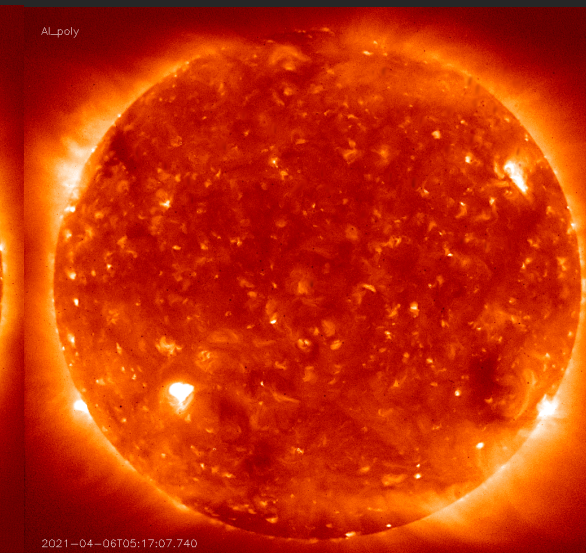
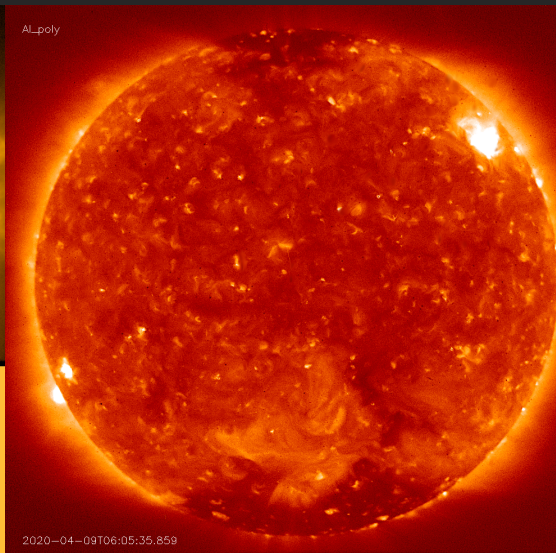
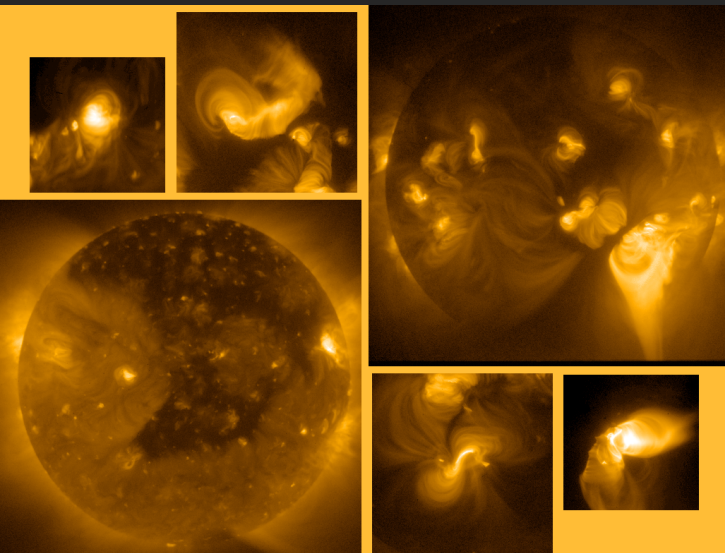


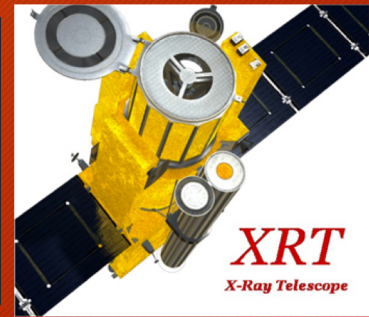
Introduction to X-Ray Telescope Data Analysis

XRT



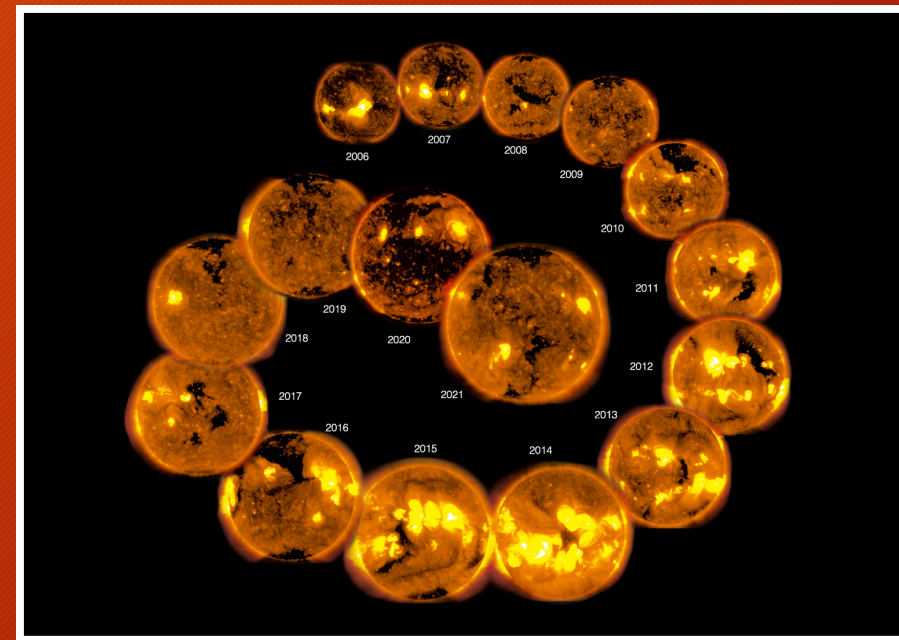
Created by
Lucas Guliano
2022/07/07

Introduction/XRT Analysis Guide



- The goal of this presentation is to provide a simplified overview of the XRT data analysis process covering:
 - Basics of XRT and XRT Data data
 - XRT data access and downloading
 - XRT Catalog use and Filtering XRT data
 - Reading and Preparing XRT data
 - XRT movie generation
 - Upcoming XRT data processing projects
- Primarily done with Solar Soft IDL pack (SSWIDL)
 - Future move towards Python (XRTpy)
- A more detailed guide to the analysis process can be found at:

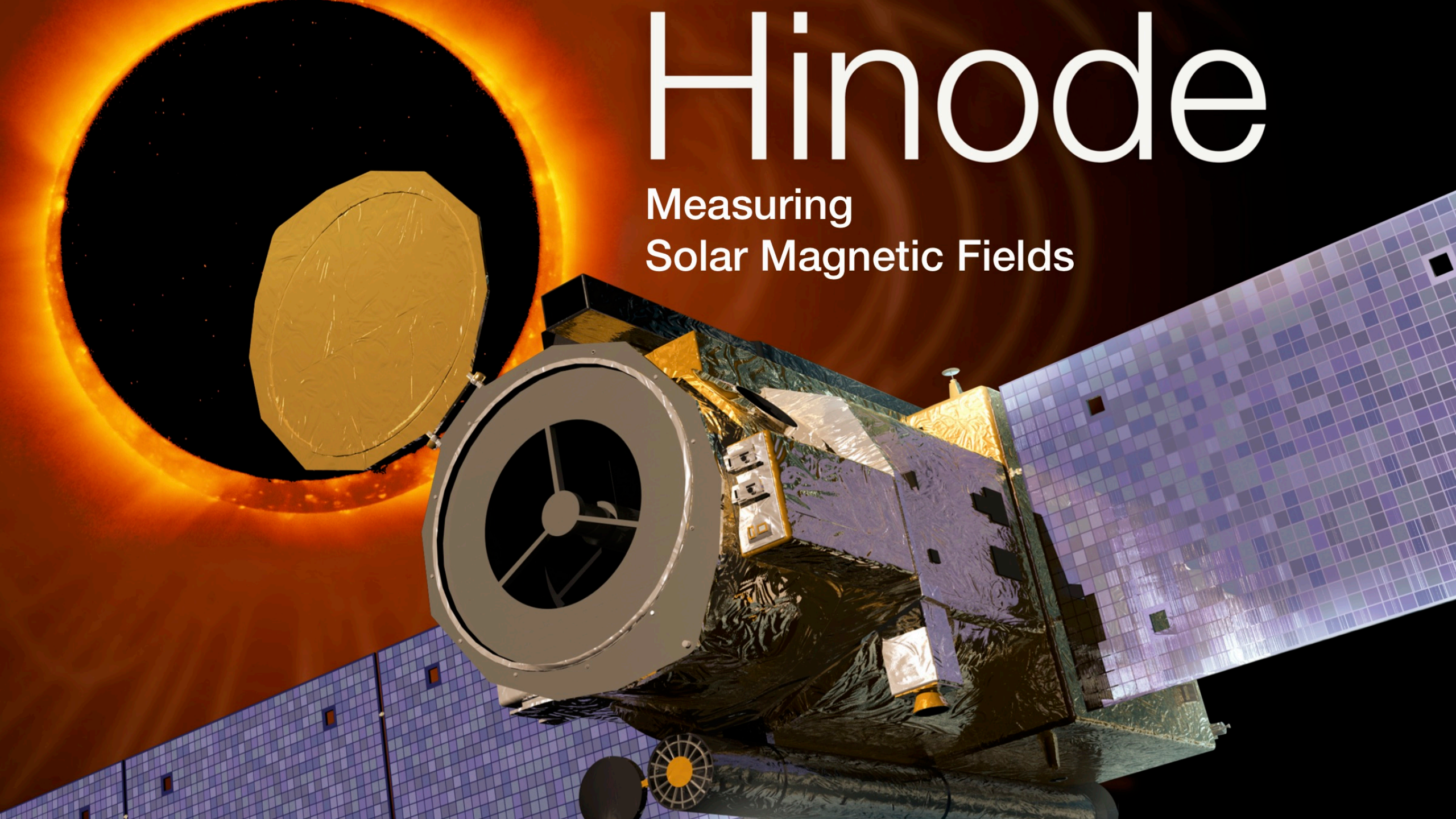
<https://xrt.cfa.harvard.edu/resources/documents/XAG/XAG.pdf>



Aki Takeda (MSU)

Hinode

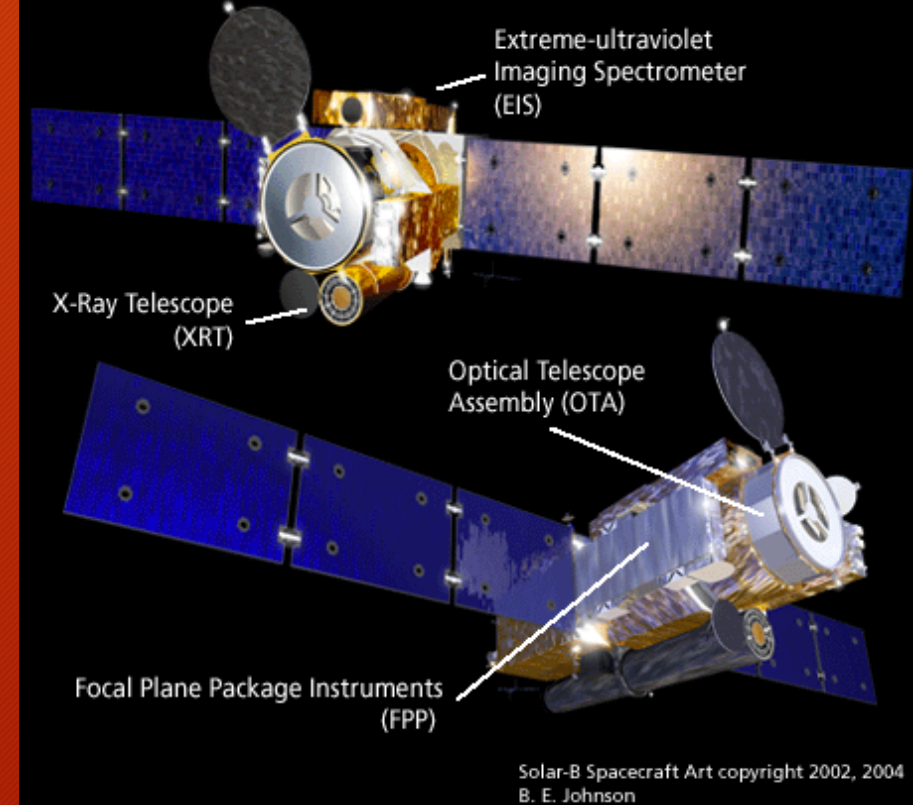
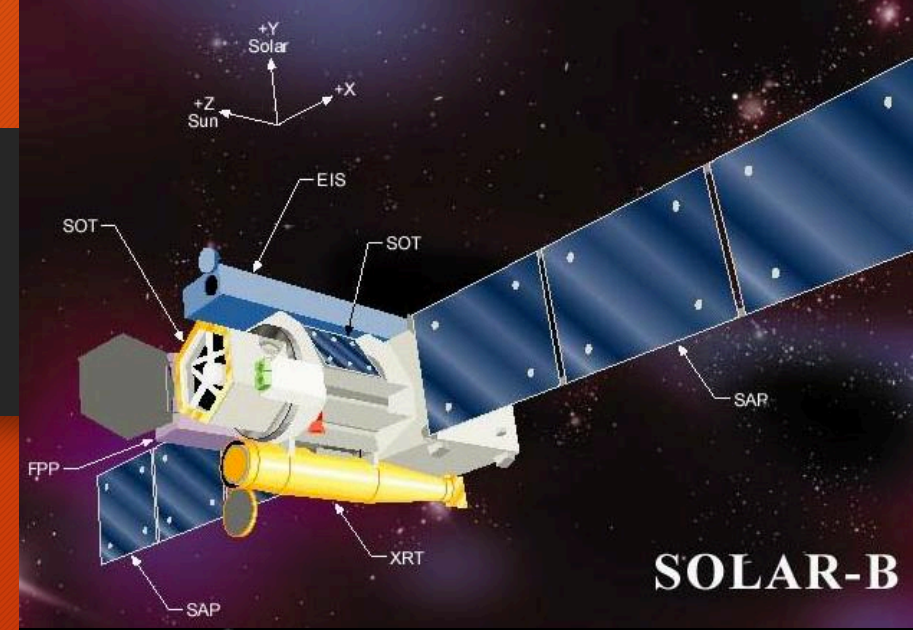
Measuring
Solar Magnetic Fields



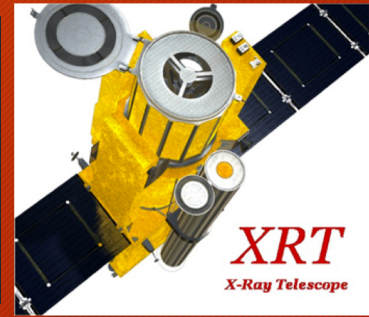
X-Ray Telescope (XRT)

<https://xrt.cfa.harvard.edu/>

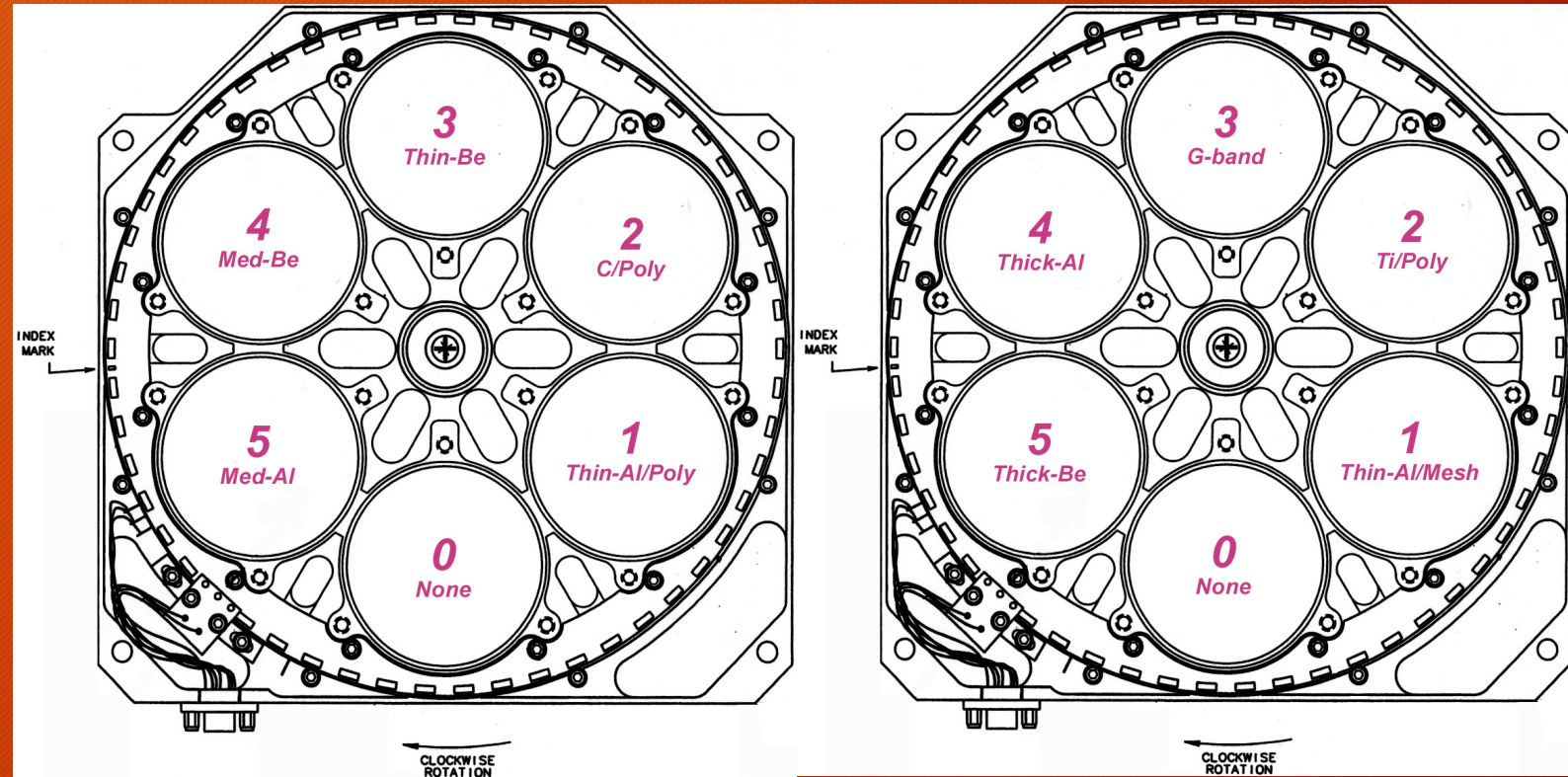
- Three instruments on Hinode:
 - X-Ray Telescope (XRT)
 - Extreme-Ultraviolet Imaging Spectrometer (EIS)
 - Solar Optical Telescope (SOT)
- First light in 2006
 - Full continuous operations (small gaps)
- High-resolution grazing-incidence telescope
 - Soft X-ray images
- Wide temperature coverage to see all the coronal features
- XRT consists of:
 - X-ray and visible light optics
 - Focal plane mechanisms (filters and shutter)
 - 2k x 2k CCD camera
- Full sun images (synoptics) or subframe images



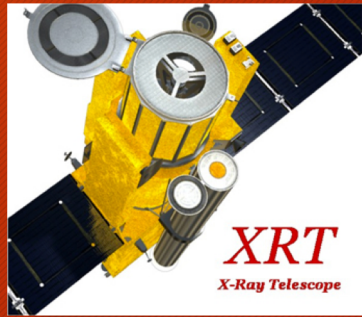
XRT Data: CCD and Filters



- CCD size: 2048×2048 pixels
- 35'× 35' field of view
 - Possible sub-frame readouts
- Approximately 1" per pixel
- Two filters wheels
 - Creates filter pairs
 - Filter ratios
- Twice daily synoptics
 - Full disk, sun center images
 - Short and long images
- Frequently focuses on ARs
- Generates ~0.7 GB daily



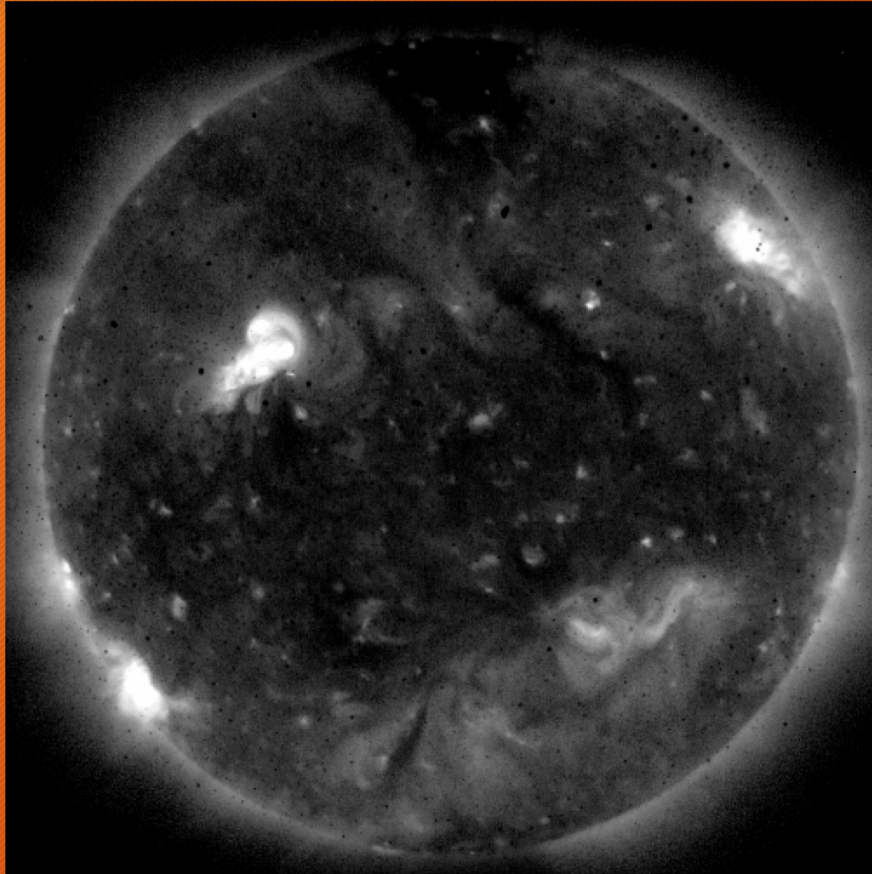
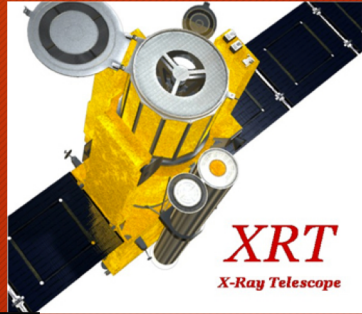
XRT Data Levels



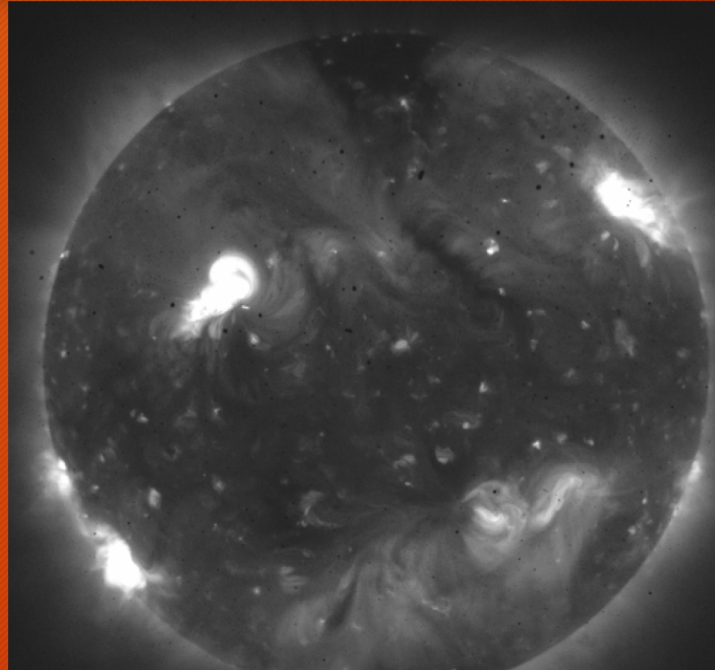
- Data is stored in levels of processing
- Each data level serves specific functions and usability

Level	Pixel values	File format	Purpose
QuickLook	Data Number (DN)	FITS	Operations, Data Verification, QuickLook movies
0	DN	FITS	Basic science
1	DN/sec	FITS	Calibrated images
2	Physical units	Any	Short and long exposures summed into one image; Differential Emission Measure; Temperature Maps

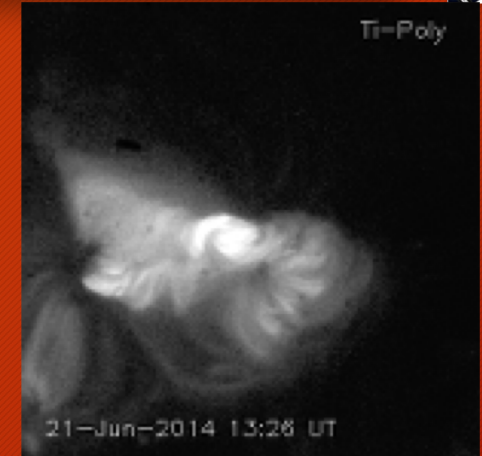
XRT Data Examples



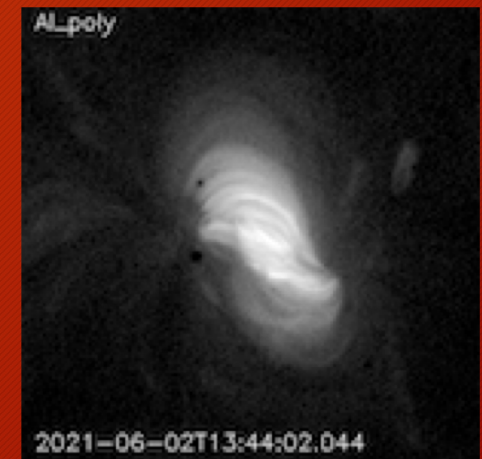
Level 1



Level 0

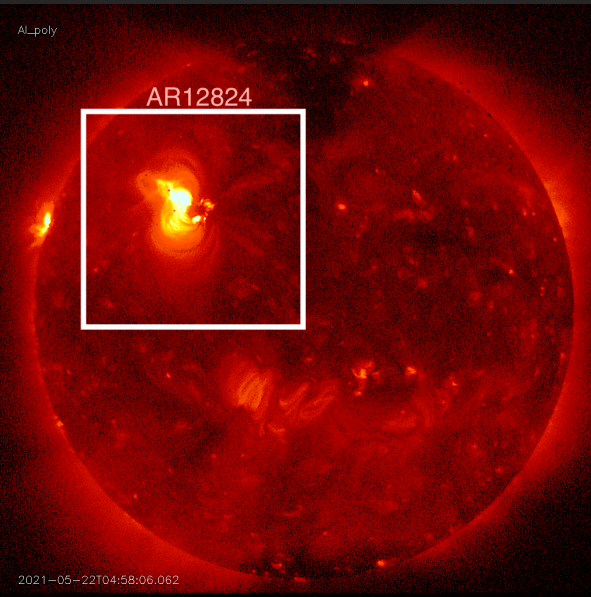


Subframe AR images

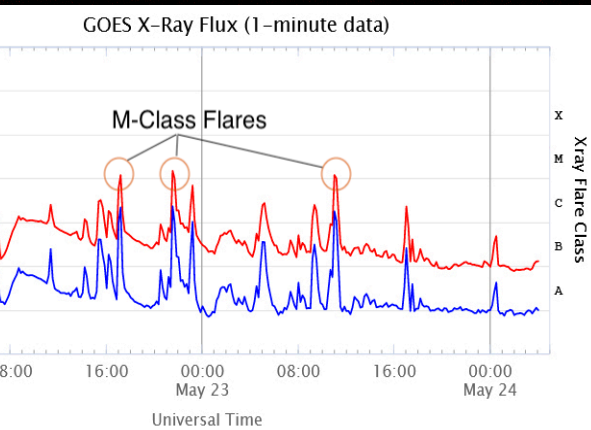
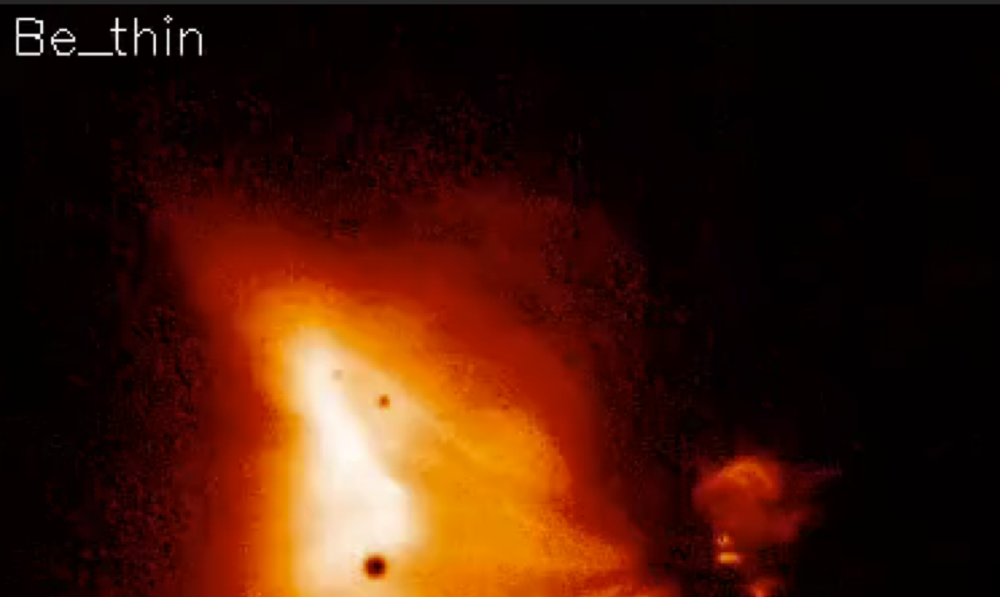


2021-06-02T13:44:02.044

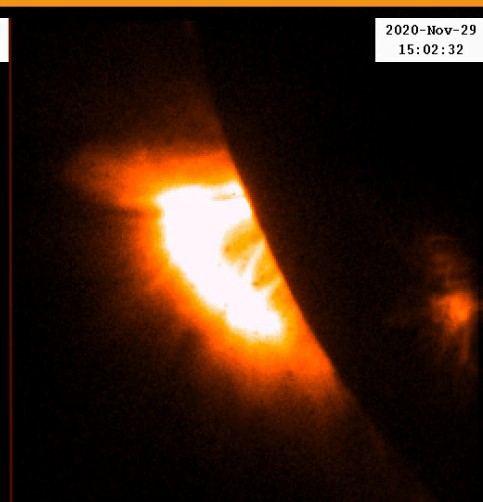
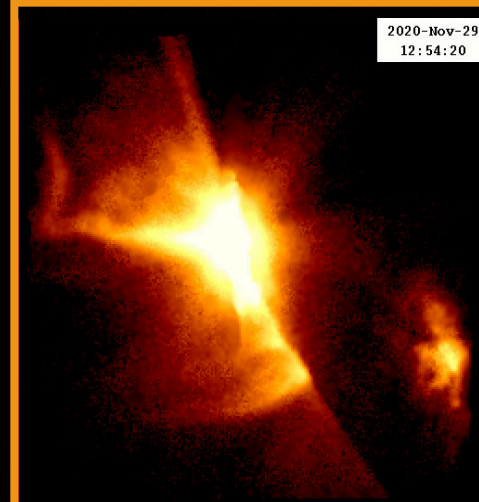
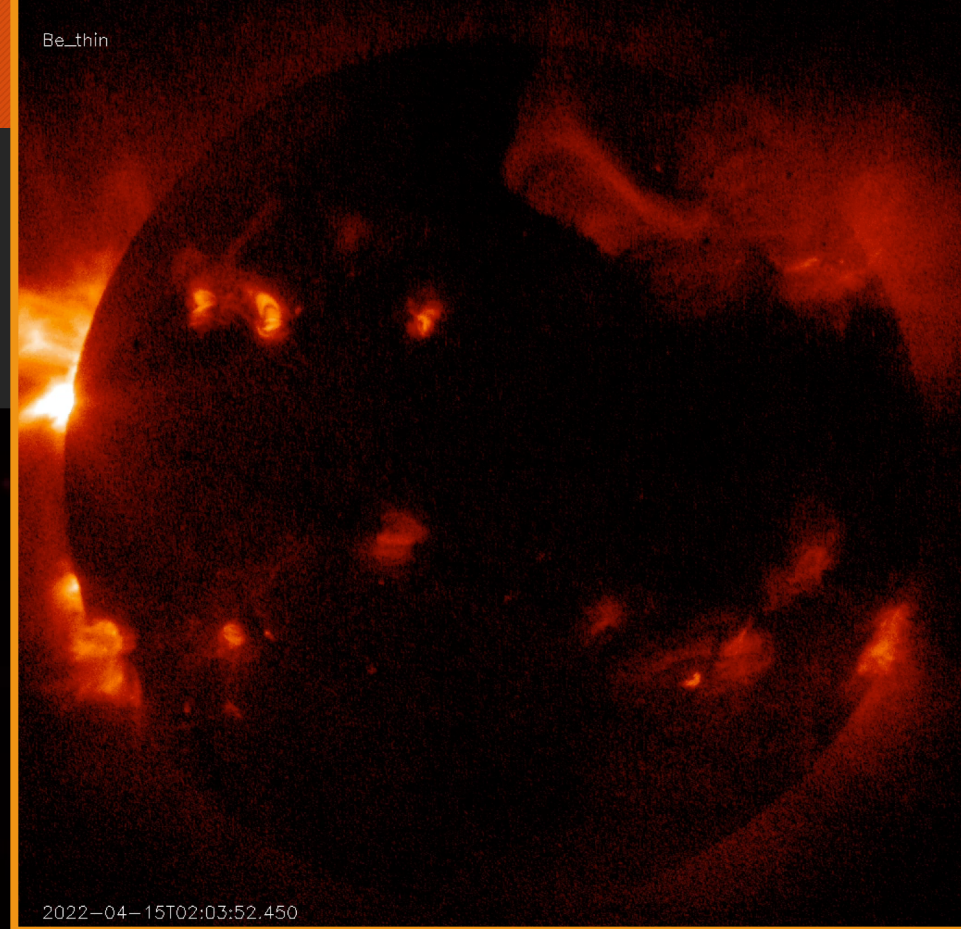
XRT Data Examples



Be_thin



2021-05-22T12:00:53.030



Finding and Getting XRT Data

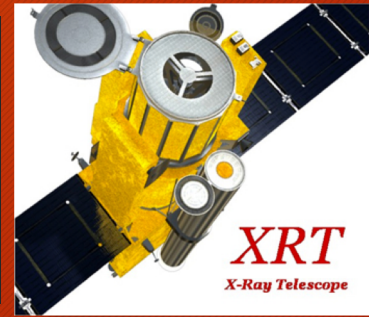
Quick Browsing XRT Data Products



- Daily Synoptic Gallery:
 - Image gallery of processed daily XRT synoptic images
- SnapView Files:
 - Summary images for each day displaying the type and location of observations from that day along with a GOES X-ray flux plot
- XRT Flare Catalog:
 - Catalog with an entry for each flare observed by XRT. Aligns with Hinode flare catalog. Contains a movie and a summary plot for each entry
- Focused Mode Catalog:
 - Catalog with an entry for each focused mode with a a summary movie and plot showing what the primary observation was during each period
- Level0 Mpeg Archive:
 - Automatically generated monthly summary movies sorted by filter
- Carrington Map Archive:
 - Images generated from XRT data showing full solar rotations

Getting Data: DARTS

<https://darts.isas.jaxa.jp/solar/hinode/>

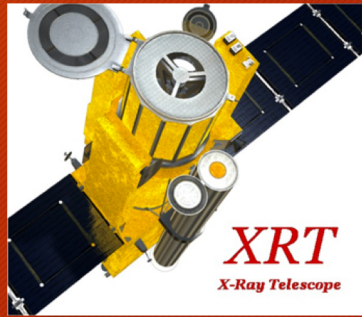


- Contains data and information for all 3 Hinode instruments; including XRT
- Full Level0 archive: <https://data.darts.isas.jaxa.jp/pub/hinode/xrt/level0/>
 - Access to all level0 (raw data) fits files
- Hinode Data Query Link: <https://darts.isas.jaxa.jp/solar/hinode/query.php?A01=Go%20to%20Search>
 - Query data on various search terms
 - Quick look and download individual or bulk data files

The screenshot shows the DARTS Solar Physics website. The top navigation bar includes the DARTS logo, logos for SODA, ISAS, and JAXA, and a Google Search box. Below the navigation bar, there are tabs for Hinode, Yohkoh, Hinotori, Trace, and Rhessi. The Hinode tab is selected. On the left, there is a sidebar menu with options: Instruments, Operations, Data (with sub-options for HTTP Processed and HTTP Preliminary), Query (highlighted), Analysis, Publications, and Links. The main content area is titled 'HINODE Data Search Systems' and contains a paragraph of text: 'DARTS Hinode Data Center provides a cross-instruments search system for observation data. It is also possible to display a quick-look image of each data and plot the observation time and observation area of the data that matches the specified conditions. Please click the link below to try it.' Below the text is a large logo for 'HinodeDataCenter' featuring a magnifying glass icon. At the bottom, it says 'Last update : June 10, 2022 (Release notes)'.

Getting Data: VSO

<http://sdac.virtualsolar.org/cgi-bin/search>



- Useful tool for searching for datasets across multiple solar observatories
- Uses search parameters to filter through XRT level 1 datasets
- Create desired dataset and download through a variety of methods

Search VSO Help or enter Cart Id:


Search for Solar Physics Data Products:

If you're new to the VSO, see [How To Search](#), the [FAQ](#) or click the [icons for online help](#).

Please select which values you wish to use to search for data products:

- Time**
Search by time interval.
[Derive time intervals from event catalogs](#)
- Observable**
Search based on physical observables [!](#)
- Instrument / Source / Provider**
Search based on instruments [!](#) or data archives [!](#)
 - Compact listing
 - Instrument / Source (not provider dependent)
 - Instrument Only (not source or provider dependent)
- Spectral Range**
Search based on a spectral range
- Nicknames**
Search based on common terms used to describe data products
Note: Nicknames generate an intersection with other search terms, so searching for a nickname, and a physical observable (or other parameter) when a nickname defines other physical observables will result in no matches.
 - Show Nickname Definitions

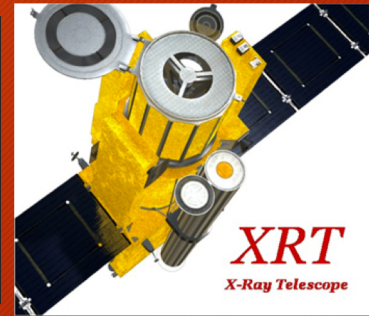
Searching against current VSO instances



Virtual Solar Observatory

Getting Data: Science Center Archive

<http://sdc.uio.no/search/>



- Select XRT data from list of current instrument data at top of the webpage
- Query on multiple data types
- Download through the retrieve feature
- Instructions for data download will be send to email

The screenshot shows the 'Hinode SDC Europe - Archive Search' interface. At the top, it displays '7.304 million files, 2006/10/18—2010/01/10, v 1.9.2' and '21 groups w/842 matching files (0.01% of all files) - 0.45 seconds.' The interface includes search controls like 'Search', 'Reset', and 'Full reset'. There are instrument selection buttons for 'EIS', 'XRT', 'SOT(all)', 'SOT/NFI (SOT/NB)', 'SOT/BFI (SOT/WB)', and 'SOT/SP'. A 'Quicklook' dropdown is set to 'Level 0'. The 'Show fields' section lists 'FILE', 'INSTRUME', 'DATE_OBS', 'DATEPATH', 'SUBPATH', 'HOURPATH', 'FILESZ', and 'GZFILESZ'. The 'SOT/SP level 1/ID options' section has a dropdown set to 'Show level 1 leads only'. The 'EIS line fit thumbs selection' table shows three entries: 'Ca XVII 192.82Å', 'Fe XII 195.12Å', and 'Fe XI 180.40Å'. The 'More search criteria' section includes buttons for 'FITS', 'Plan', 'Quality', 'Misc', 'EIS', 'XRT', and 'SOT'. At the bottom, there are navigation buttons for 'Search', 'Reset', 'Full reset', 'Home', 'User Survey', and 'Hinode Europe'.

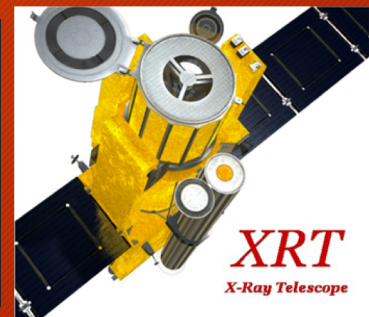
Using XRT Data

with Solar Soft IDL

XRT Solar Soft (SSWIDL) Set Up

- Installation and SolarSoft information can be found at:
 - <https://www.lmsal.com/solarsoft/>
- Utilizes scripts written in the Interactive Data Language (IDL) format
- Include Hinode/XRT libraries during installation process
 - In order to use the code provided here, some ancillary XRT files are necessary and can be installed by running `sswdb upgrade` from within SSWIDL and adding the `hinode/xrt` branch of the SSWDB tree (if not done at initial installation)

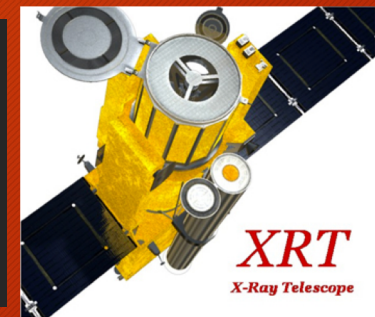
XRT Data Catalog Search



- The XRT catalog contains a subset of XRT FITS header keywords, (FOV, filters, size, etc...) for each XRT observation
- Returns XRT catalog records suitable for selecting data as a structure array
- Runs in IDL/SSWIDL
 - Same structure as https://www.lmsal.com/solarsoft/xrt_cat.html

```
IDL> t0='2007-04-18T02:30:00'  
IDL> t1='2007-04-18T12:30:00'  
IDL> xrt_cat, t0, t1, catx, ofiles  
IDL> help, catx  
    CATX    STRUCT    = -> <Anonymous> Array[311]  
IDL> help, ofiles  
    OFILES  STRING    = Array[311]
```


XRT Data Filtering



- Filter of XRT with the IDL command line using FITS keywords
 - All FITS keywords can be utilized
 - Keywords can be found in each FITS file header
- Basic filter example:
 - Normal image types
 - X axis size of 512

```
>filt=where(catx.ec_imty eq 'normal' and catx.naxis1 eq 512)
```

EC.IMTY.: Image type; input string values of 'dark' or 'normal'.

EC.FW1.: Filter Wheel 1 position; input string values of 'Open', 'Al_poly', 'C_poly', 'Be_thin', 'Be_med', 'Al_med'

EC.FW2.: Filter Wheel 2 position; input string values of 'Open', 'Al_mesh', 'Ti_poly', 'Gband', 'Al_thick', 'Be_thick'

EC.VL.: Visible light shutter position; input string values of 'open' or 'closed'.

NAXIS1: General FITS keyword for pixel length in the x -direction; input integer value. XRT images are generally 384×384, 512×512 or 1024×1024; though any given area of the CCD can be read out.

Reading XRT Data

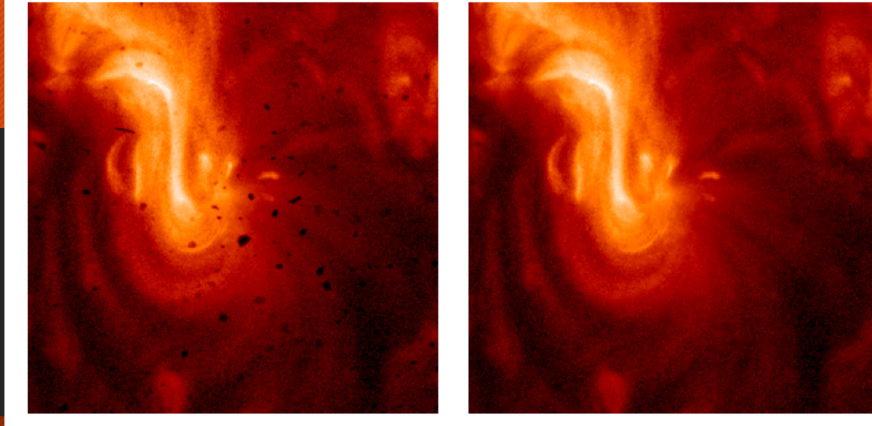


- XRT image headers and data can be read using the IDL routine `read_xrt.pro`
- Data read into arrays storing pixel information and header values

Basic call, to read headers and data:

```
IDL> ss=where(catx.ec_imty_ eq 'normal' and catx.naxis1 eq 2048)
IDL> read_xrt, ofiles[ss], index, data
IDL> help, ofiles[ss]
    <Expression>    STRING    = Array[5]
IDL> help, index
    INDEX           STRUCT    = ->  <Anonymous>  Array[5]
IDL> help, data
    DATA           INT       = Array[2048, 2048, 5]}
```

Calibrating XRT Data



- Utilizes routine `xrt_prep.pro` to convert level 0 to level 1
- Basic call: `IDL> xrt_prep, input1, input2, index out, data out`

Read in raw FITS image(s) from a filelist or read in a datacube and structure.

Fill pixels of value = 0 (missing data) with a "missing data value" = -999.

Replace near-saturated pixels for values greater than some threshold (default: 2500 DN).

Option to remove radiation-belt/cosmic-ray hits and streaks.

Calibrate for read-out signals.

Locate missing pixels and replaces their values with a linear patch to improve Fourier filter performance.

Remove the CCD bias (pedestal), and dark current (using the subroutine `xrt clean ro.pro` which also calibrates the read-out signals).

Remove vignetting.

Option to normalize each image for exposure time.

Option to compute map of calibration uncertainties.

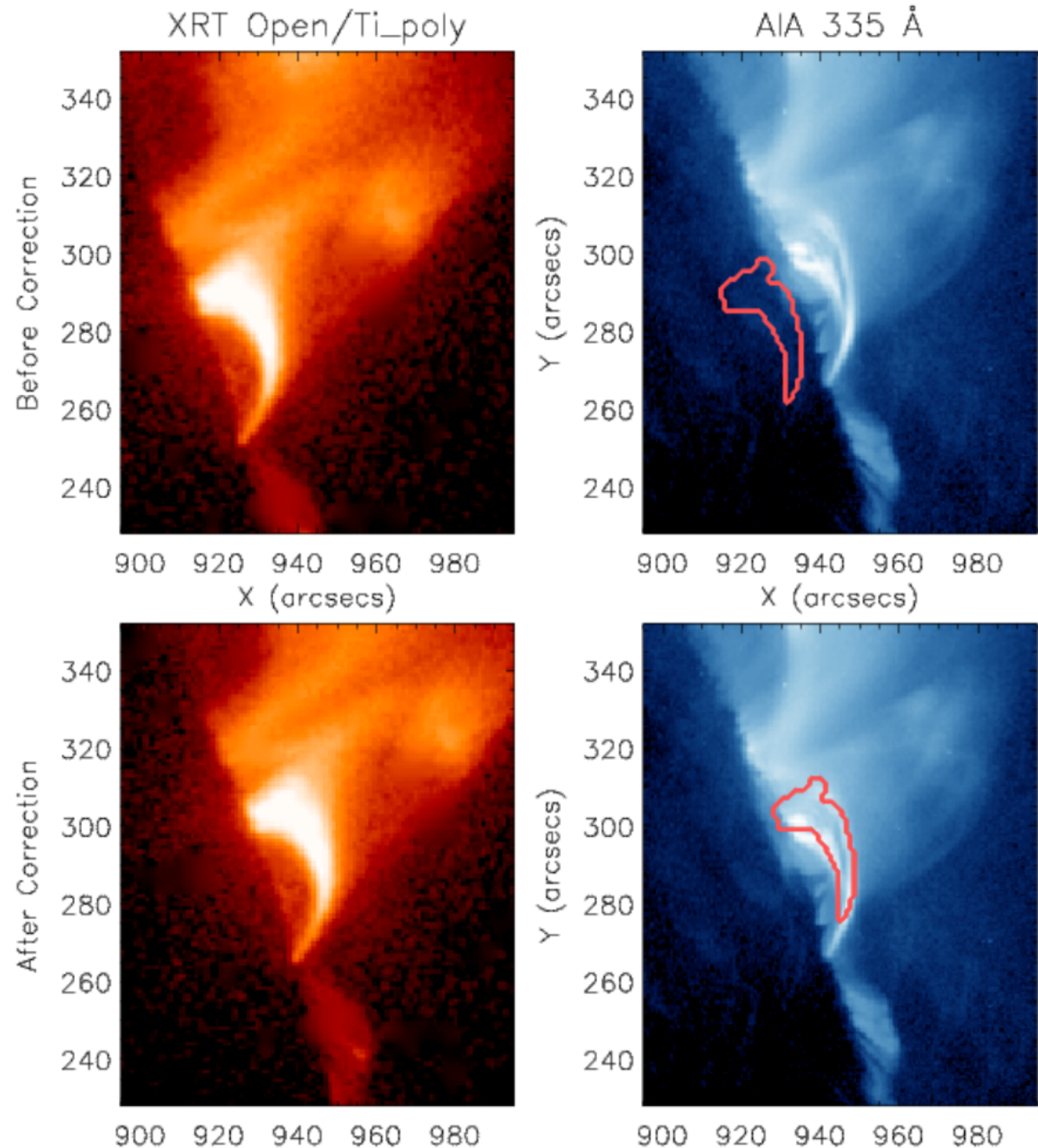
Option to cosmetically correct for contamination spots or dust.

Output the corrected image(s) in an updated structure and data cube.

Option to coalign XRT data using `xrt read coaldb.pro`.

Co-aligning XRT Data

- Updates the alignment of XRT data
 - Useful for comparing between instruments
- Called as part of the data prep routine
- Does not alter XRT data and only updates FITS keywords
- Users can determine what type of co-alignment calibration was performed by reading the image history keyword
- Basic Call: `IDL> new_index = xrt_read_coaldb(index)`



Making Composite Images



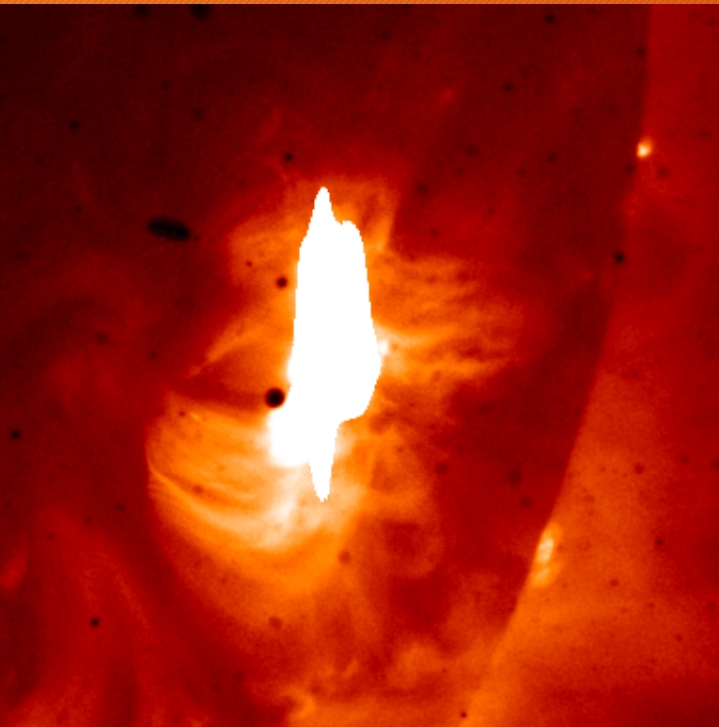
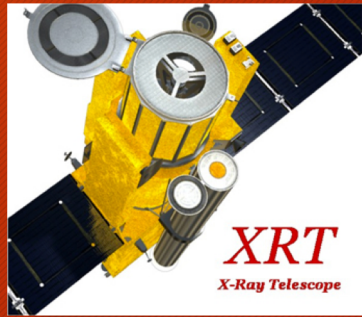
- Two routines available for making composite images
- **Mk_xrt_composite** combines a single long and short exposure pair of images to increase the dynamic range and to replace saturation with unsaturated data:

```
IDL> mk_xrt_composite, l_idx, l_da, s_idx, s_da, c_idx, c_da
```

- Can be done in batches with the **xrt_batch_composite** routine

```
IDL> xrt_batch_composite, l_idx, l_da, s_idx, s_da, index_out, data_out
```

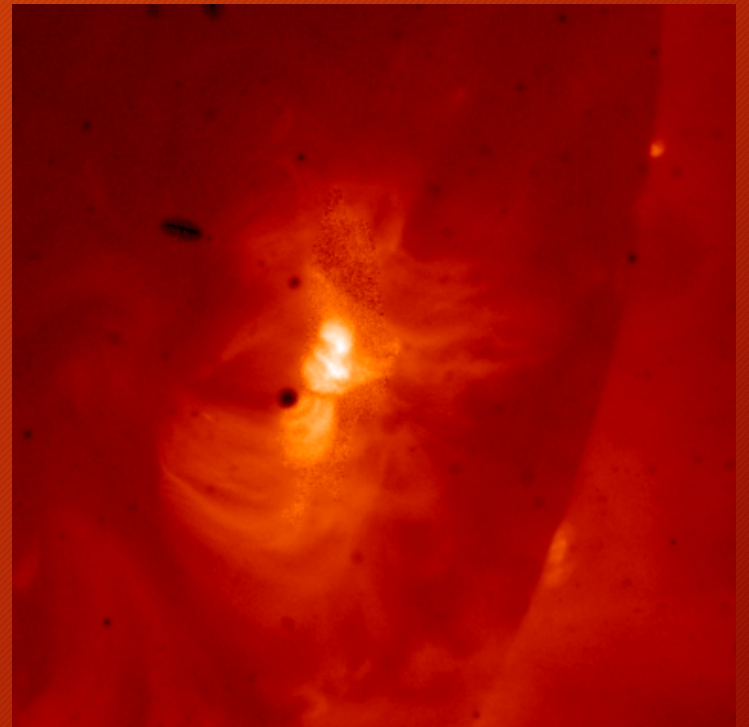
Example of Composite Images



+



=



Al_poly long image
5.8 second exposure time

Al_poly short image
0.2 second exposure time

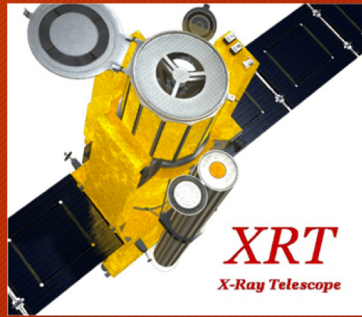
Composite image

Deconvolving the Point Spread Function



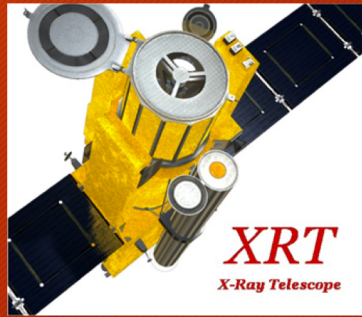
- A point spread function (PSF) was developed for XRT
- Can be deconvolved to improve quality using `XRT_deconvolve`
- `IDL>xrt_deconvolve,in,da,new_in,new_da`
- Improves image clarity and decreases blurring effects

Instrument Responses and Inferring Physical Quantities



- Please refer to section 2.11 of the Analysis Guide for detailed summary
- XRT data analysis requires understanding the physical units of the relevant values and functions
- Information regarding details of these properties is well summarized in the analysis guide
 - Somewhat complicated and nuanced procedure

XRT Movie Generation (Gather Data)



Read Dataset from file

```
file = DIALOG_PICKFILE(FILTER='*.txt')
OPENR, lun, file, /GET_LUN
flist1 = ""
line = ""
WHILE NOT EOF(lun) DO BEGIN & $
    READF, lun, line & $
    flist1 = [flist1, line] & $
ENDWHILE
FREE_LUN, lun
```

Read from Catalog

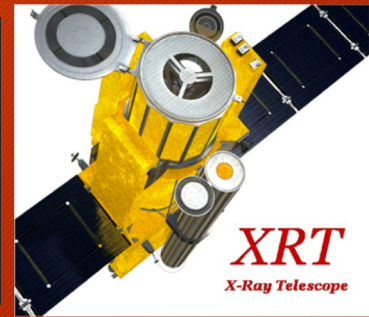
```
tt0 = '2021-10-08T10:45:00'
tt1 = '2021-10-08T11:15:00'
xrt_cat, tt0, tt1, catx1, ofiles1
filt1 = where(catx1.ec_fw1_ eq 'Be_Thin' and
catx1.naxis1 eq 256)
flist1 = ofiles1[filt1]
```

XRT Movie Generation (Prepare Data)



- Read in the XRT data from flist1 array
 - `read_xrt, flist1, index1, data1`
- Prepare data using `xrt_prep` commands
 - Explicitly call `despike_despot`
 - `xrt_prep, index1, data1, index_out1, data_out1, /despike_despot`
- Create an array to hold rescaled data:
 - `xy = size(data_out1, /dimensions)`
 - `image_set = make_array(xy[0], xy[1], xy[2])`
- Get number of files
 - `numf = xy[2]`

XRT Movie Generation (Scale)



```
loadct, 3
```

Load red temperature
color table

Rescale logarithmically

```
for i = 0, numf do begin $
```

```
  image=sigrange(data_out1[*,*],i, frac=.9999, range=range) &$
```

```
  if range[0] gt 0 then imin=log10(range[0]) else imin=log10(20.0) &$
```

```
  imax = log10(range[1]) &$
```

```
  image=log10(image > 1.0^imin) &$
```

```
  image = image <imax &$
```

```
  image_set[*,*],i = image &$
```

```
  stretch, 0, 255, 1.1 &$
```

```
  wdef, 0, xy[1] &$
```

```
  tvscl, rebin(image, xy[0], xy[1]) &$
```

```
  xyouts, 0.03, 0.03, index1[i].date_obs, /normal, size=2.0 &$
```

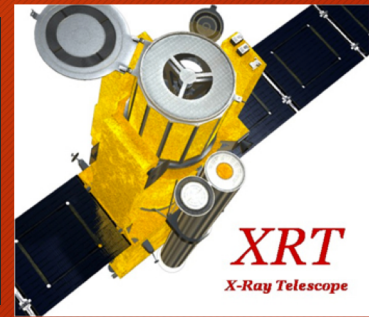
```
  if index1[i].EC_FW1_ eq 'Open' then xyouts, 0.03, 0.95, index1[i].EC_FW2_, /normal, size=2.0 &$
```

```
  if index1[i].EC_FW2_ eq 'Open' then xyouts, 0.03, 0.95, index1[i].EC_FW1_, /normal, size=2.0 &$
```

```
  wait, 0.0
```

Write the time and
filter to each image

XRT Movie Generation (Save)



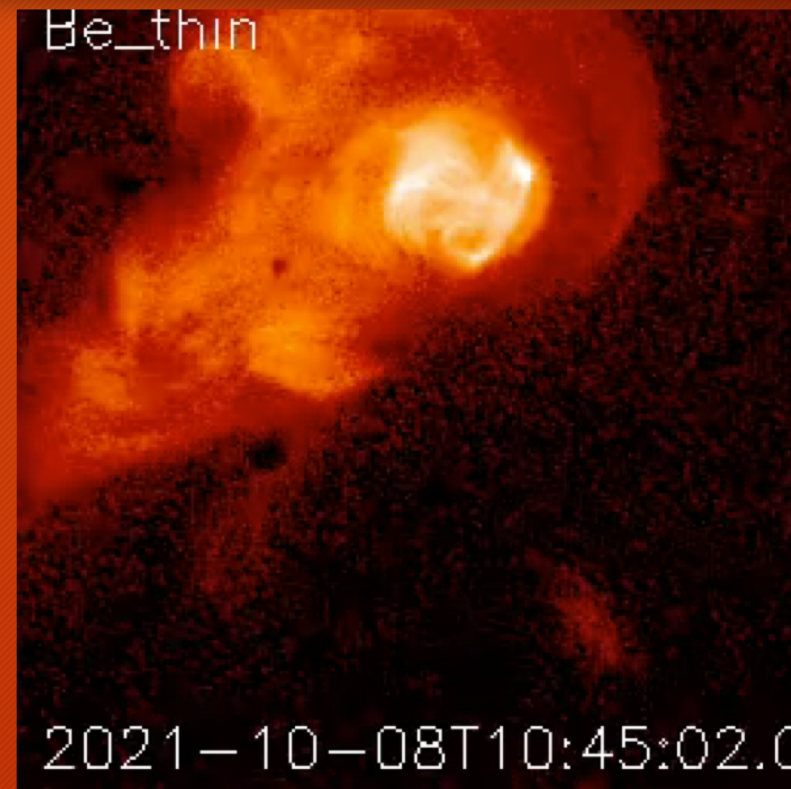
```
for i = 0, numf do begin $
  DEVICE, GET_DECOMPOSED=old_decomposed &$
  DEVICE, DECOMPOSED=0 &$
  LOADCT, 3 &$
  WINDOW, 1, XSIZE=XY[0], YSIZE=XY[1] &$
  stretch, 0, 255, 1.1 &$
  wdef, 0, xy[1] &$
  tvscl, rebin(image_set[*], *, i), xy[0], xy[1]) &$
  xyouts, 0.03, 0.03, index1[i].date_obs, /normal, size=2.0 &$ &$
  if index1[i].EC_FW1_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW2_, /normal, size=2.0 &$
  if index1[i].EC_FW2_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW1_, /normal, size=2.0 &$
  filename = 'XRT_'+strtrim(string(i, format='(I04)'), 2) + '.png' &$
  WRITE_PNG, filename, TVRD(/TRUE)
```

Display each image

Write time and filter info

Save to image format

XRT Movie Generation



```
ffmpeg -framerate 10 -pattern_type glob -i '*.png' -c:v libx264 -r 30  
-pix_fmt yuv420p 20211008_High_Cad.mp4
```

End

