channel.

```
int precalibratedFunctionLength = 1000;
std::vector<float> precalibratedFunction(precalibratedFunctionLength);
for (int i = 0; i < precalibratedFunction.size(); i++) {
    precalibratedFunction[i] = i;
}
rc = ATS_GPU_NUFFT_SetLinearizationFunction(
            boardhandle, precalibratedFunction,
            &precalibratedFunction[0]);
// Error handling
```

Here, we generated a linear linearization function. Setting a linear precalibrated function represents a signal that is sampled linearly in k-space, thus equivalent to applying regular FFT.

The precalibrated linearization function can have any length as ATS-GPU-NUFFT will internally take care of re-sampling the function to a length equal to samplesPerRecordPerChannel. ATS-GPU-NUFFT will also normalize the function. The precalibrated linearization can therefore have any start and end values. The values of the precalibrated linearization function must always be increasing such as x[i]<x[i+1].

We then choose the window function applied to the acquired data before the FFT processing phase. The most common usage pattern is to first generate a window function using ATS_GPU_OCT_GenerateWindowFunction(), then to download it to the board using ATS_GPU_NUFFT_SetWindowFunction(). It is possible however to use entirely custom window functions instead of the ones generated by the API. It is also possible to use complex window functions by way of downloading two arrays of points: the first for the real part of the window and the other for the imaginary one.

```
rc = ATS_GPU_OCT_GenerateWindowFunction(
            FFT_WINDOW_HANNING, &window[0],
            samplesPerRecordPerChannel);
// Error handling

rc = ATS_GPU_NUFFT_SetWindowFunction(
            boardHandle, samplesPerRecordPerChannel,
            &window[0], NULL);
// Error handling
```

We then allocate memory on the GPU and CPU for data to be transferred to, and we post those buffers to the board. For this purpose, we use ATS_GPU_NUFFT_AllocBuffer(). This function allocates buffers on the GPU, and sets up all the intermediary states necessary for ATS-GPU-NUFFT to successfully transfer data. It also allocates data on the CPU to receive the processed data.


```
for (int i = 0; i < numberOfBuffers; i++)
{
    buffers[i] = (float*) ATS_GPU_NUFFT_AllocBuffer(
        boardHandle, bytesPerResultBuffer, NULL);

    rc = ATS_GPU_NUFFT_PostBuffer(
        boardHandle, buffers[i], bytesPerResultBuffer);
    // Error handling
}
```

We can then start the acquisition with ATS_GPU_NUFFT_StartCapture(). Once the acquisition is started, ATS_GPU_NUFFT_GetBuffer() must be called as often as possible to retrieve a buffer containing processed data on the CPU. The data can then be used by the calling application. When no longer needed, the buffer needs to be posted back.

```
for (size_t i; i < buffers_per_acquisition; i++)
{
    rc = ATS_GPU_NUFFT_GetBuffer(
        boardHandle, buffers[bufferIndex],timeout_ms);
    // Error handling

    // TODO: Process sample data in this buffer.

    rc = ATS_GPU_NUFFT_PostBuffer(
        boardHandle, buffers[bufferIndex], bytesPerResultBuffer);
    // Error handling
}
```

When acquisition is complete, ATS_GPU_NUFFT_AbortCapture() must be called. Buffers allocated with ATS_GPU_NUFFT_AllocBuffer() should then be freed with ATS_GPU_NUFFT_FreeBuffer().

```
ATS_GPU_NUFFT_AbortCapture(boardHandle);

if (gpuFile != NULL)
    fclose(gpuFile);

// Free buffers
for (int i = 0; i < numberOfBuffers; i++) {
    ATS_GPU_NUFFT_FreeBuffer(boardHandle, buffers[i]);
}
```

4.2 API Reference

enum ATS_GPU_NUFFT_OPTIONS

Linearization source specifier. If ATS_GPU_NUFFT_KLCOCK_LINEARIZATION is used, k-clock signal must be connected to CHANNEL_A. If ATS_GPU_NUFFT_PRESET_LINEARIZATION is used, a linearization calibration function must be set using ATS_GPU_NUFFT_SetLinearizationWindowFunction(). This is used in *ATS_GPU_NUFFT_Setup()*.

Values:

ATS_GPU_NUFFT_PRESET_LINEARIZATION = 1 << 0

ATS_GPU_NUFFT_KCLOCK_LINEARIZATION = 1 << 1

RETURN_CODE **ATS_GPU_NUFFT_AbortCapture**(HANDLE *boardHandle*)

Stops the acquisition.

Aborts an acquisition, stops data processing, and releases allocated resources.

Return ApiSuccess

Parameters

- `boardHandle`: Handle to the board

void ***ATS_GPU_NUFFT_AllocBuffer**(HANDLE *boardHandle*, U32 *bytesPerBuffer*, void **reserved*)

Allocates page-aligned pinned memory for ATS and GPU boards.

This function must be called after *ATS_GPU_NUFFT_Setup()* to perform the necessary memory allocations. This function returns a CPU result buffer pointer.

Parameters

- `boardHandle`: Handle to the board
- `bytesPerBuffer`: Total number of bytes to allocate per buffer
- `reserved`: Pass NULL.

RETURN_CODE **ATS_GPU_NUFFT_EnableVerificationMode**(BOOL *enable*, U32 *boardType*)
Enable verification mode to supply already acquired data.

Parameters

- `enable`: Pass 1 to enable
- `boardType`: Board identifier used to perform the acquisition.

RETURN_CODE **ATS_GPU_NUFFT_FreeBuffer**(HANDLE *boardHandle*, void **buffer*)
Free buffers allocated with *ATS_GPU_NUFFT_AllocBuffer()*;.

Parameters

- `boardHandle`: Handle to the board
- `buffer`: Buffer pointer allocated by *ATS_GPU_NUFFT_AllocBuffer()*

RETURN_CODE **ATS_GPU_NUFFT_GetBuffer**(HANDLE *boardHandle*, void **buffer*, U32 *timeout_ms*)

Get processed buffer.

This function must be called at average rate that is equal to or greater than the rate at which DMA buffers complete. This function returns the GPU-processed buffer.

Return `ApiSuccess` if the board received sufficient triggers to fill a DMA buffer.

Return `ApiNotInitialized` if *ATS_GPU_NUFFT_StartCapture()* was not called before calling this function, or it was called and failed.

Return `ApiInvalidHandle` if the `boardHandle` parameter is not valid.

Return `ApiBufferOverflow` if the board filled all the available DMA buffers and its on-board memory. This may happen if the acquisition rate exceeds the bus bandwidth or the GPU processing bandwidth.

Return `ApiWaitTimeout` if the timeout interval expired before the board received a sufficient number of triggers to fill a buffer.

Return `ApiFailed` if a system or internal error occured.

Parameters

- `boardHandle`: Handle to the board
- `buffer`: Pointer to the buffer
- `timeout_ms`: Time the board will wait for a trigger before throwing an error.

RETURN_CODE **ATS_GPU_NUFFT_GetVersion**(U8 **major*, U8 **minor*, U8 **revision*)
Get ATS-GPU-NUFFT version number.

Parameters

- `major`: ATS-GPU-NUFFT major version number.
- `minor`: ATS-GPU-NUFFT minor version number.
- `revision`: ATS-GPU-NUFFT revision number.

RETURN_CODE **ATS_GPU_NUFFT_PostBuffer**(HANDLE *boardHandle*, void **buffer*, U32 *bytesPerBuffer*)

Signal the library a particular buffer can be used for data transfer.

This function is the equivalent of AlazarPostAsyncBuffer for ATS-GPU-NUFFT. Buffers posted must have previously been allocated with *ATS_GPU_NUFFT_AllocBuffer()*.

Parameters

- `boardHandle`: Handle to the board
- `buffer`: Pointer to a previously allocated buffer
- `bytesPerBuffer`: Size in bytes of the buffer, must be the same size as setup for the acquisition.

RETURN_CODE **ATS_GPU_NUFFT_SetBuffer**(void **dataInputBuffer*, void **CPUResultBuffer*, U32 *samplesPerBuffer*)

Supply a buffer for verification mode.

Parameters

- `dataInputBuffer`: Pointer to data buffer to be processed
- `CPUResultBuffer`: Pointer to data buffer to contain result data
- `samplesPerBuffer`: Size in samples of the buffer

RETURN_CODE **ATS_GPU_NUFFT_SetLinearizationFunction**(HANDLE *boardHandle*, U32 *precalibratedFunctionLength*, float **precalibratedFunction*)

Set linearization function used in NUFFT calculation. This call should be made if *ATS_GPU_NUFFT_Setup* was called using ATS_GPU_NUFFT_PRESET_LINEARIZATION as a parameter for NUFFTFlags.

Parameters

- `boardHandle`: Handle to the board
- `precalibratedFunctionLength`: Length of the linearization function, can be different from samplesPerRecordPerChannel.
- `precalibratedFunction`: Pointer to array of size precalibratedFunctionLength that contains the linearization function. Passing `null` is equivalent to passing a linearly spaced linearization grid.

RETURN_CODE **ATS_GPU_NUFFT_SetWindowFunction**(HANDLE *boardHandle*, U32 *samplesPerRecord*, float **realWindowArray*, float **imagWindowArray*)

Set window function used in FFT calculation.

Parameters

- `boardHandle`: Handle to the board
- `samplesPerRecord`: Length of the window, equal to the number of samples per FFT.
- `realWindowArray`: Pointer to array of size samplesPerRecord that contains the real part of the window. Passing `null` is equivalent to passing an array filled with ones.
- `imagWindowArray`: Pointer to array of size samplesPerRecord that contains the imaginary part of the window. Passing `null` is equivalent to passing an array filled with zeros.

RETURN_CODE **ATS_GPU_NUFFT_Setup**(HANDLE *boardHandle*, U32 *channelSelect*, long *transferOffset*, U32 *samplesPerFFT*, U32 *FFTsPerBuffer*, U32 *FFTsPerAcquisition*, U32 *autoDMAFlags*, U32 *OCTFlags*, U32 *FFTLength*, U32 *NUFFTFlags*, void **reserved*, U32 **bytesPerResultBuffer*)

Prepares the ATS board and GPU for acquisition.

This function calls `ATS_GPU_Setup()` internally and most parameters are passed directly to it. In addition, it sets up the GPU for DMA transfers and receives options specific to NUFFT processing.

Parameters

- `boardHandle`: Handle to the board. Set to `NULL` for data validation mode.
- `channelSelect`: Channel mask with each channel identifier OR'd.
- `transferOffset`: Pass a negative integer for pretrigger samples.
- `samplesPerFFT`: Number of samples in a record or transfer.
- `FFTsPerBuffer`: Number of records in a buffer, 1 for triggered streaming and continuous streaming modes.
- `FFTsPerAcquisition`: In this version of the library, it is required to pass `0x7FFFFFFF` to this parameter, which stands for an infinite acquisition. It is possible to interrupt the acquisition at any time using *ATS_GPU_NUFFT_AbortCapture()*
- `autoDMAFlags`: ATSApi flags for `AlazarBeforeAsyncRead`
- `OCTFlags`: Defines the types of data outputs to be obtained from the NUFFT acquisition. This parameter can receive one or more elements of ATS_GPU_OCT_OPTIONS, or'ed with the binary OR operator.
- `FFTLength`: Length of FFT, should be a power of 2.
- `NUFFTFlags`: Determines source of linearization. This parameter can receive one element of *ATS_GPU_NUFFT_OPTIONS*.
- `reserved`: Pass NULL
- `bytesPerResultBuffer`: Returns the size of a result buffer

RETURN_CODE **ATS_GPU_NUFFT_StartCapture**(HANDLE *boardHandle*)

Start the acquisition.

Use this function in replacement of AlazarStartCapture(). It starts the acquisition. The application must be ready to call *ATS_GPU_NUFFT_GetBuffer()* to prevent data overflows

Parameters

- `boardHandle`: Handle to the board

CHAPTER

FIVE

ATS-CUDA-NUFFT

ATS-CUDA-NUFFT provides a framework to allow non-uniform data processing on a CUDA-enabled GPU. ATS-CUDA-NUFFT internally calls ATS-CUDA and ATS-CUDA-OCT and should be used with ATS-CUDA for buffer and stream manipulation. ATS-CUDA-NUFFT requires an AlazarTech board on the system in order to be used.

5.1 API Reference

atsNuFFTPlan ***ATS_CUDA_NUFFT_CreateNuFFTPlan**(U32 *FFTLength*, U32 *samplesPerRecordPerChannel*, U32 *FFTsPerBuffer*, cudaStream_t *stream*)

Creates a non-uniform FFT plan and associates it with a CUDA stream. A non-uniform FFT plan contains all the data and GPU resources necessary to perform a non-uniform fast Fourier transform.

This function is used to allocate resources on a GPU and configure a GPU kernel to perform non-uniform FFT processing. It also associates the newly created non-uniform FFT plan with a CUDA stream. All kernels executed with this plan are to be run on this stream.

Return This function returns a pointer to the created non-uniform FFT plan.

Parameters

- `FFTLength`: Length of FFT, should be a power of 2 for performance.
- `samplesPerRecordPerChannel`: Number of samples in a record.
- `FFTsPerBuffer`: Number of FFTs to perform per buffer.
- `stream`: The CUDA stream to run the FFT plan with.

RETURN_CODE **ATS_CUDA_NUFFT_NuFFT**(atsNuFFTPlan **NuFFTPlan*, void **GPUBaseBuffer*, void **GPUNuFFTOut*, void **GPULinearizationBuffer*, ATS_CUDA_Input_DataType *inputDataType*, void **GPUWindow*)

Launches a kernel on the GPU to perform the non-uniform Fast Fourier Transform.

Parameters

- `NuFFTPlan`: Pointer to a non-uniform FFT plan created with ATS_CUDA_NUFFT_CreateNuFFTPlan().
- `GPUBaseBuffer`: Pointer to a GPU buffer on which to apply NuFFT kernel. This buffer should have 8 bits, 16 bits or float32 data packing and have de-interleaved channels.
- `GPUNuFFTOut`: Pointer to a GPU NuFFT result buffer. Output buffer has complex float32 precision.
- `GPULinearizationBuffer`: Pointer to a GPU linearization buffer with float32 precision. Must have the same samplesPerRecordPerChannel and same recordsPerBuffer as GPUBaseBuffer. Can be generated from ATS_CUDA_NUFFT_GetLinearizationFromPrecalibratedFunction() or ATS_CUDA_NUFFT_GetLinearizationFromKclock()
- `inputDataType.`: Data type of GPUBaseBuffer. This parameter must receive one element of ATS_CUDA_Input_DataType.
- `GPUWindow`: Pointer to a GPU window buffer allocated with ATS_CUDA_OCT_GenerateGPUWindowFunction()

RETURN_CODE **ATS_CUDA_NUFFT_DestroyNuFFTPlan**(atsNuFFTPlan **NuFFTPlan*)
Destroy a non-uniform plan.

Frees all GPU resources associated with a non-uniform FFT plan.

Parameters

- `NuFFTPlan`: Pointer to the non-uniform FFT plan to be destroyed.

atsLinearizationPlan ***ATS_CUDA_NUFFT_CreateLinearizationPlan**(U32 *samplesPerRecordPerChannel*, U32 *recordsPerBuffer*, ATS_CUDA_Input_DataType *inputDataType*, cudaStream_t *stream*)

Creates a linearization plan and associates it with a CUDA stream. A linearization plan contains all the data and GPU resources necessary to compute the linearization function from a k-clock signal.

This function is used to allocate the required resources and configure a GPU kernel to perform the necessary processing to obtain a linearization buffer from a k-clock signal. It also associates the newly created linearization plan with a CUDA stream. All kernels executed with this plan are to be run on this stream.

Return This function returns a pointer to the created linearization plan.

Parameters

- `samplesPerRecordPerChannel`: Number of samples in each k-clock record.
- `recordsPerBuffer`: Number of records in the k-clock signal.
- `inputDataType.`: Data type of the k-clock signal. This parameter must receive one element of ATS_CUDA_Input_DataType.
- `stream`: The CUDA stream to run the linearization plan with.

RETURN_CODE **ATS_CUDA_NUFFT_GetLinearizationFromKclock**(atsLinearizationPlan **WNPlan*, void **pKclock*, void **GPULinearizationBuffer*)

Launches a kernel on the GPU to get the linearization function from a k-clock signal.

Parameters

- `WNPlan`: Pointer to a linearization plan created with ATS_CUDA_NUFFT_CreateLinearizationPlan().
- `pKclock`: Pointer to a GPU buffer containing k-clock data. K-clock buffer data type must be as specified in ATS_CUDA_NUFFT_CreateLinearizationPlan().
- `GPULinearizationBuffer`: Pointer to a GPU buffer containing the linearization buffer that can be passed to ATS_CUDA_NUFFT_NuFFT(). Linearization buffer has float32 precision and has same size as pkclock buffer.

RETURN_CODE **ATS_CUDA_NUFFT_DestroyLinearizationPlan**(atsLinearizationPlan *WNPlan)

Destroy a linearization plan.

Frees all GPU resources associated with a linearization plan.

Parameters

- `WNPlan`: Pointer to the linearization plan to be destroyed.

RETURN_CODE **ATS_CUDA_NUFFT_GetLinearizationFromPrecalibratedFunction**(void **GPUPrecalibratedFunction*, void **GPULinearizationBuffer*, U32 *samplesPerRecordIn*, U32 *samplesPerRecordOut*, U32 *recordsPerBuffer*, cudaStream_t *stream*)

Generates a linearization buffer from a precalibrated function.

This function prepares a GPU linearization buffer that can be passed to ATS_CUDA_NUFFT_NuFFT().

Parameters

- `GPUPrecalibratedFunction`: Pointer to a GPU buffer of size samplesPerRecordIn of type float32 that contains the linearization function.
- `GPULinearizationBuffer`: Pointer to a GPU buffer of size samplesPerRecordOut * recordsPerBuffer and float32 precision where the linearization buffer is to be written.
- `samplesPerRecordIn`: Length of the GPU PrecalibratedFunction.
- `samplesPerRecordOut`: Length of each record of the GPU LinearizationBuffer.
- `recordsPerBuffer`: Number of times the GPUPrecalibratedFunction is repeated in GPULinearizationBuffer.
- `stream`: Stream identifier on which processing is to take place.

RETURN_CODE **ATS_CUDA_NUFFT_GetVersion**(U8 **major*, U8 **minor*, U8 **revision*)
Get ATS-CUDA-NUFFT version number.

Parameters

- `major`: ATS-CUDA-NUFFT major version number.
- `minor`: ATS-CUDA-NUFFT minor version number.
- `revision`: ATS-CUDA-NUFFT revision number.

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