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The Instrument Control Unit processing hardware and software of the Wide Field Monitor on eXTP

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ABSTRACT

The eXTP (enhanced X-ray Timing and Polarimetry) mission is a joint large mission of the Chinese Academy of Sciences (CAS) and European partners designed to study the state of matter under extreme conditions of density, gravity and magnetism. One of the four major instruments on eXTP is the Wide Field Monitor (WFM) which consist of 3 pairs of coded mask cameras with a total combined Field of View (FoV) of $90 \times 180$ degrees at zero response. With its enormous FoV, a source localization accuracy of 1 arcmin and an energy range of 2-50 keV the primary objective of the WFM is to provide triggers for the pointing instruments on the eXTP with less than one day reaction time. Its large area and resolution will be enough to detect state changes in compact objects as well.

The WFM instrument is controlled by the Data Handling Unit located inside the Instrument Control Unit. The challenging requirement of broadcasting time and end-position of the triggering event to end-users in 30s necessitates special on-board data processing software (the eXTP burst online trigger, or XBOT), a hardware that can perform such processing and associated control software that would feed the raw data from the cameras into the XBOT and relaying alerts to the on-board data handling unit on the spacecraft side. Moreover, the WFM software performs several tasks related to the science data preparation, telecommand and telemetry management, and control of the cameras utilizing four LEON4 processing cores of E698 PM SoC from OCE Technology. This presentation discusses the details of the processing hardware and the interaction between different software components of the WFM on eXTP.

Keywords: Manuscript format, template, SPIE Proceedings, LaTeX
1. INTRODUCTION

The eXTP (enhanced X-ray Timing and Polarimetry) mission is a joint large mission of the Chinese Academy of Sciences (CAS) and European partners designed to study the state of matter under extreme conditions of density, gravity and magnetism. eXTP is currently in Phase B with the proposed launch date of 2027.

The scientific payload of eXTP includes four instruments: SFA (Spectroscopy Focusing Array) and PFA (Polarimetry Focusing Array) - led by Chinese institutions - and LAD (Large Area Detector) and WFM (Wide Field Monitor) - led by European institutions in Italy and Spain. Together, they offer an unique simultaneous wide-band (0.5 - 50 keV) X-ray spectral and timing capability and polarimetric sensitivity. A basic CAD model of the satellite with the main instruments are shown in Fig. 1.

Figure 1. eXTP with its 4 main instruments: Large Area Detector (LAD), Polarimetric and Spectroscopic Focusing Arrays (PFA & SFA), and the Wide Field Monitor (WFM). The WFM includes three pairs of cameras, however one of the pairs cannot be seen in this figure due to the viewing angle of the satellite.

The pointed instruments of the eXTP have been designed with complementarity in mind. The SFA is a set of X-ray telescopes with an effective area of 7000 cm$^2$ at 2 keV, energy resolution better than 180 eV (FWHM) at 6 keV and the expected angular resolution less than 1 arcmin (HPD). The LAD, on the other hand, is a collimated narrow field of view (FOV) instrument (1 degree FWHM) with an enormous area of 3.4 m$^2$ at 8 keV, working in energy range (2-30) keV, with a spectral resolution better than 240 eV at 6 keV. Both instruments use Silicon Drift Detectors (SDD) with very little dead-time. The PFA, on the other hand, has a set of X-ray telescopes with Gas Pixel Detectors (GPDs) on the focal plane with polarimetric capability. The energy band is (2-10) keV, with an energy resolution of 15-20% at 6 keV - and an effective area of 900 cm$^2$ at 2 keV.

The fourth instrument, for which this article describes the processing hardware and software, is the Wide Field Monitor (WFM) which consist of 3 pairs of coded mask cameras with a total combined Field of View (FoV) of 90×180 degrees at zero response. The design is similar to the one proposed under LOFT with less number of camera pairs. The instrument is expected to have a source localization accuracy of 1 arcmin and will operate in the energy range of 2-50 keV. The primary objective of the WFM is to provide triggers for the pointing instruments on the eXTP with less than one day reaction time. Its large area and resolution will be enough to detect state changes in compact objects as well. An update on the details of the instrument and its scientific capability will be presented within these proceedings.

The processing hardware (see §2) resides in the Instrument Control Unit (ICU) of the WFM. The ICU (actually two units in cold redundancy) is located inside the spacecraft platform cabin (service module). It is connected to the cameras with a harness carrying cables. The average distance between the ICU and cameras is 4.2 m (see Galvez et al. for the mechanical design of the cameras). Fig. 2 describes the general functionality of the cameras and the ICU. The ICU itself consists of two parts, the Data Handling Unit (DHU) and the Power
Figure 2. Functional block diagram of the WFM. The Back-End-Electronics (BEE) prepares the raw data from the Front-End Electronics (FEE) of the camera for further processing and storage by the Instrument Control Unit (ICU) Software. PSU and PDU stands for Power Supply Unit, and Power Distribution Unit, respectively. DHU stands for Data Handling Unit.

Figure 3. Electrical and data interfaces of the WFM. The ICU Control Software manages all interfaces (see also Fig. 4).

Each camera consists of 4 SDDs and a corresponding Front End Electronics (FEE) for immediate readout. The events then are time tagged and filtered by the Back End Electronics (BEE). BEE also performs other necessary data acquisition tasks (see also §3). The BEE architecture includes a microprocessor to handle interfaces with the DHU. The telecommand (TC) and telemetry (TM) will be handled through a Spacewire.
interface (see Fig. 3). The BEE-DHU interface includes Pulse-per-second (PPS) line and a clock line as well for accurate timing of events using the high accuracy atomic clock (HAC) line XXX.

The article first discussed the properties of the processing hardware in §2, and then describes the details of the processing software in §3. The overall software design and an emulator for the early testing of the software components are described in §4. The on-board trigger software is discussed separately in §5 before discussing the current progress and future outlook in §6.

2. PROCESSING HARDWARE

The DHU hardware baseline design is in its functionality and strong synergy a direct heritage from the Data Processing Unit (DPU) developed and built by DTU Space for the Modular X- and Gamma-ray Sensor (MXGS\textsuperscript{10}) instrument of the ESA Atmosphere Space Interactions Monitor (ASIM\textsuperscript{11}) mission on the International Space Station currently in operation (launched 2018). For the WFM ICU DHU hardware baseline, a suitable CPU component has been selected to comply and fulfill both, the ITAR-free components restrictions and also very high computational power required for the on-board processing software. The current ICU DHU consolidated hardware baseline uses a powerful new generation CPU, the E698PM Radiation-hardened SPARC V8 Quadcore Processor, System-on-Chip (SoC) from O.C.E. Technology Ltd\textsuperscript{*}.

![Hardware interfaces of the eXTP WFM ICU processing hardware. Some parameters will be finalized at the end of Phase B studies.](https://ocetechnology.com/)

Figure 4. Hardware interfaces of the eXTP WFM ICU processing hardware. Some parameters will be finalized at the end of Phase B studies.

The hardware design and development is under DTU Space responsibility. During the phase-A study, a breadboard model of the hardware concept has been developed and evaluated for the critical space-wire interfaces and identify possible critical ITAR-free components list. An Electrical Ground Support Equipment (EGSE) was also developed at DTU Space and used for specific DHU hardware evaluation.

Fig. 4 shows the preliminary block diagram of the DHU. The E698 device, ITAR-free, uses ESA qualified Leon4 cores of a 32-bit processor compliant with the IEEE-1754 (SPARC V8) architecture. The E698PM

\textsuperscript{*}https://ocetechnology.com/
processor and components from O.C.E. Technology have flight heritage from several space mission, including in particular Chinese space missions.

3. PROCESSING SOFTWARE

An important part of the ICU is the software that runs on the described hardware which controls cameras, performs on-board analysis for triggers (see §5) and performs other tests summarized in Fig. 2. In this section, the details of these tasks are provided as well as the state machine of operation.

3.1 Software Blocks

The main software blocks to control WFM are shown in Fig. 5. Each block’s functionality can be described as follows.

The boot software is the basic startup software when the ICU is powered on which performs a health check and provides the initial communication with the Satellite Management Unit (SMU) to provide the boot status of the WFM. This software may implement a safe mode under specific conditions during boot up. The boot software is under joint responsibility of DTU Space and teams from Turkey (Sabanci University and TÜBİTAK-UZAY).

The control software is the main application for controlling the instrument via different observing modes, monitoring subsystems and their health, receiving telecommands (TC) from and sending telemetry (TM) to the SMU. It manages the PPS and HAC lines as well and it is also responsible for the Fault Detection, Isolation and Recovery (FDIR) activities.

The Science Software is the primary data processing software that utilizes data coming from the back-end-electronics (BEE). It manages a cyclic buffer together with XBOT and performs several histogramming tasks to create spectra, light curves and images over several time intervals as processed data. The science and control software are under the responsibility of Sabanci University and TÜBİTAK-UZAY in Turkey.

The eXTP Burst Online Trigger (XBOT) software runs trigger algorithms based on data coming from the BEE and generated alerts based on pre-defined criteria for bright bursts (see §5). The XBOT is provided by CEA-Saclay.

The BEE software is the first processor of the electronic signals produced by the cameras. For each trigger, the BEE software adds a time tag, validates and filters data based on defined criteria, performs pedestal and noise subtraction, determines interaction position on the detector, calculates photon energy, applies event threshold, and collects housekeeping (HK) data as well. The BEE software is provided by the Eberhard Karls Universitat.

![Figure 5. The software blocks and interactions between them. SMU stands for Satellite Management Unit.](image-url)
3.2 WFM State Machine

The general state machine of WFM operation is shown in Fig. 6. The available modes are

- Off
- Instrument safe
- Stand By
- Configuration
- Memory maintenance
- Diagnostics
- Observation

Instrument Safe or Safe Mode is managed by the boot software. ICU enters the Safe Mode right after boot up, in reaction to FDIR function, or as commanded by a TC. In Safe Mode, all cameras are turned off and no observation data transfer shall take place, but limited HK data transfer will be done. A Health Check process will be initialized to enter the StandBy mode. It is also safe to switch-off the instrument power in this mode. This mode is managed by the Boot Software.

The Stand-By mode is the nominal instrument safe state while “waiting” before entering observations. In Stand-By mode the cameras are turned off.

The Configuration Mode allows changing BEE configuration parameters in RAM. The cameras are turned off, and parameters are written to the camera next time the cameras are turned on.

The Memory Maintenance Mode allows updating the software. It is also used to change the default software parameters in the EEPROM. The cameras are off during this mode.

![State Machine Diagram](image)

Figure 6. Operation modes of the WFM and allowed transitions between them. The main science mode is Camera Observation Event mode in which all photons are saved and transmitted.

The Diagnostic Mode is an engineering mode, in which the instrument is put in a safe operational mode allowing investigations and diagnostic, both for software and hardware problem solution. Used for general troubleshooting and performance verification. The mode is used rarely in orbit, but extensively during ground testing to obtain the maximum information about the detected X-ray and background events. All the BEE
submodes can be commanded on. The BEE can also be commanded directly with a Direct Command TC. The raw data from the BEE is forwarded to a TM.

Observation is the nominal science mode for which the high voltage (HV) is turned on, cameras are operating and performing data collection and analysis. In addition to scientific data, housekeeping data are collected and processed in this mode. For each camera, following submodes can be enabled separately and independently: ObservationSlew, ObservationEvent, and ObservationBurst. In ObservationSlew and ObservationEvent modes, the default is to download all individual event data. The Observation Burst sub-mode can be separately enabled/disabled in the Observation Mode. This mode enables, in addition to the already activated TM, the Burst TM and Burst VHF (and burst detection and triggering processing through XBOT).

3.3 Time and Space Partitioning
A possible time and space partitioning and memory management architecture is shown in Fig. 7. For the case of well-separated jobs in partitions, one CPU can be provided to the Control Software, one CPU to the Science Software and 2 CPUs to the XBOT. Depending on the CPU loads, it is possible to handle Control and Science Softwares with one CPU and computation power hungry XBOT with 3 CPUs. If necessary a hypervisor layer (such as Xtratum\textsuperscript{1}) may be considered as well.

![Diagram](https://i.imgur.com/5555555.png)

Figure 7. Time and space portioning architecture envisioned to handle different tasks related to the main software blocks (see Fig 5).

4. SOFTWARE DESIGN AND EMULATION
This section describes the software design in detail, and the emulation of the flight software on a PC. Two emulation software packages are being developed in order to test the interfaces of ICU software shown in Fig. 5.

- Basic HW Interface Data Emulation (XBOT Shared Memory, WFM PDU Analog HK Data, WFM PDU I/O etc.)
- Basic TM/TC Interface Data Emulation (SMU TM/TC Interface)

\textsuperscript{1}https://fentiss.com/products/hypervisor/
4.1 Software development and software testing environment

The software shall have a modular design, using a hardware / OS abstraction model, so that most software components can be compiled and tested on a standard PC running Linux.

The hardware specific components shall be replaceable by components that simulate the hardware behaviour. The RTOS-specific components shall be replaceable by implementations for Linux OS.

The verification will be done using OCE Technology – E698 PM Development Board and SPW Test Equipment (see §2).

The WFM Flight Software Architecture is given in Fig. 8.

![WFM Flight Software Architecture](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 8. WFM Flight Software Architecture.**

WFM Processor Module has a SPARC instruction set architecture LEON4 CPU which has the same instruction set with LEON3. QEMU-LEON3 emulator will be used to run WFM application software.

QEMU is a machine emulator, which can run target architecture’s CPU binary (including operating system, drivers, applications, libraries) on a virtual machine. QEMU has support with patches for single CPU LEON3 architecture. RTEMS will be used as RTOS of the WFM Flight software.

RTEMS is an open source Real Time Operating System used by embedded system application and support many CPU families including SPARC. LEON2/3/4 BSP and drivers are available as open source.

WFM software has a software abstraction layer to create a portable and reusable real time embedded system software. Operating System Abstraction Layer (OSAL) has necessary OS abstraction, the same embedded software could compile and run on a number of RTOS.

WFM software is running through a message driven software bus. The Software Bus (SB) is an inter-application message-based communications system. The main aim of this bus is to provide a mechanism that allows all applications to send packets to self or other applications.

CORDET Framework is ESA’s Packet Utilization Standard (PUS) compatible generic architecture for service oriented applications. Those services use a set of logically and functionally related abilities which an application provides to other applications. WFM is utilizing CORDET framework for PUS communication between On-Board Computer and WFM Flight Software through the SPW Server Task.

Some PUS services foreseen on WFM are TC Verification, Housekeeping and Diagnostic Data, Event Reporting, Time Management, Onboard Monitoring, Memory Management, Function Management, In-Flight Testing, Information Distribution, Science Data Transfer Services. CORDET Framework provides all those services except last five, which will be added to the library to complete all necessary PUS services.

Here we go through the summary of all tasks envisioned to operate the WFM. Science and XBOT tasks handle specific data analysis tasks for the payload.
Management task handles all high level requirements which is not assigned for any other task specifically.

Sync task handles a pre-configured table driven TDMM (Time Division Multiplexed Message) distribution through Software Bus which synchronize all tasks. TDMM has 100 Hz running frequency. All other tasks except Sync Task could run any multiple of this frequency.

MemWash task is used for scrubbing SRAM, SDRAM for correcting single bit errors with an error correction code, writing corrected data back to the memory and detecting multiple bit error for information. It is also used for PROM and EEPROM to only detect single and multiple bit errors. EEPROM will be refreshed if data retention duration is less than the Spacecraft lifetime. MemWash task is running during idle periods, therefore it has minimum priority after idle task.

WFM has server tasks for communication via hardware input/output ports.

SPW Server Task handles communication between Camera BEE’s for payload data and SMU for TM/TC. BEE data is processed by Science and XBOT Tasks. Generated scientific data will be sent through same SPW task to the SMU.

SPI and UART Server Tasks are to be used for power control of WFM, ADC reading and on/off power management of sub-modules.

Shared Memory task are to be used for inter-process communication of distributed processes on different CPU’s (see Fig. 7).

There are also two simulation tasks only for development purpose on QEMU and will not be available on the flight software. These simulations are to be replaced by driver calls (open/read/write/close) instead of message queue communication calls (mq_register/mq.recv/mq.send/mq.close) between simulator and server tasks.

- On-Board Computer simulator task will send commands to other tasks and receive telemetries from other tasks through SPW server task.
- BEE & Power simulator tasks will get necessary commands from the WFM Software and send BEE & Power telemetries and payload data through SPW, UART, SPI server task to the requesting tasks.

All commands, telemetries and payload data are to be simulated as real data transfer ratio among each other.

4.2 Software Development Approach

ICU Software development strategy is based on the incremental / iterative SW development which is based on delivery of required functionality for the model philosophy of the entire project. After defining software requirements and architectural design, SW development will be accomplished in stages (builds). ICU Software will be developed in increments. Each increment is started with an update of the requirements document covering the detailed requirements. Then the agreed functionalities are coded and unit tested in a work station. At the end of the increment, the new functionalities will be integrated to the main SW and tested. After an increment delivery, it will be delivered to the system testing at the ICU breadboard.

5. EXTP BURST ON-BOARD TRIGGER (XBOT)

The extremely large FOV of the WFM means that it will pick up a large number of gamma-ray bursts (GRB) and will be exposed to other explosive phenomena. It is well known that early follow up observations of GRBs in X-rays and other bands are scientifically extremely valuable. The WFM will contribute strongly in this field. The importance of the prompt emission makes it necessary to produce and distribute alerts as quick as possible, and more importantly, the eXTP can maneuver to the GRB (or other burst) location to take full advantage of the pointed instruments with large area, good timing and energy resolution and polarimetric capability.

For this reason, the eXTP community is planning to implement the eXTP Burst Alert System (XBAS). The XBAS has three components:
• **XBOT** : eXtp Burst Onboard Trigger, the WFM onboard software to detect bursts and transients in real-time and generate alerts

• **XBAR** : eXtp Burs Alert Relay system which relays alerts from XBOT to an Alert Center in real-time

• **XBAC** : eXtp Burst Alert Center which disseminates alerts to community and supervise functioning of the alert system

The XBAR will transmit alerts from bright events to the science community within 30 s through XBAC. To download information from the satellite there will be 15 VHF ground stations around the equator (the SVOM\textsuperscript{13,14} network will be utilized). BeiDou Navigation Satellite System or relay satellite communication system are alternatives for quick transmission of alerts.\textsuperscript{1}

![Figure 9. XBOT functions and interfaces with other software.](image-url)

The initial trigger decision will be made by the XBOT software (see Fig. 9 for XBOT interfaces). It reads data from shared memory (Data pre-processed by the Science Software), runs image-trigger & count-rate trigger algorithms with configuration and cyclic Attitude/Earth pointing information from the Control Software and generates alert messages to be transmitted to Earth via BeiDou and UHF/VHF. Alerts satisfying pre-defined criteria (TBD) will result in autonomous pointing of the eXTP to the source.

The trigger algorithms are based on a similar trigger system that will operate on the ECLAIR instrument on SVOM.\textsuperscript{13} Two concurrent algorithms are necessary to be able to detect very short and intense bursts as well as longer and dimmer bursts. The ‘count-rate trigger’ runs on many time scales (10 ms to 10 s) and detector counts are analyzed in overlapping energy bands and on several detector zones (coincident in X & Y camera pair). Significant count rate excesses over fitted background model in given time slices are stored in a buffer. The sky image is constructed from the excess and a new source will be searched.

The ‘image trigger’, on the other hand, runs on larger timescales (10 s to 10 min) and full sky imaging will be performed in different energy bands and after removing known bright sources, new sources will be searched for. The time scales and exact energy bands are still considered as part of the Phase B study of the eXTP.

### 6. DISCUSSION AND OUTLOOK

The European instruments on eXTP is currently under a Phase B study with the expected Preliminary Design Review (PDR) in 2023. While both the LAD and the WFM has tremendous heritage from LOFT, the eXTP configuration and constraints require several design adjustments, the most important being completely US free design of hardware and software. The choice of processing hardware and software components reflects this requirement. Since it is expected that the Phase B evaluation of instruments will be conducted based on European regulations, all the design documentation is done using European Coordination for Space Standardization (ECSS\textsuperscript{5}) For similar reasons, CORDET framework is adapted for Packet Utilization Standard (PUS) services

\textsuperscript{5}ecss.nl
for the interface between instruments. Both hardware and software activities are progressing both in terms of
design documentation to prepare for the PDR, as well as desktop model testing and emulation studies to make
sure that all requirements will be met in the implementation phases.

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