



# GST Imaging Data Registration and Alignment

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**NJIT**

New Jersey Institute of Technology



# Outline

- **Motivation**

  - User friendly and convenient data products

- **Introduction**

  - GST data reduction

  - Image registration and alignment

- **Methods (algorithms)**

  - Scale Invariant Feature Transform (SIFT)

  - Optical Flow (OF)

- **Applications**

# Motivations

- **Multi-wavelength data analysis**

Construct a comprehensive picture of a solar event

- **Campaign observations**

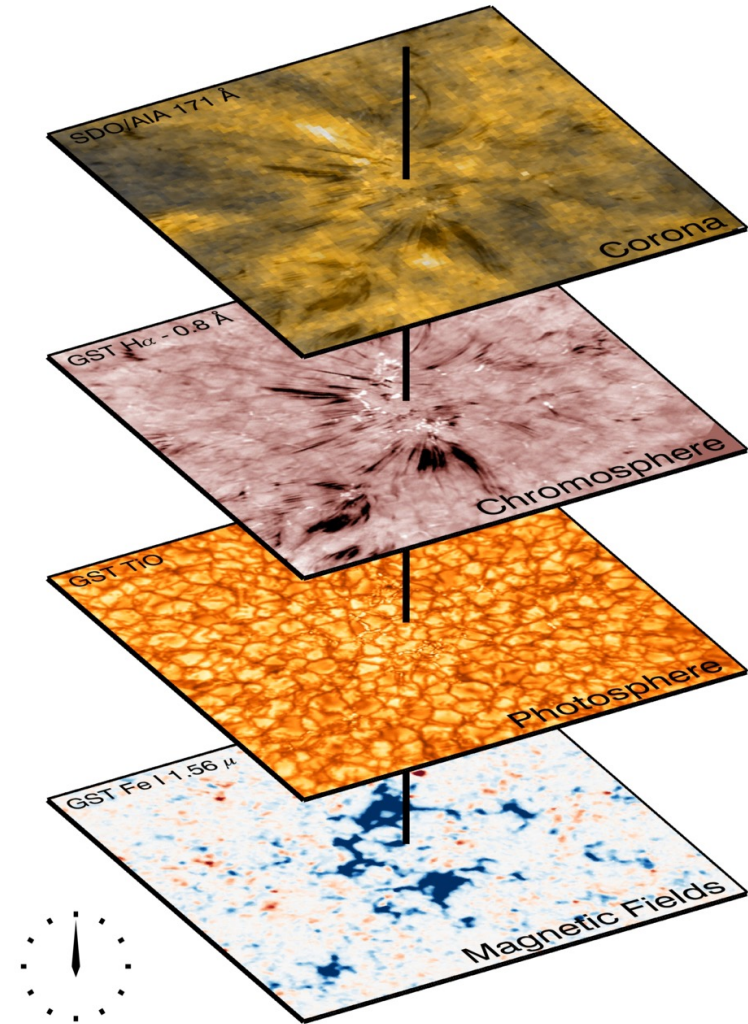
Multiple facilities and instruments

SDO, IRIS, SoHO, Hinode

GST, DKIST, DST, GREGOR, SST, NVST

SUNRISE, Hi-C

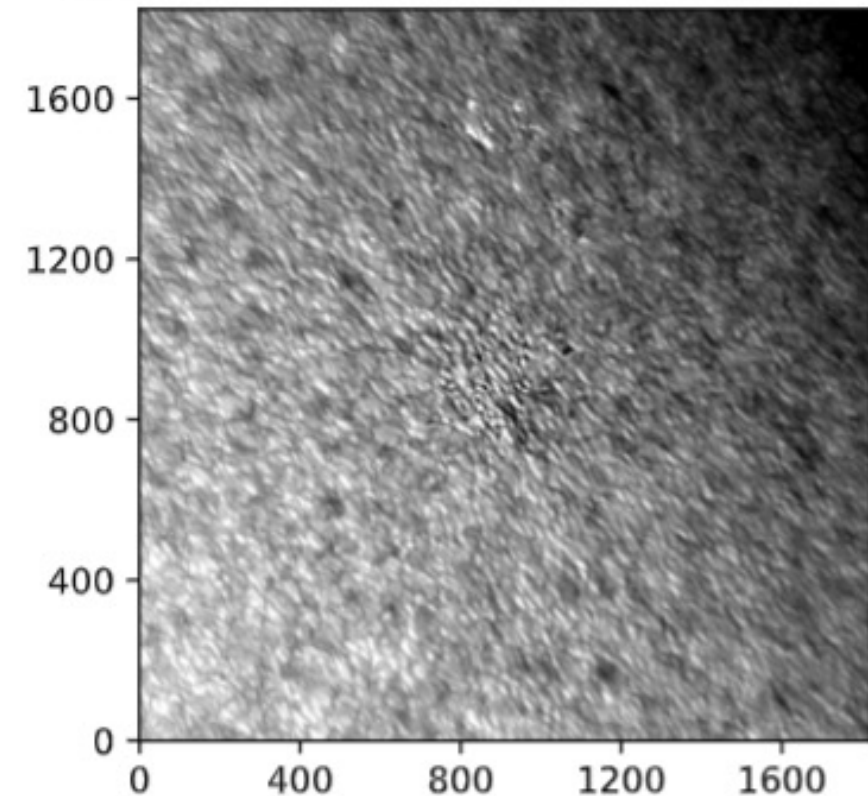
Samanta et al, Science, 2019



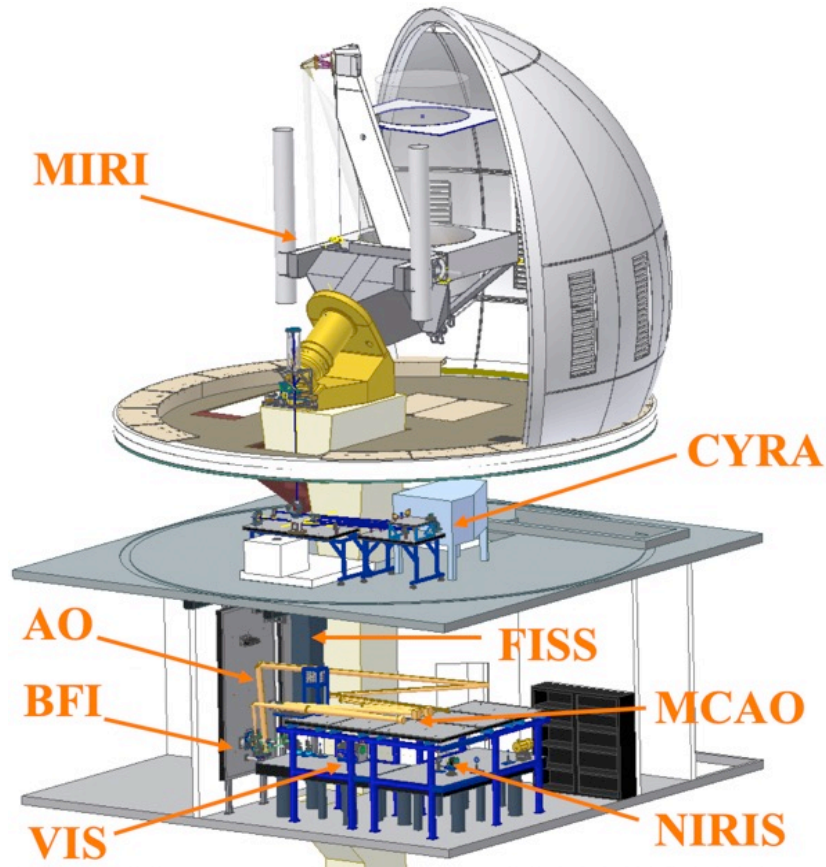
# Motivations

- **Co-alignment of multi-instrument and multi-wavelength data**
- **Ground-based telescopes**
  - High-resolution imaging
  - Localized field of view (FOV)
- **Difficulties to get accurate heliocentric coordinates**
  - Telescope pointing and tracking system (flexure)
  - Difference in each specific focal plane instrument (different optical path/camera array)
  - Seeing distortion (in time sequence dataset)

(a1) Observation with GST/BFI

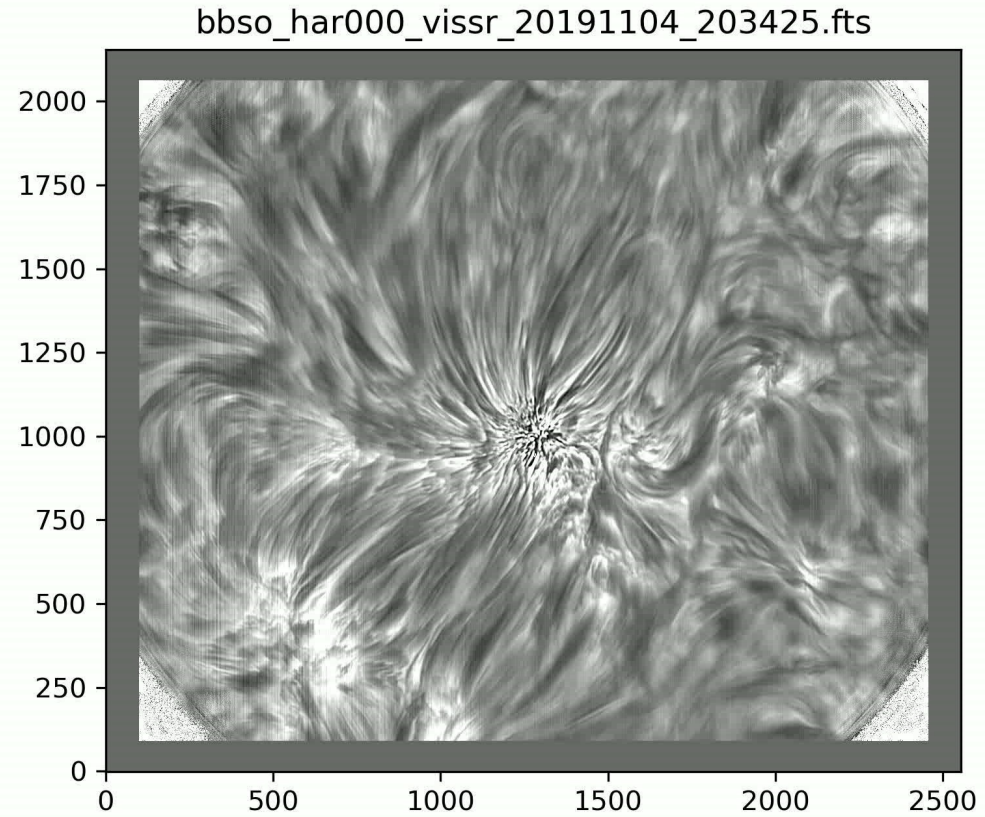
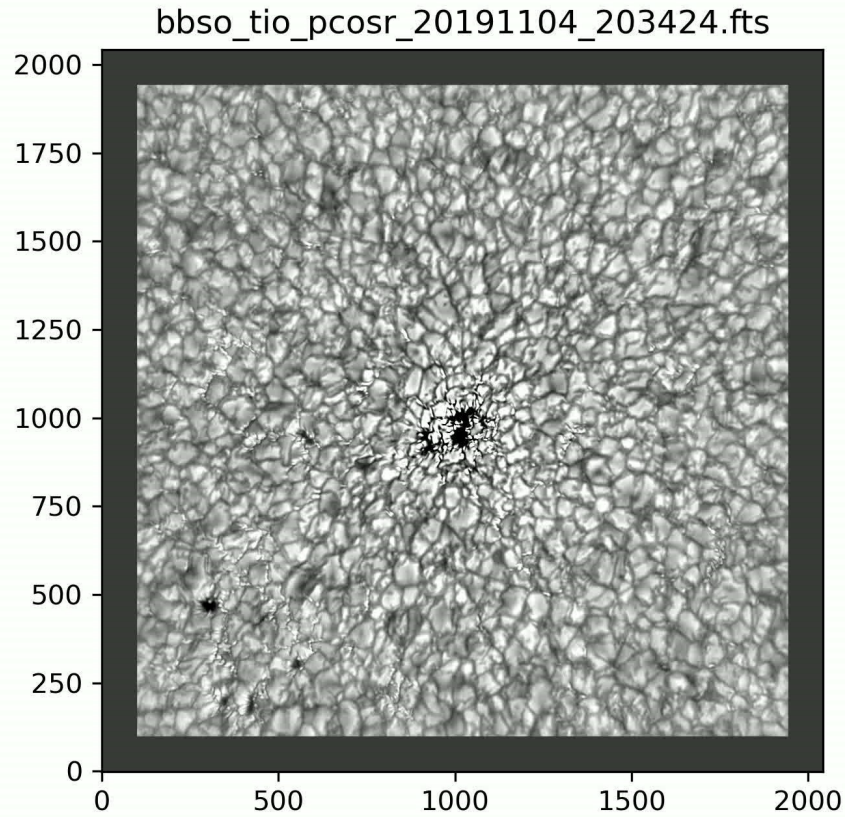


# GST Focal Plane Instruments

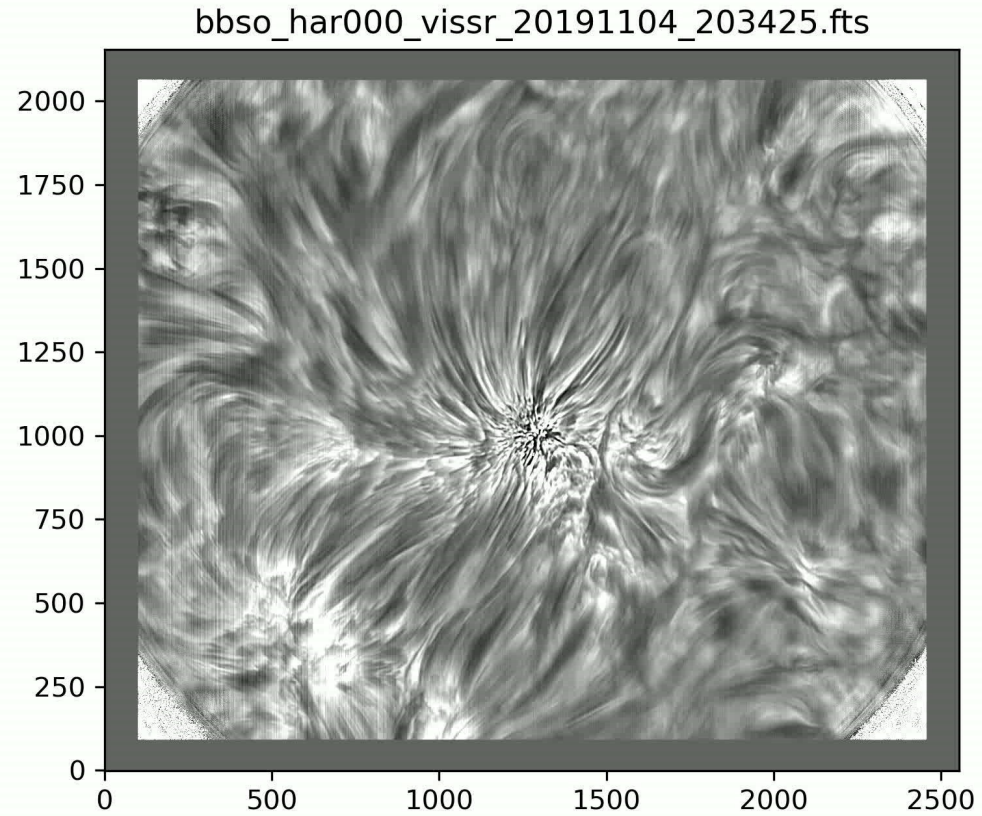
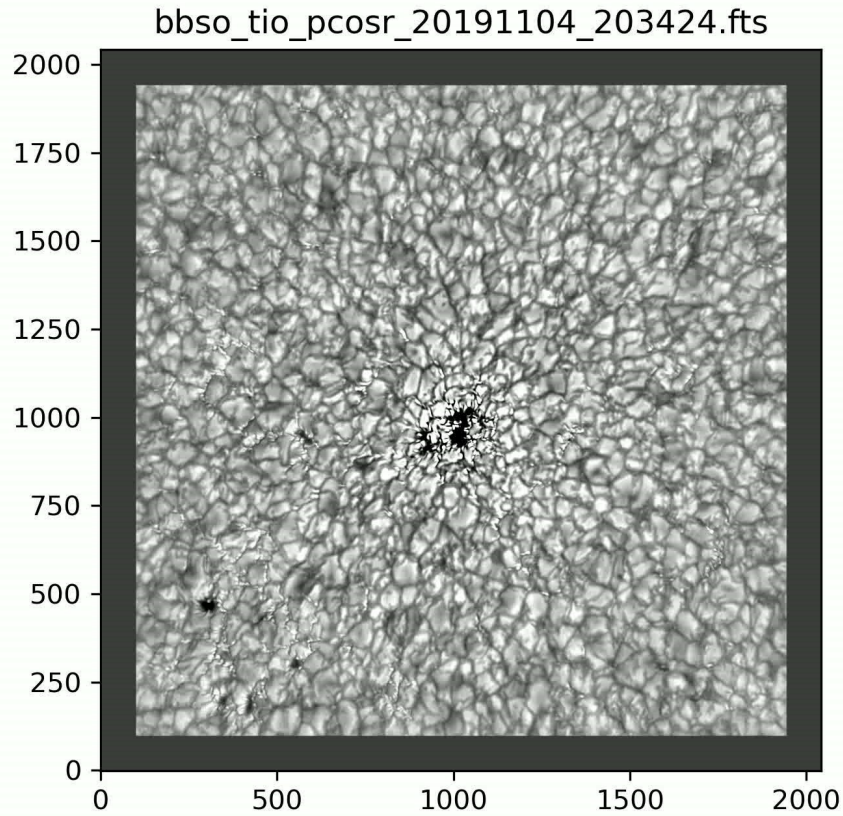


- Broad Band Filter (**BFI**)  
TiO 7057 Å, imaging
- Visible Imaging Spectrometer (**VIS**)  
H $\alpha$  6563 Å 13 $\lambda$  (-1.2~1.2 Å), imaging spectroscopy
- Near Infrared Imaging Spectropolarimeter (**NIRIS**)  
He I 10830 Å (-0.8~0.8 Å), imaging spectroscopy  
Fe I 15648 Å, imaging spectropolarimetry
- NASA Mid Infrared Imager (**MIRI**)  
5  $\mu$ m, 8  $\mu$ m, imaging
- Fast Imaging Solar Spectrograph (FISS)
- Cryogenic Solar Spectrograph (CYRA)

# GST Data Reduction (Imaging)



# GST Data Reduction (Imaging)





# Image Registration: Accurate Heliocentric Coordinates

- ❖ Telescope pointing and tracking system
  - Accuracy (Flexure)
  - Coordinates/ Rotation/ Image Scale
- ✓ Image Registration





# Image Registration: Accurate Heliocentric Coordinates

❖ ~~Telescope pointing and tracking system~~

~~Accuracy (Flexure)~~

~~Coordinates/Rotation/Image Scale~~

✓ Image Registration

Local high-resolution images (GST) → full-disk heliograms (SDO/HMI)

❖ Manual image registration (zoom-in/rotation/move/contour)

~~Subjective qualification/ impacted by multiple individual freedoms.~~

~~Low-contrast features~~



# Image Registration: Accurate Heliocentric Coordinates

~~❖ Telescope pointing and tracking system~~

~~Accuracy (Flexure)~~

~~Coordinates/Rotation/Image Scale~~

✓ Image Registration

~~Local high-resolution images (GST) → full-disk heliograms (SDO/HMI)~~

~~❖ Manual image registration (zoom-in/rotation/move/contour)~~

~~Subjective qualification/ impacted by multiple individual freedoms.~~

~~Low-contrast features~~

✓ A numerical algorithm deploying an automatic and accurate image registration method is highly desired!



# GST Time Sequence Dataset Alignment

- Image rotation  
Zenith telescope
  - ✓ Constant rotation rate (360 in 24 hours)
- Image displacement  
Telescope tracking  
Seeing distortion
  - ✓ Time sequence alignment
- Image stretching  
Seeing distortion
  - ✓ De-stretching



# Filter-based Spectroscopic Image: Co-alignment between Wavelengths

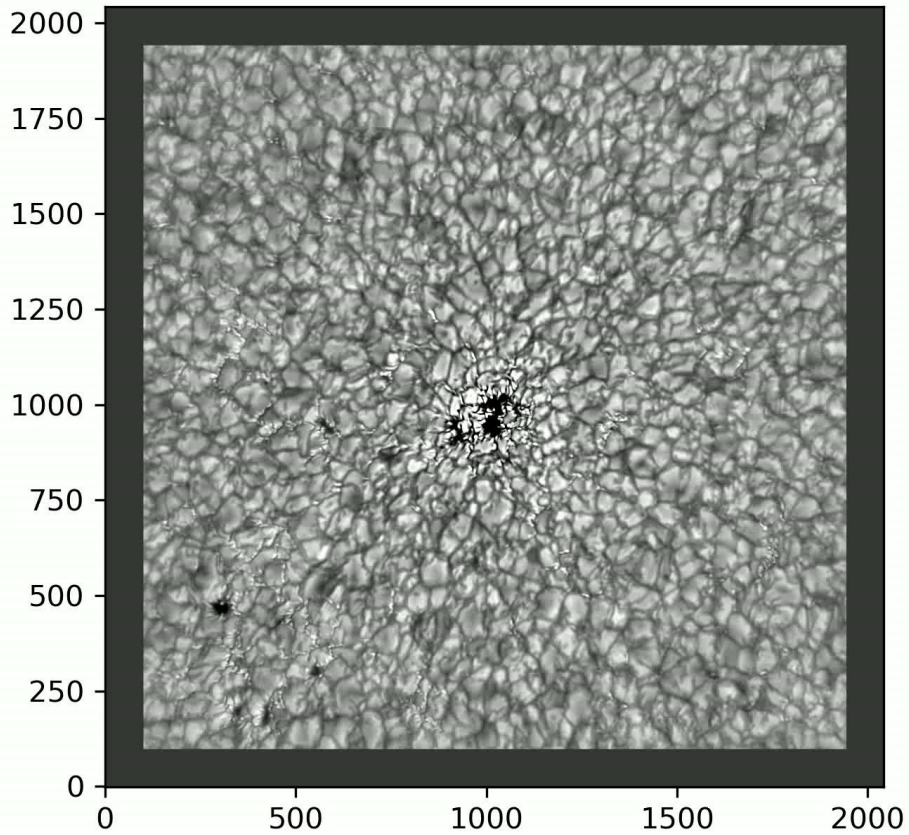
H $\alpha$  6563 Å line center  $\pm$  0.2, 0.4, 0.6, 0.8, 1.0, 1.2 Å  
1.5s cadence between wavelengths

He I 10830 Å line center  $\pm$  0.2, 0.4, 0.6, 0.8 Å  
2.5s cadence between wavelengths

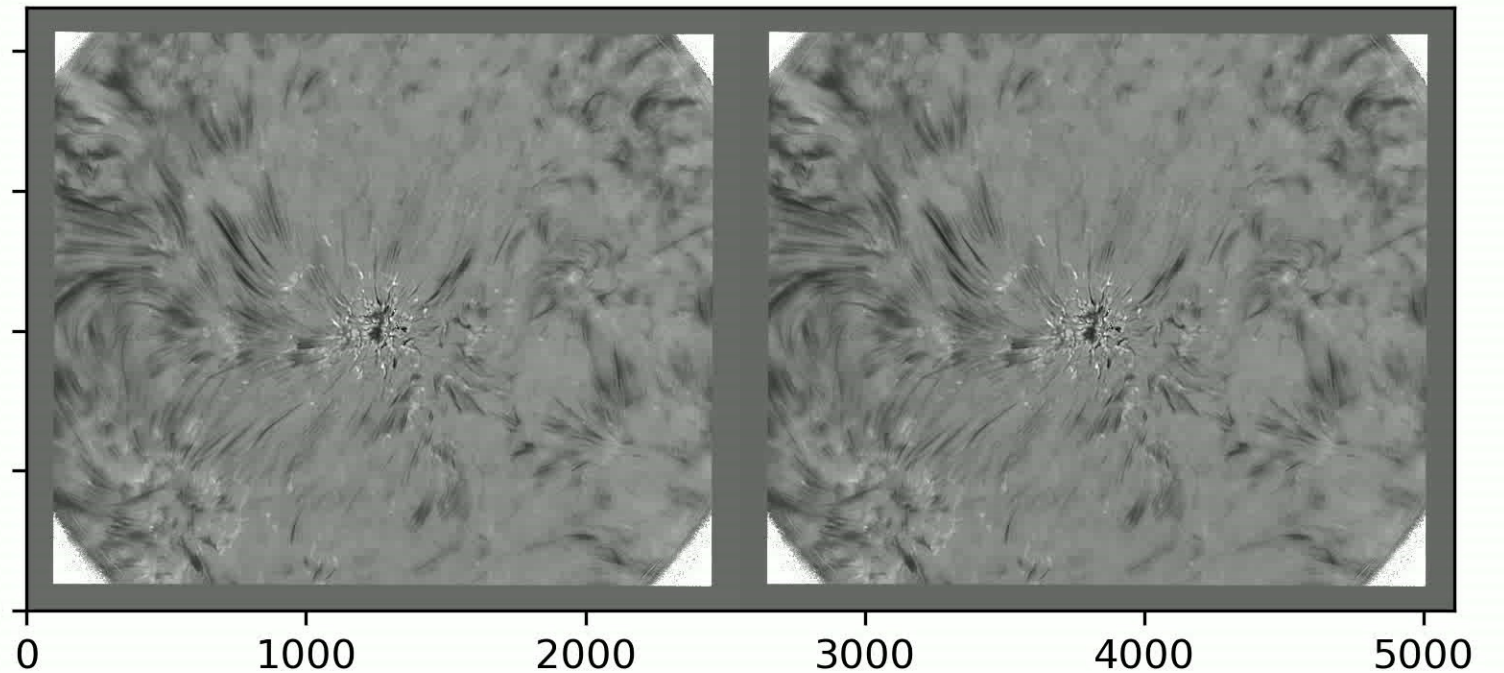
Need a fast co-alignment algorithm for multi-wavelength dataset.

# Image De-stretching with Kalman Filter

bbso\_tio\_pcosr\_20191104\_203424.fts



bbso\_hab080\_vissr\_20191104\_203418.fts





# GST Imaging Data Reduction: Level 0.5 → Level 1

## Accurate Heliocentric Coordinates:

- Image Registration
- Multi-wavelength data co-alignment
- Time sequence dataset alignment



# Image Registration -- Methods

In general, can be divided into two groups according to the feature detection technique they use:

I. Area-based methods (Correlation-like or template matching)

Statistical information

Outstanding for translational transforms with a sub-pixel accuracy, while it is arduous for scaling and rotational transforms

II. Feature-based methods:

prominent regions, lines, or points in images as distinct reference features

Good for accuracy. Need for computing power.



# Feature-based: Scale Invariant Feature Transform (SIFT)

- Lowe (2004) designed and developed the Scale-Invariant Feature Transform (SIFT) method.
- Yang (2017) first applied this method to a photospheric magnetogram observed by the Solar Magnetic Field Telescope (SMFT) at the Huairou Solar Observing Station (HSOS).
- Ji (2019) registered photospheric and chromospheric heliograms acquired by NVST with HMI and the Global Oscillation Network Group (GONG) full disk data.





# Area-based: The optical flow (OF)

- Important research direction of computer vision, and it describes the **instantaneous apparent motion** of an object (Brown 1988).
- This method is mainly used in object recognition and object tracking aimed at deriving object motion parameters from **two neighboring images in the time domain**.
- Cai (2022) developed an algorithm to **co-align multi-wavelength** imaging spectroscopic data collected by NVST and evaluated its performance accuracy using raster images acquired by FISS.



# Suppose We have an Observation Datasets Sample

✓ SDO (HMI)

Continuum Intensity, time sequence – IDL (aia\_prep), Sunpy

➤ GST (BFI/VIS/NIRIS) ?

BFI/TiO, time sequence

VIS/H $\alpha$ , spectroscopy, time sequence

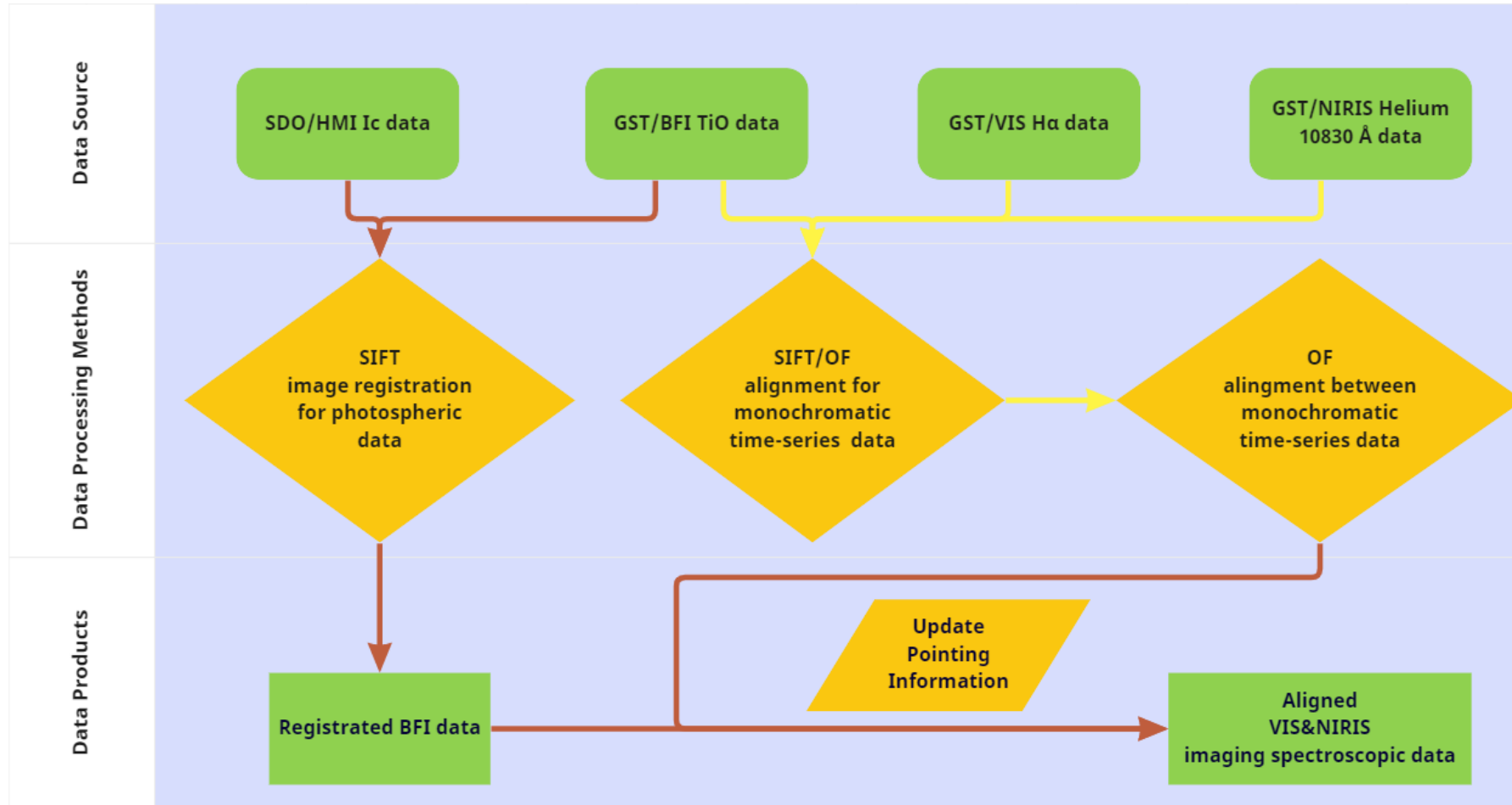
NIRIS/He I 10830, spectroscopy, time sequence



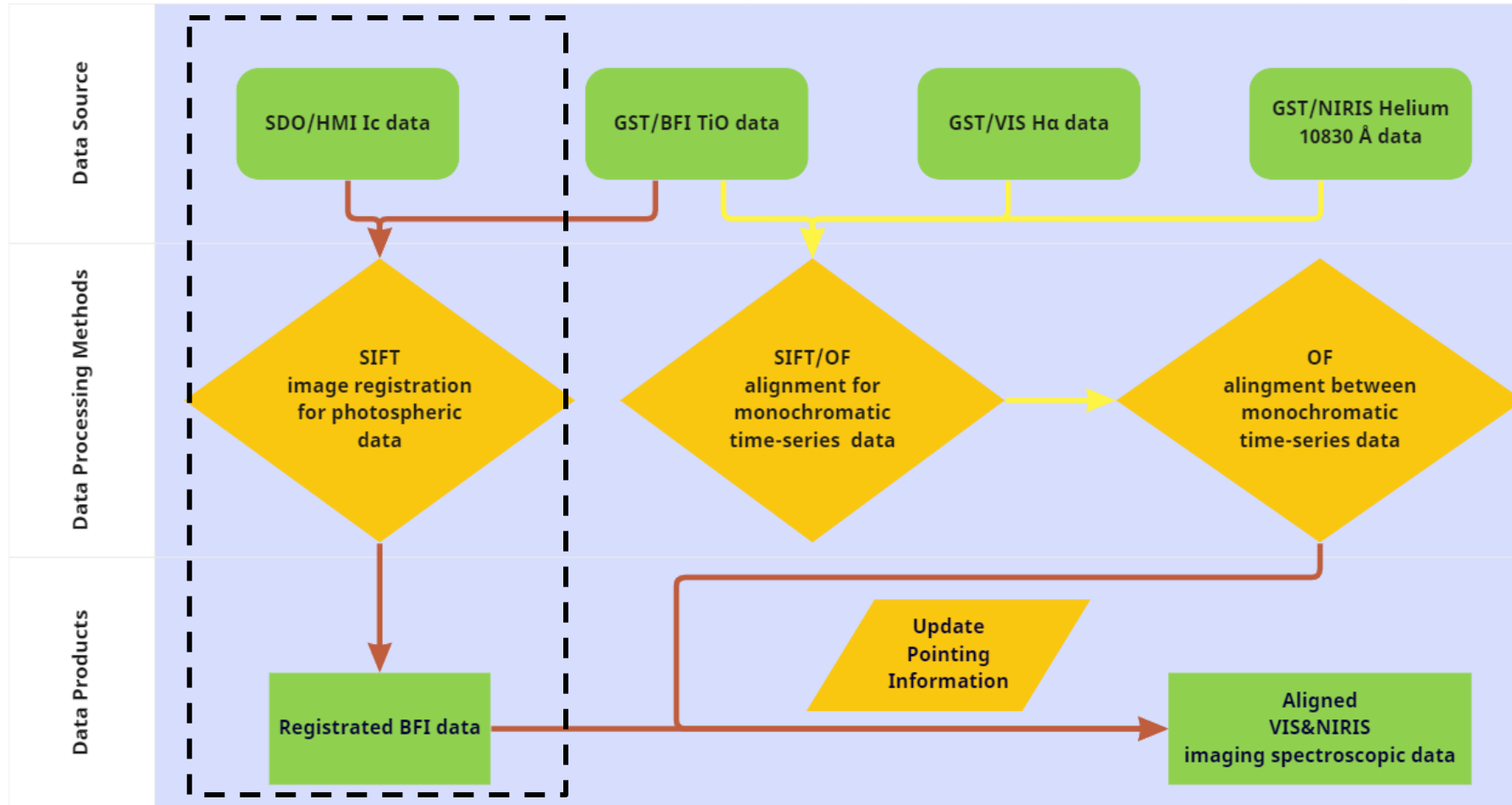
# Strategy for GST Data Registration and Alignment

- Pick-up a reference time
  1. Image registration: BFI/TiO → HMI/lc; get pointing/rotation information
  2. Time sequence alignment (to reference time) for BFI/TiO, VIS/H $\alpha$ , NIRIS/He I 10830
  3. Alignment between wavelengths for spectroscopic images: VIS/H $\alpha$ , NIRIS/He I 10830
  4. Image Registration between GST instruments: VIS/H $\alpha$  → BFI/TiO, NIRIS/He I 10830 → BFI/TiO; update pointing/rotation information

# Workflow Chart

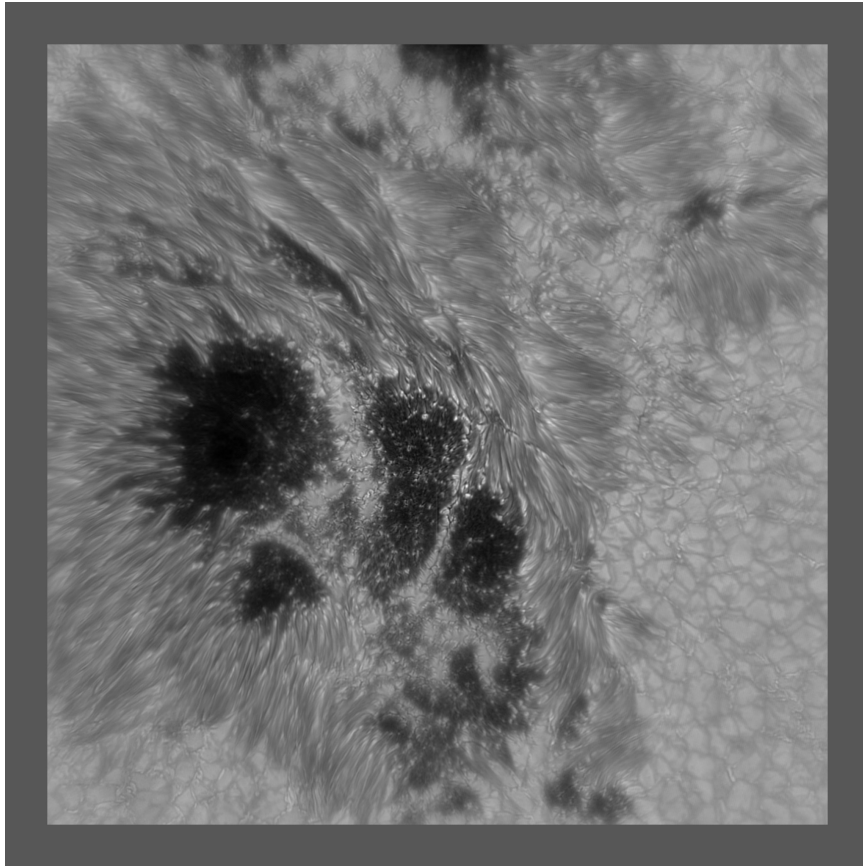


# Workflow: GST/BFI/TiO → SDO/HMI/Ic

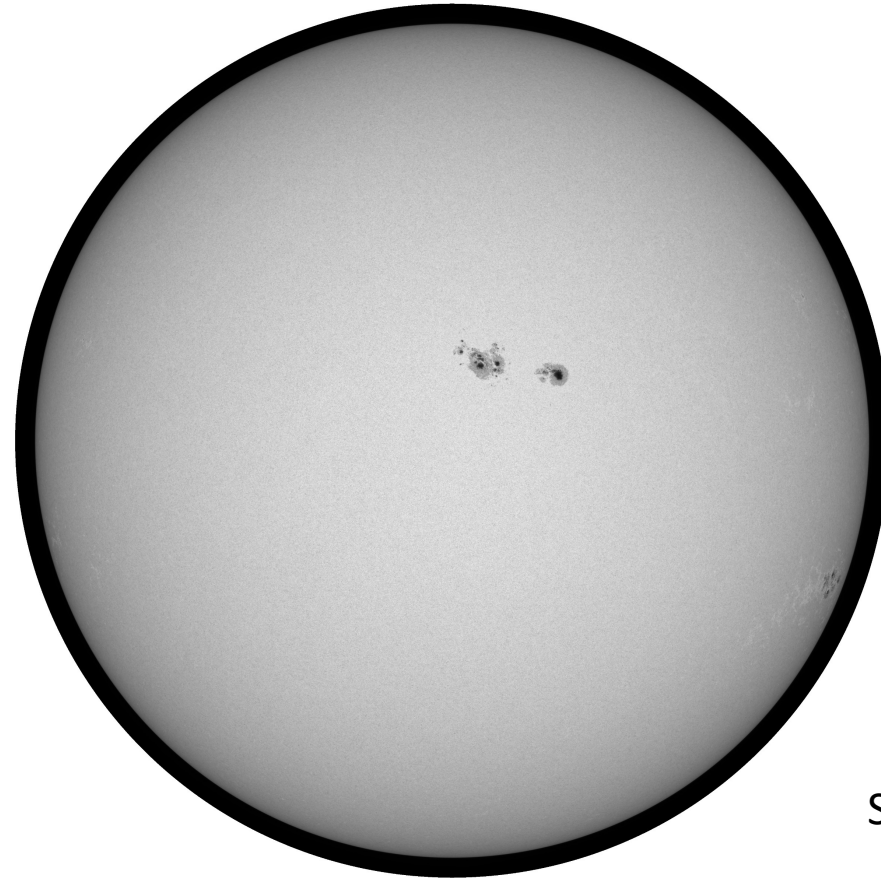




2015-06-22 AR 12371



GST/BFI/TiO



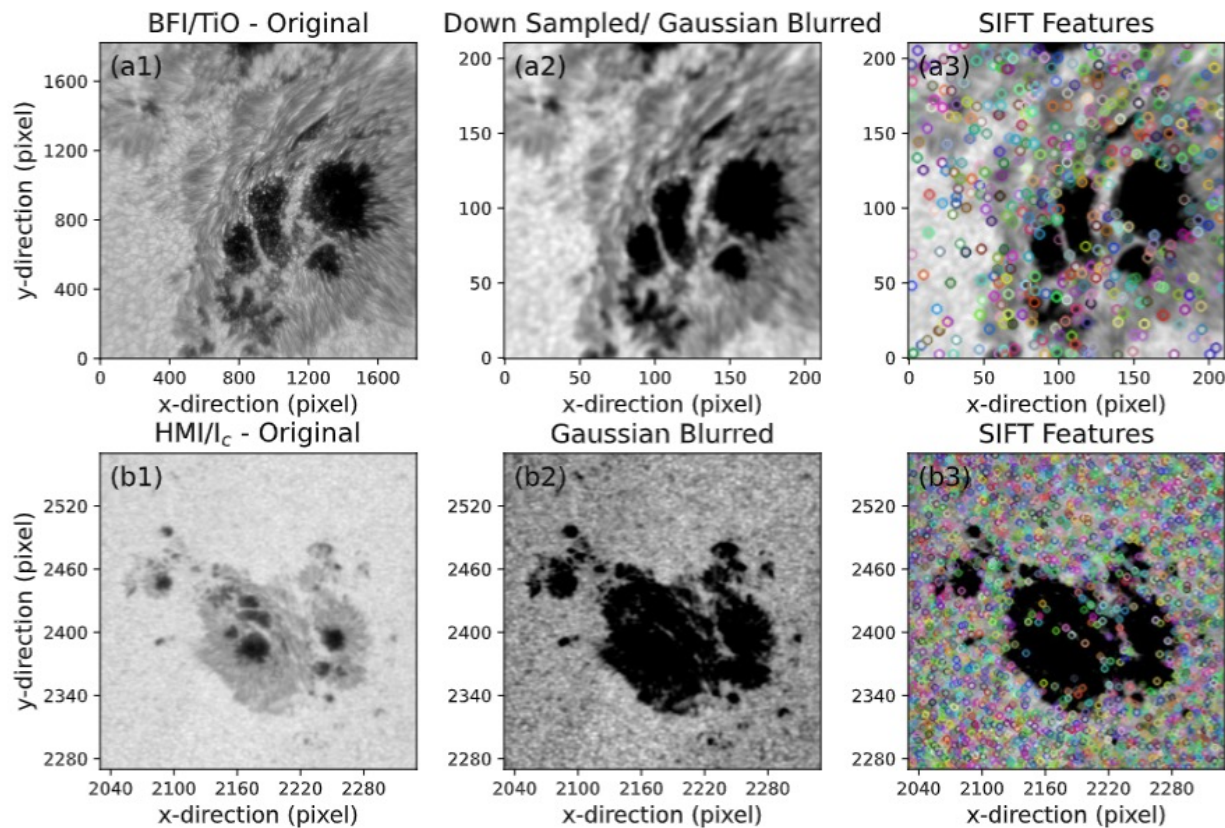
SDO/HMI/IC



# SIFT Approach

- Scale Invariant Feature Transform ([SIFT, Lowe 1999, 2004.](#)) for image registration.  
Extract the Features: invariant to uniform scaling, orientation, and illumination changes.
- Fast Library for Approximate Nearest Neighbors (FLANN, Muja 2009)  
Speed up the matching process.
- Random Sample Consensus (RASAC, Fischler 1981)  
Iterate the matching process to increase the matching accuracy and avoid faulty matches.

# Image Registration with SIFT I: From SDO/HMI/I<sub>c</sub> to GST/BFI/TiO



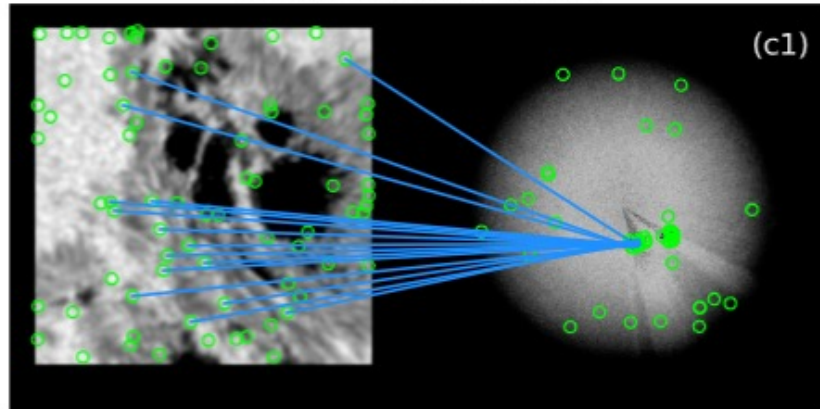
(a1): Original GST/BFI/TiO data;  
 (a2): Down-sampled (to match HMI/I<sub>c</sub> image scale) and intensity rescaled to 8 bit. Bright and dark features are blocked-out by a image mask.  
 (a3) 543 SIFT features are extracted from TiO image.

(b1): Original SDO/HMI/I<sub>c</sub> data in a localized FOV;  
 (b2): Intensity rescaled to 8 bit. Bright and dark features are blocked-out by a image mask.  
 (b3) 271886 SIFT features are extracted from full disk HMI/I<sub>c</sub> image.

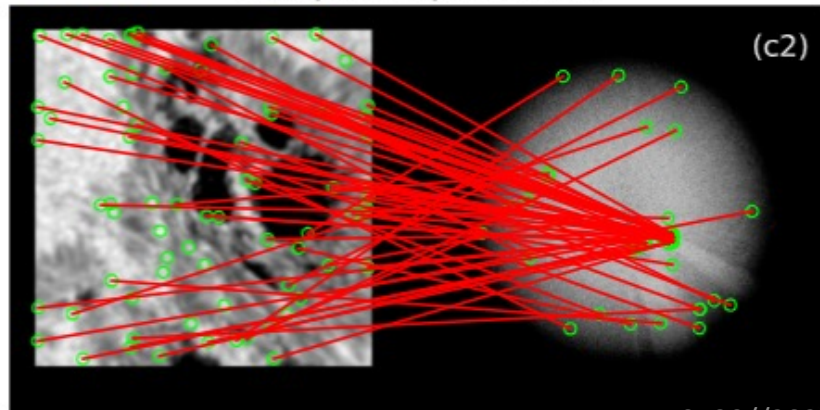


# Image Registration with SIFT I: From SDO/HMI/I<sub>c</sub> to GST/BFI/TiO

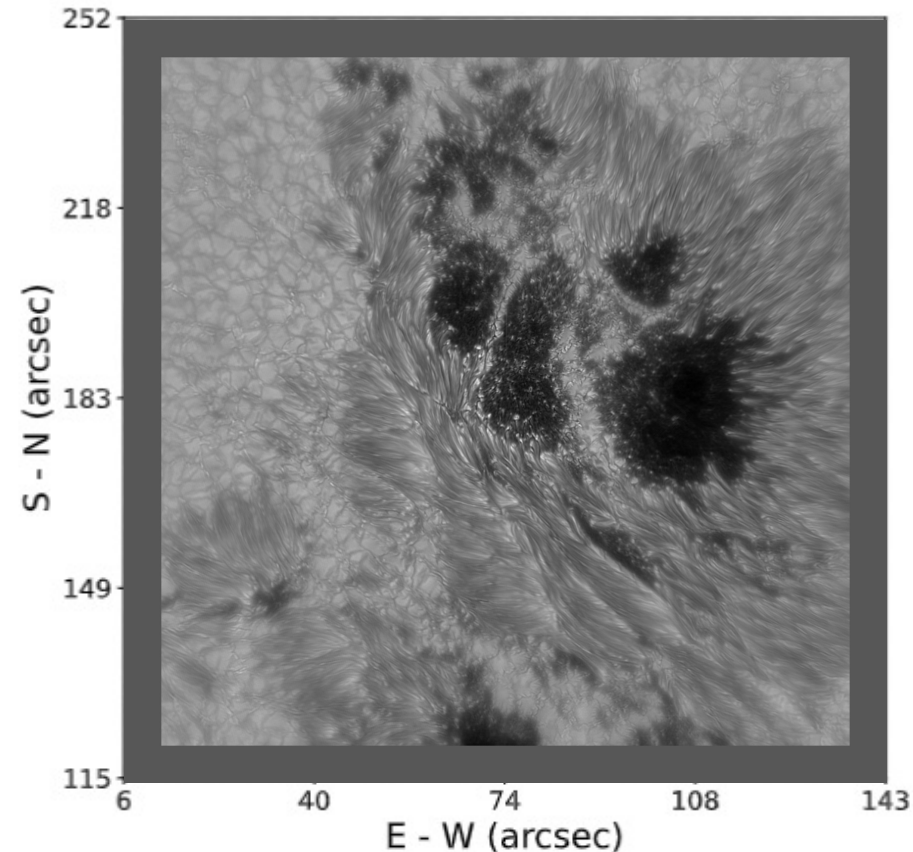
Correct correspondences



Faulty correspondences



HMI/I<sub>c</sub> filled with BFI/TiO

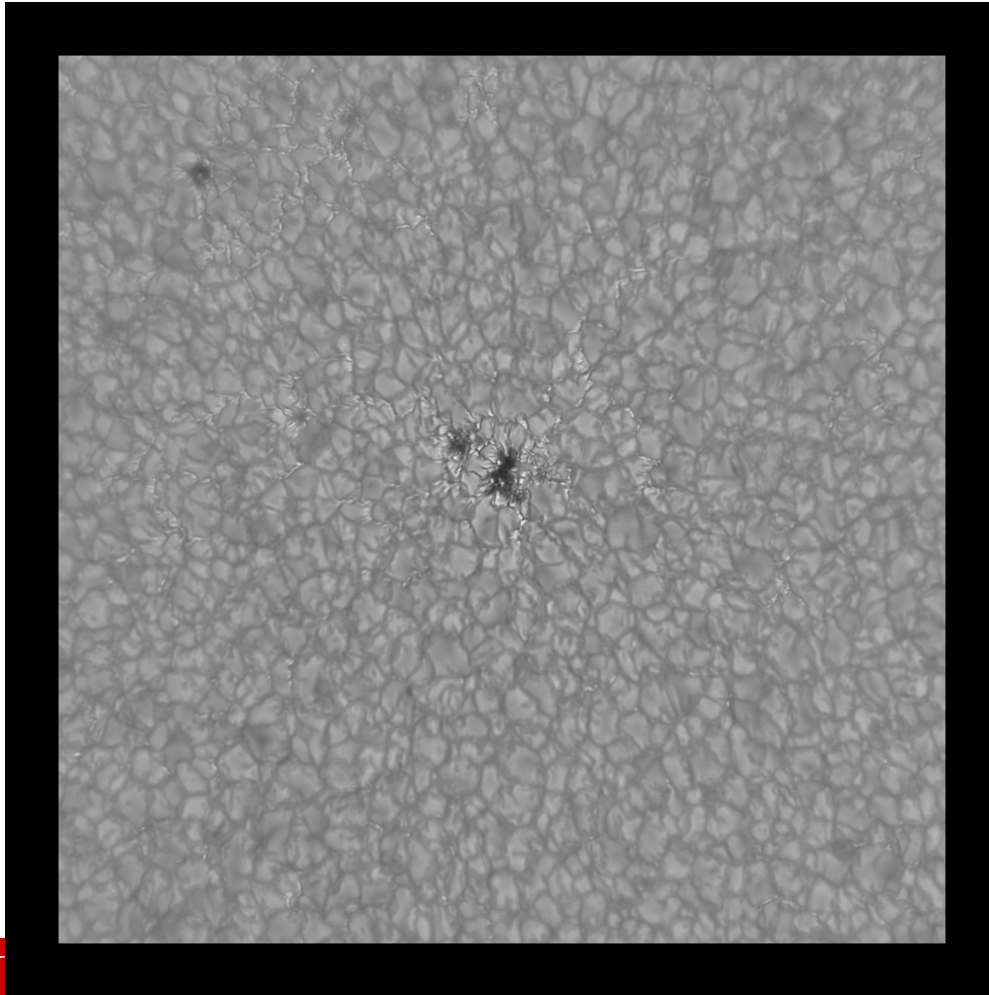


Detected 74 initial matching points (FLANN); 15 of them were verified to be correct (RASAC).

**Heliocentric coordinates:**  
x=74''.30, y=183''.41  
0.3% difference in the calculated image scale.

Make map with SSW or Sunpy commands.

# SIFT Works Better on QS Data



The more features, the more accurate.

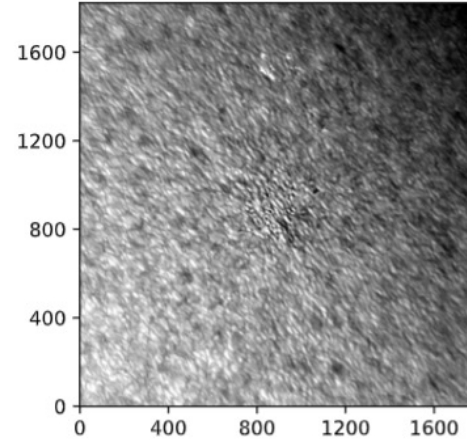
To extract more features, we need to adjust the gaussian blur and the mask parameters to make the ROI more uniform (block the non-uniform global extrema, e.g. sunspots).

2019-11-04

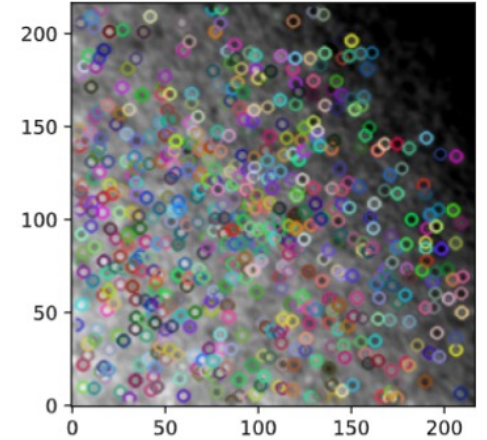
# Limb Darkening Removal

- The more features are extracted, the more possible to make a successful registration.
- Limb darkening effect will limit the number of extracted features by affecting the intensity rescaling process.
- Fit 2d background and remove the limb darkening effect.
- 957 features were extracted from the original TiO image, while 1571 features were generated from the background removed TiO image.

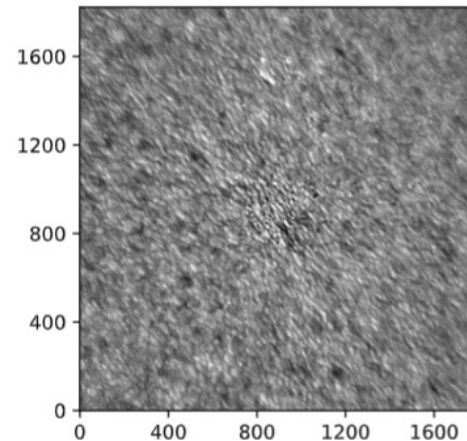
(a1) Observation with GST/BFI



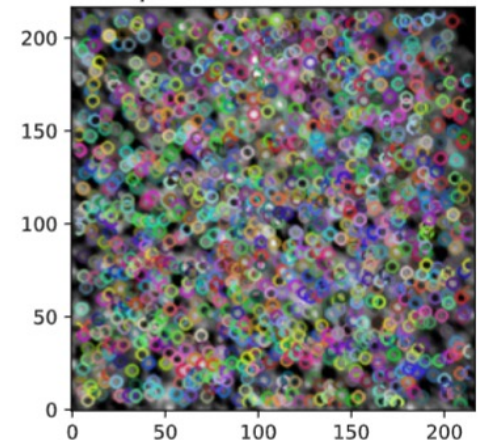
(a2) Limb SIFT Features



(b1) Limb Darkening Removal



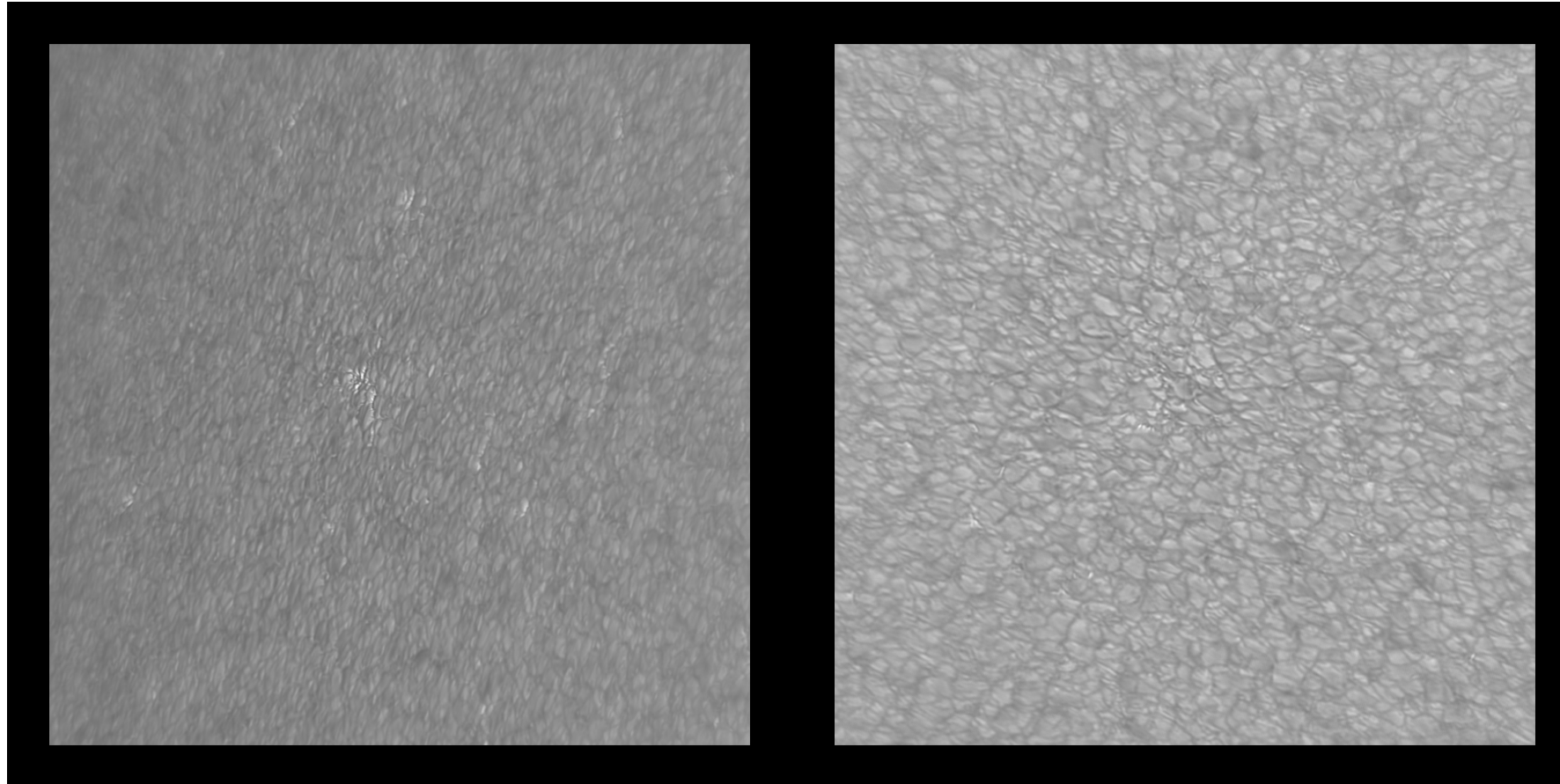
(b2) Improved SIFT Features



2020-07-22 at 17:04 UT,  $x=-33''$ ,  $y=841''$



# SIFT for QS: Near Limb and On-disk

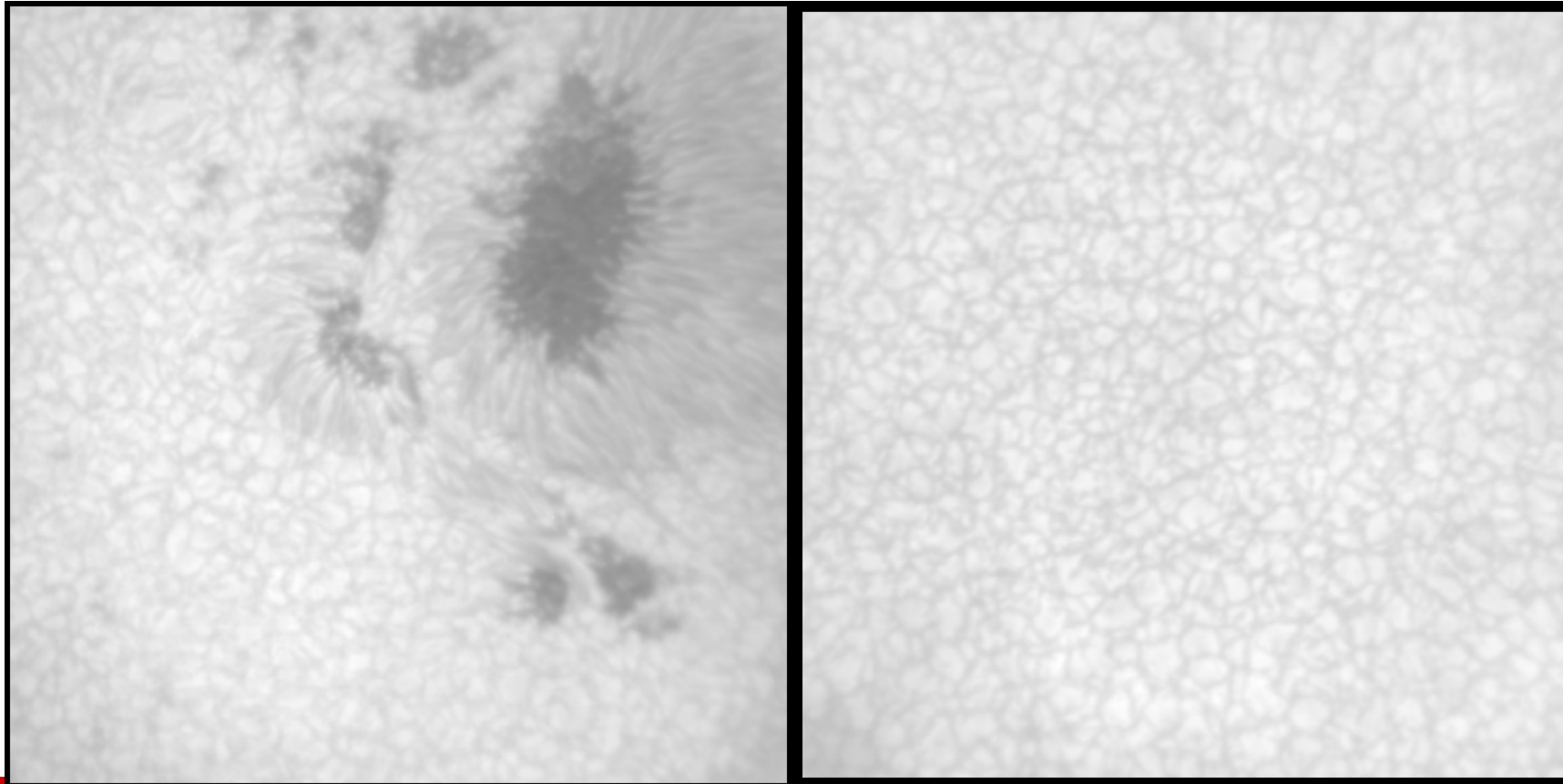




# SIFT: NIRIS Fe I 15648 Stokes I $\rightarrow$ HMI/Ic

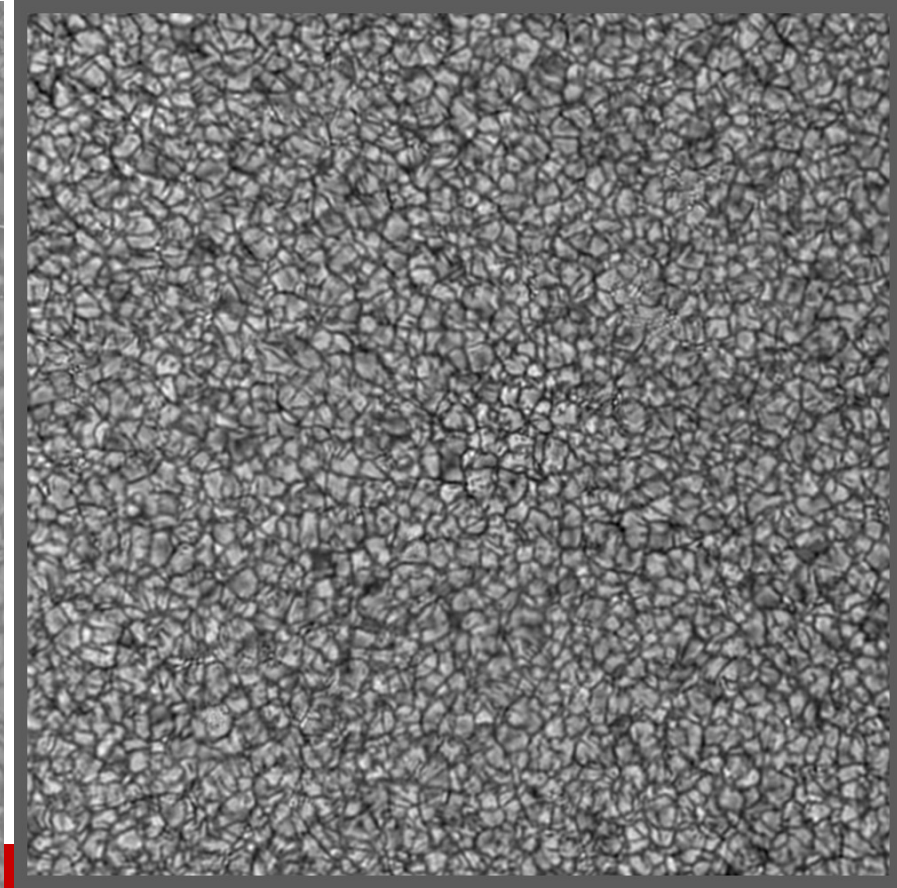
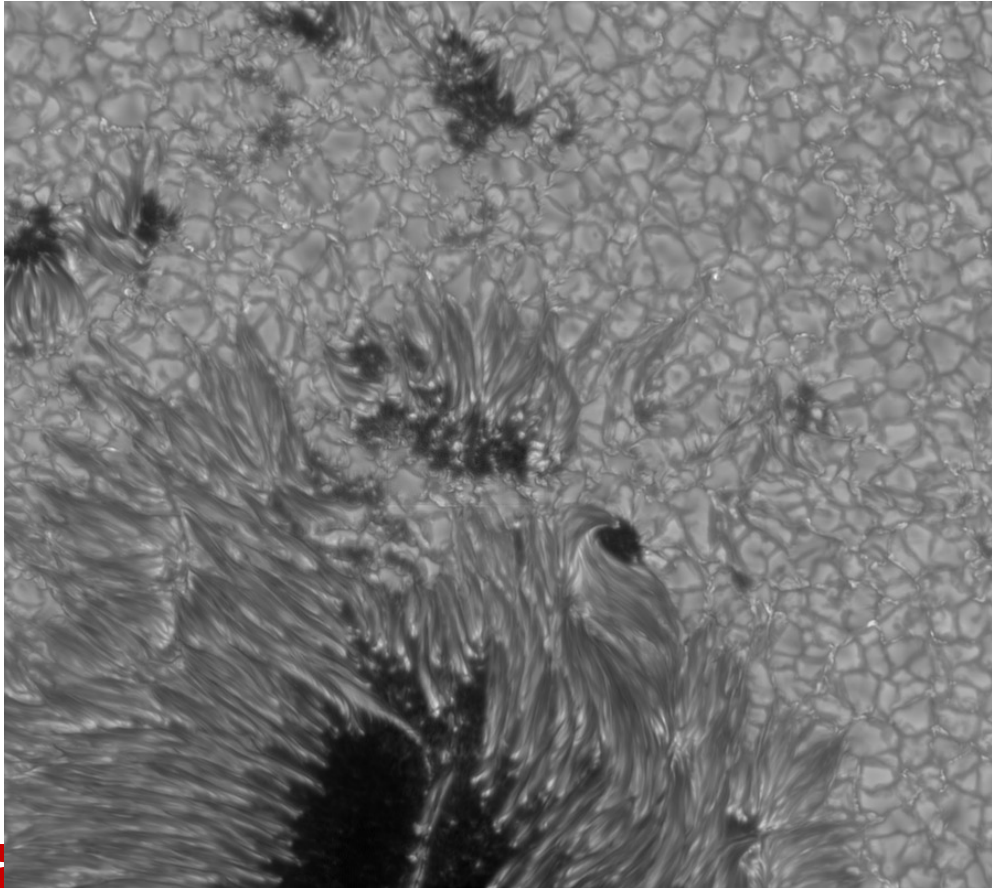
2016-09-07

2020-07-15

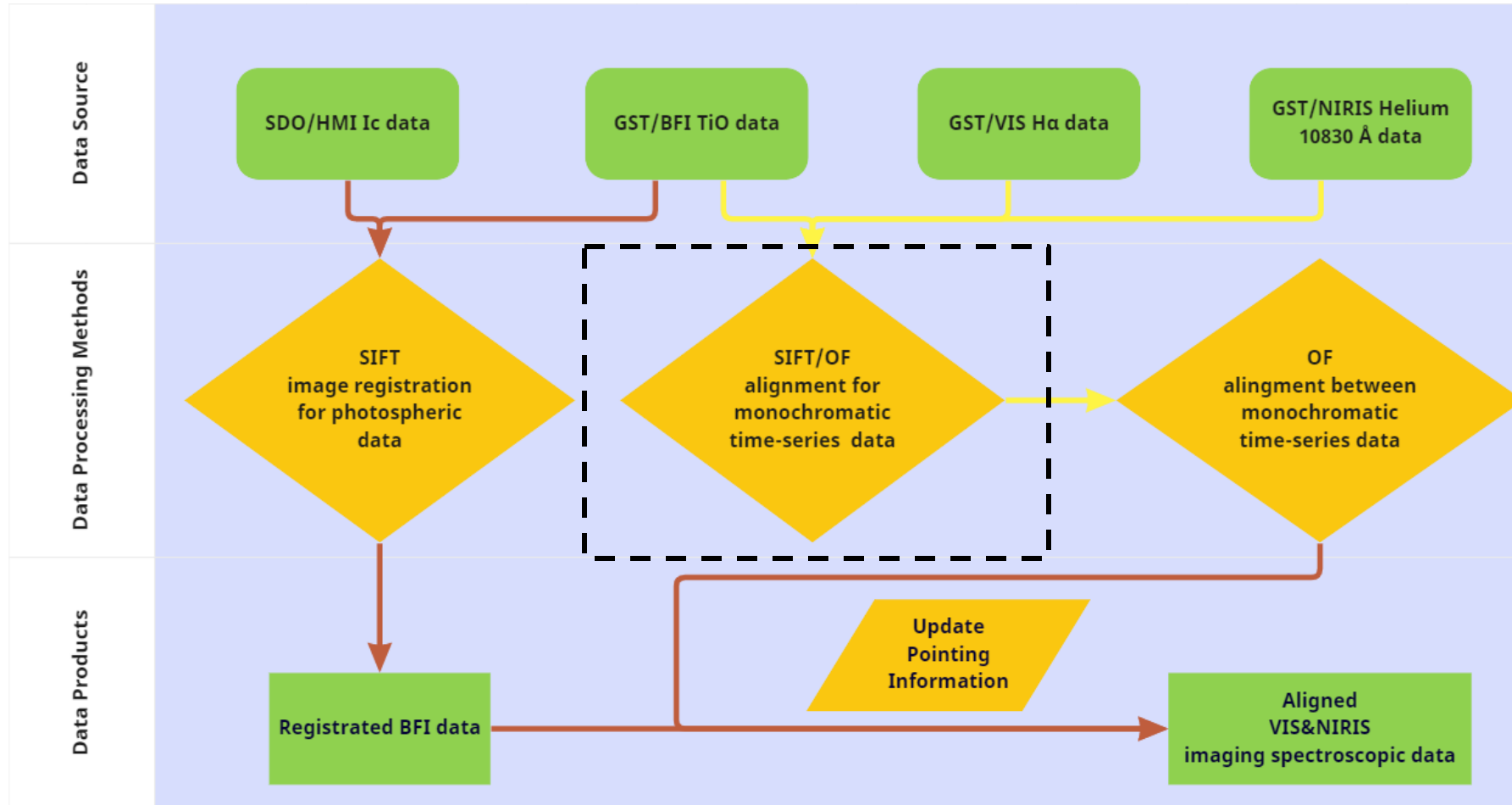




# SIFT Works on Various of Instruments: SST/ DST/ NVST



# Workflow: Time-sequence Alignment with OF/SIFT



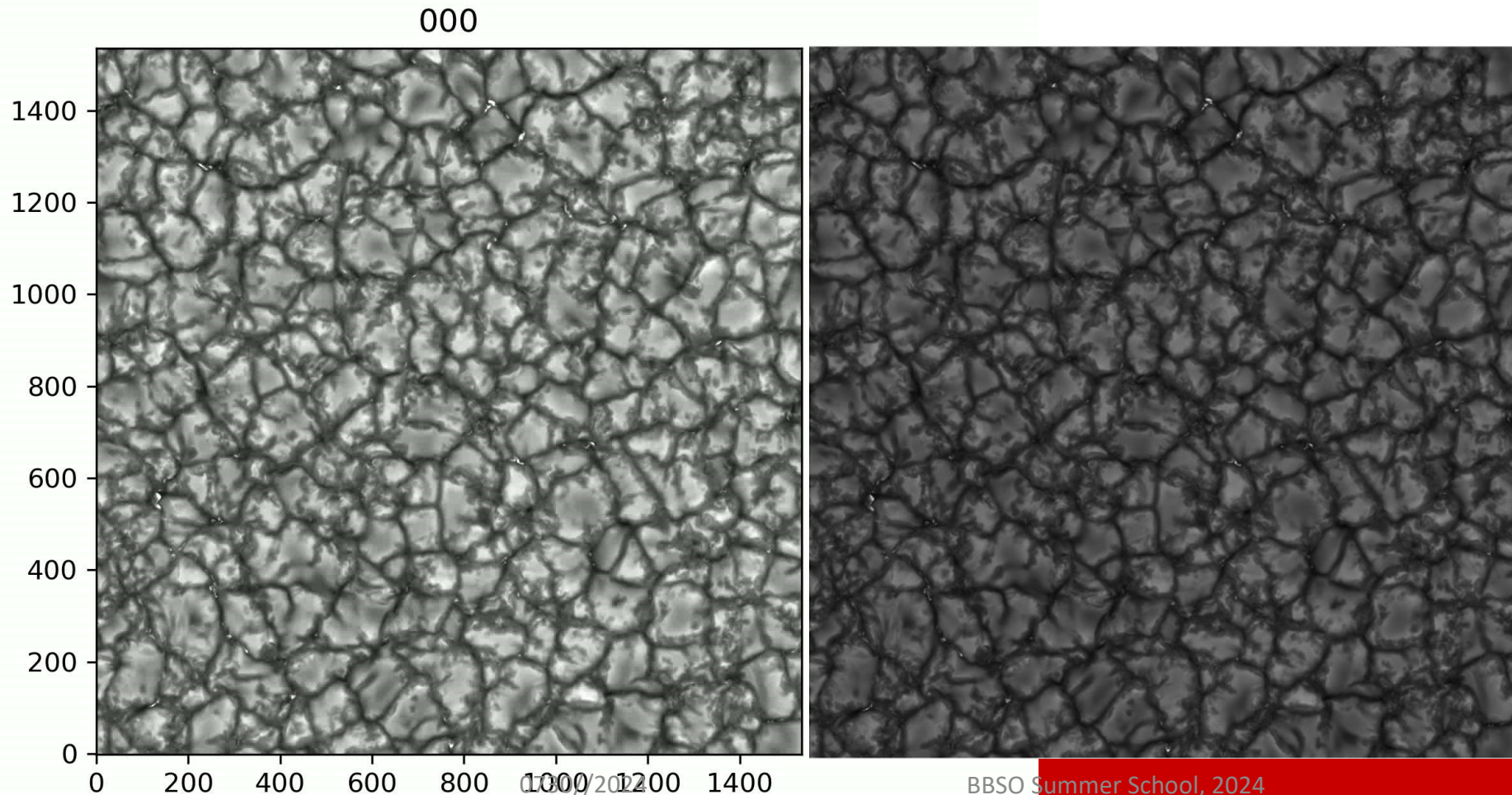


# Time Sequence Dataset from GST

- Image rotation:
  - Zenith telescope system
  - Constant rotation rate: 360 in 24 hours
  - ✓ De-rotation: manual rotation at FOV center
  
- Image displacement:
  - Seeing distortion
  - Few pixels
  - ✓ Displacement calculation-correction: OF/SIFT (LCT/GCT)
  - ❖ Align one by one. Problem of accumulate error.



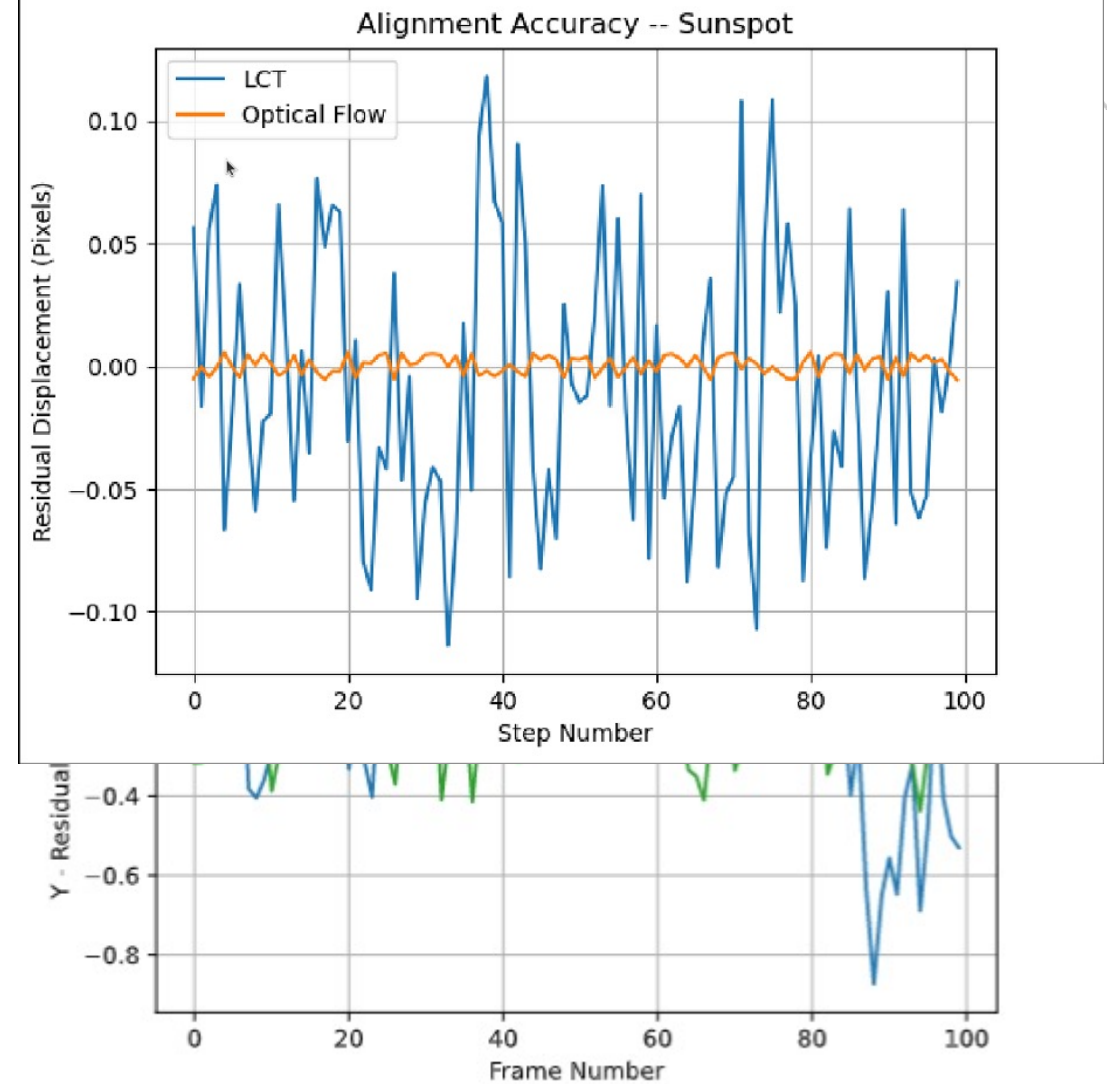
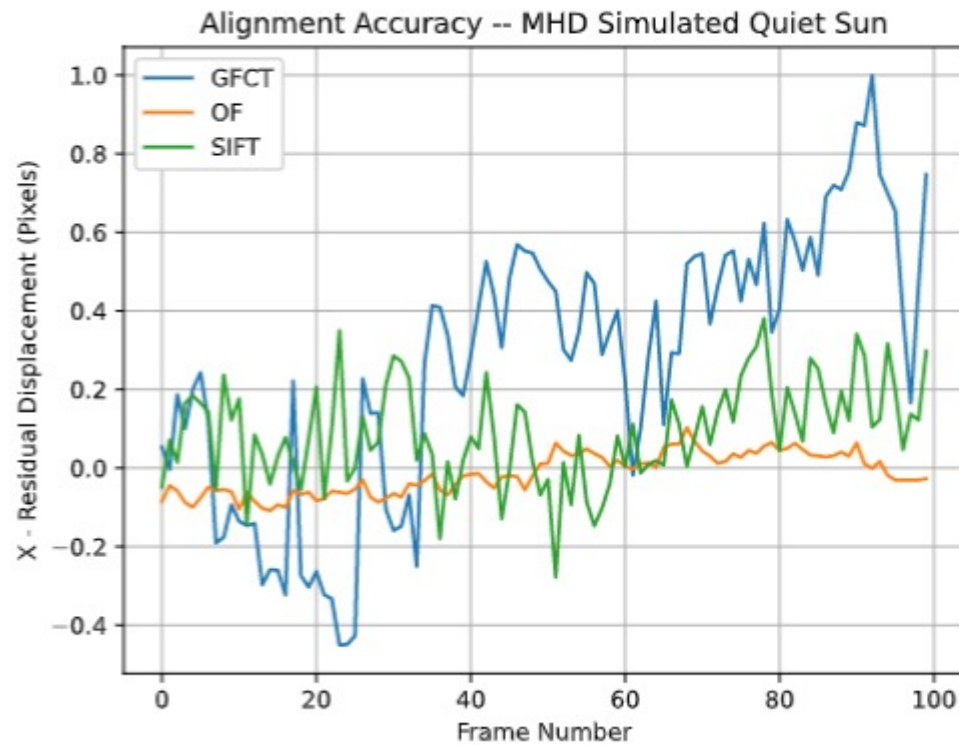
# Compare Alignment Accuracy for Different Methods



Standard Test Set  
from Numerical  
Simulations: **MURaM**  
16 km grid  
50 Mm wide domain  
100 frame  
Random displacement  
in x- and y- directions

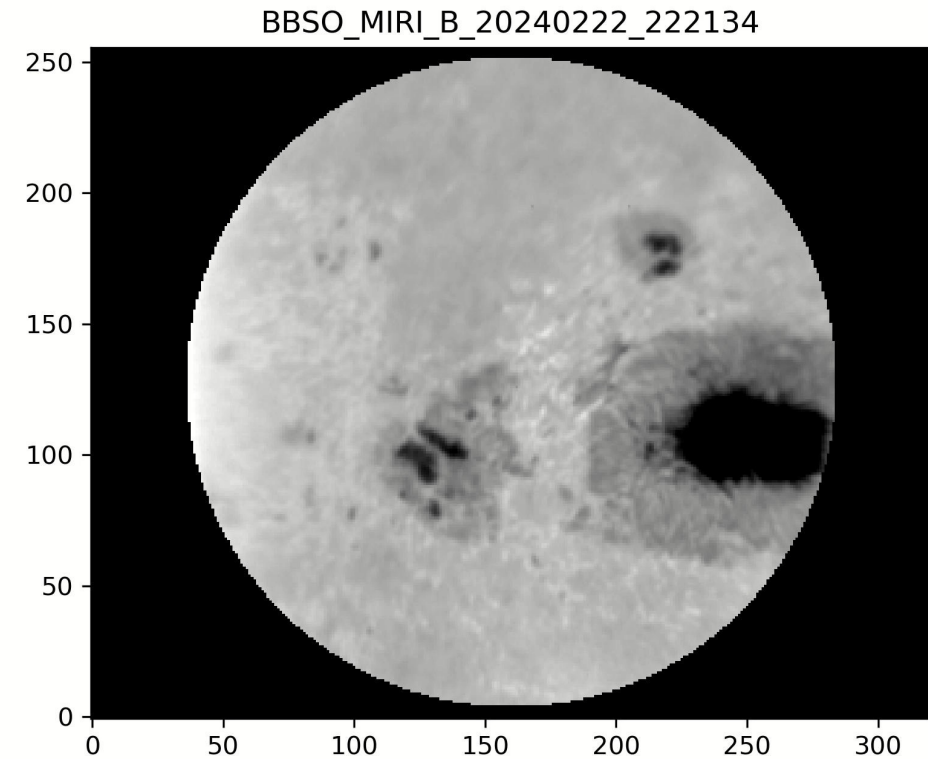
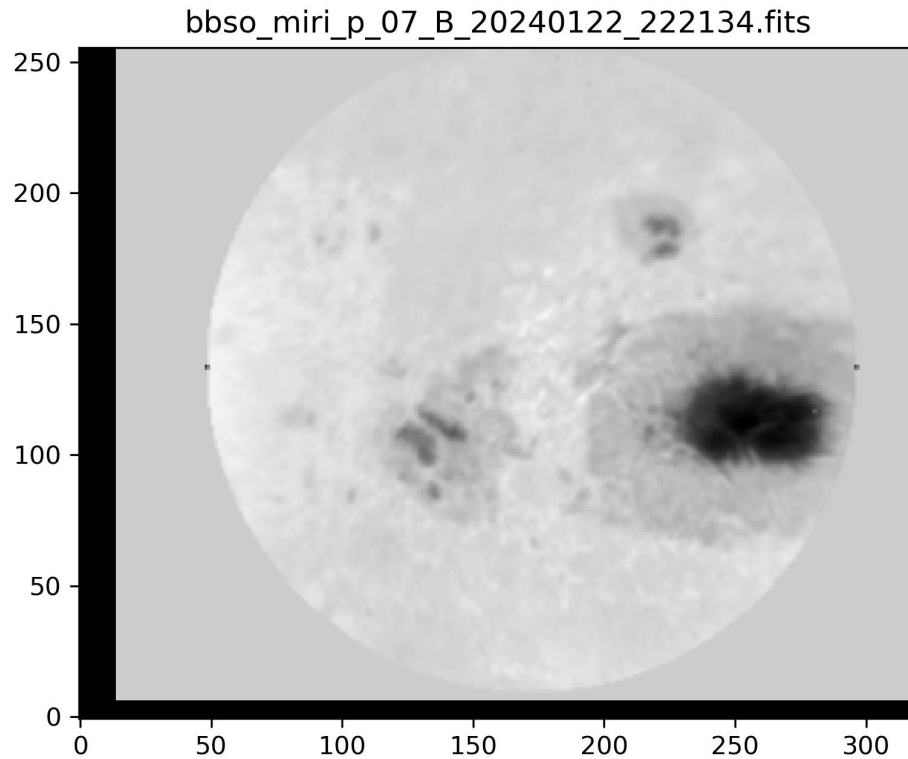
Courtesy: Rempel  
Rempel 2014, 2015

# Alignment Accuracy



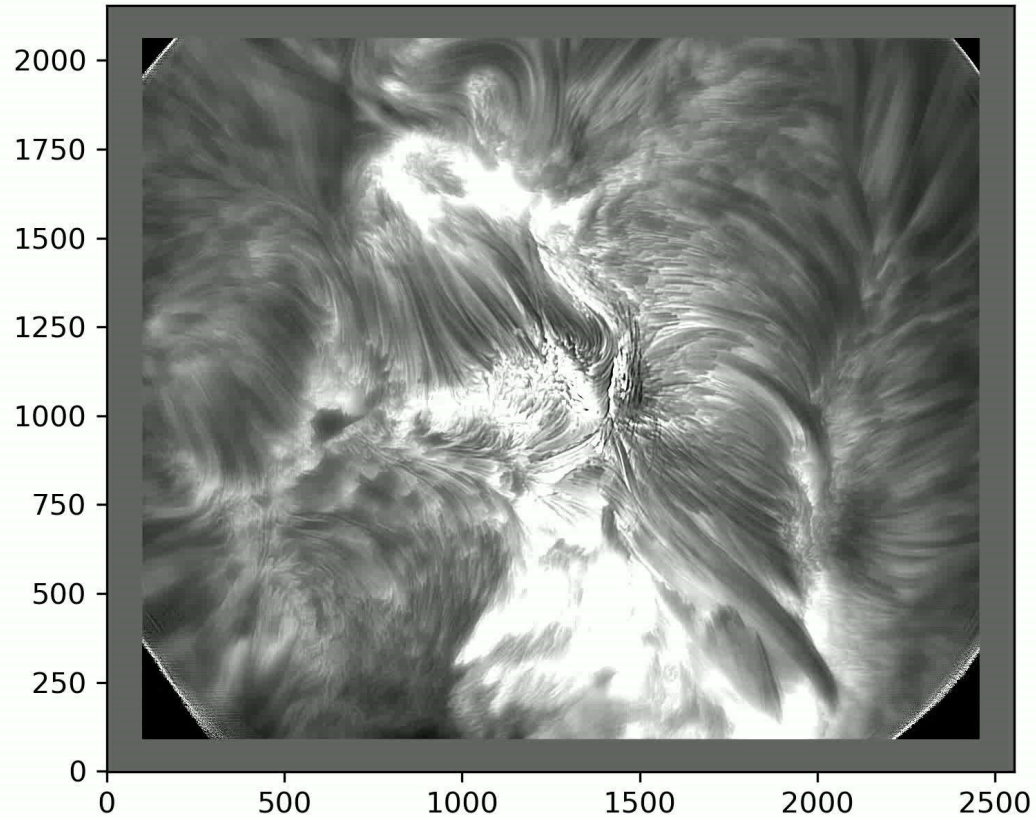
Cai, Yun-Fang et al 2022 RAA, for more detailed OF method qualification (with FISS Spectrum).

# MIRI: Cloud removal & OF Alignment

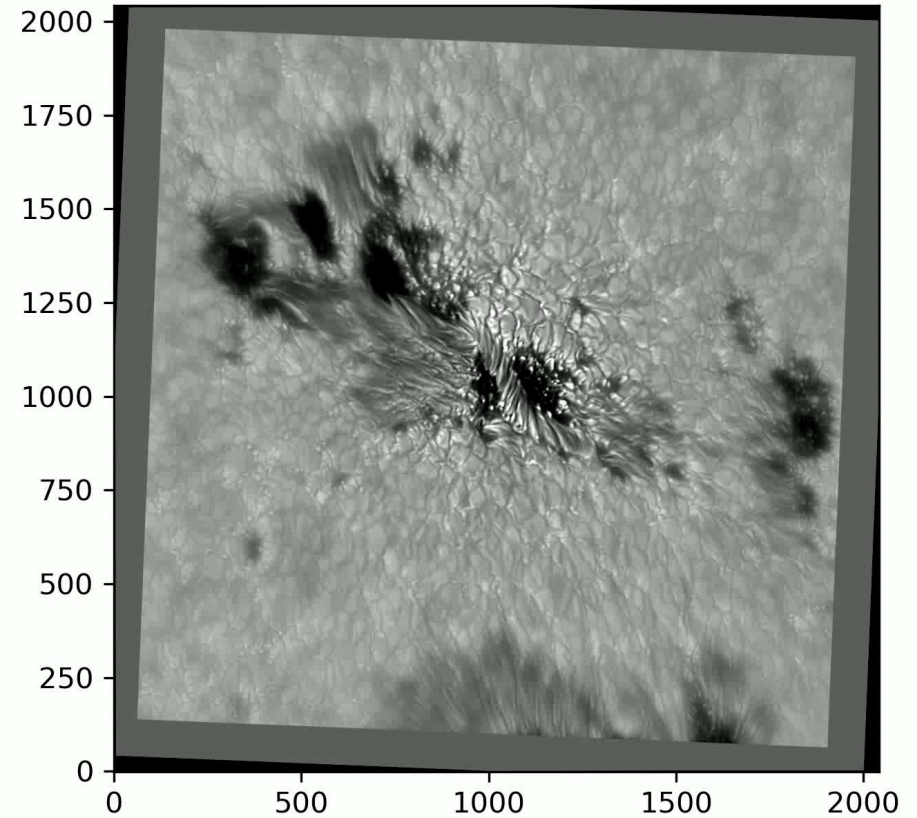


# SIFT for Filament Eruption

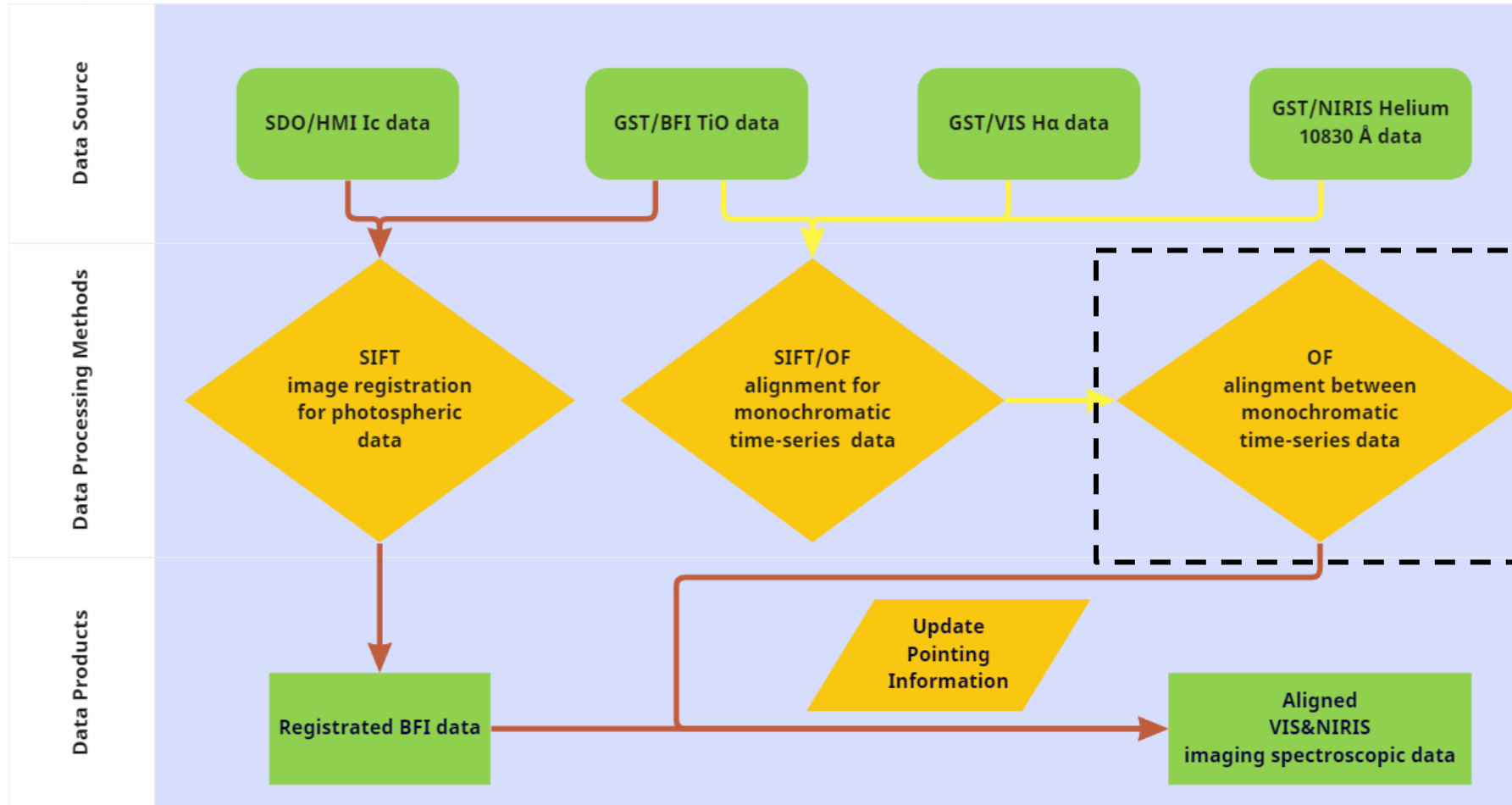
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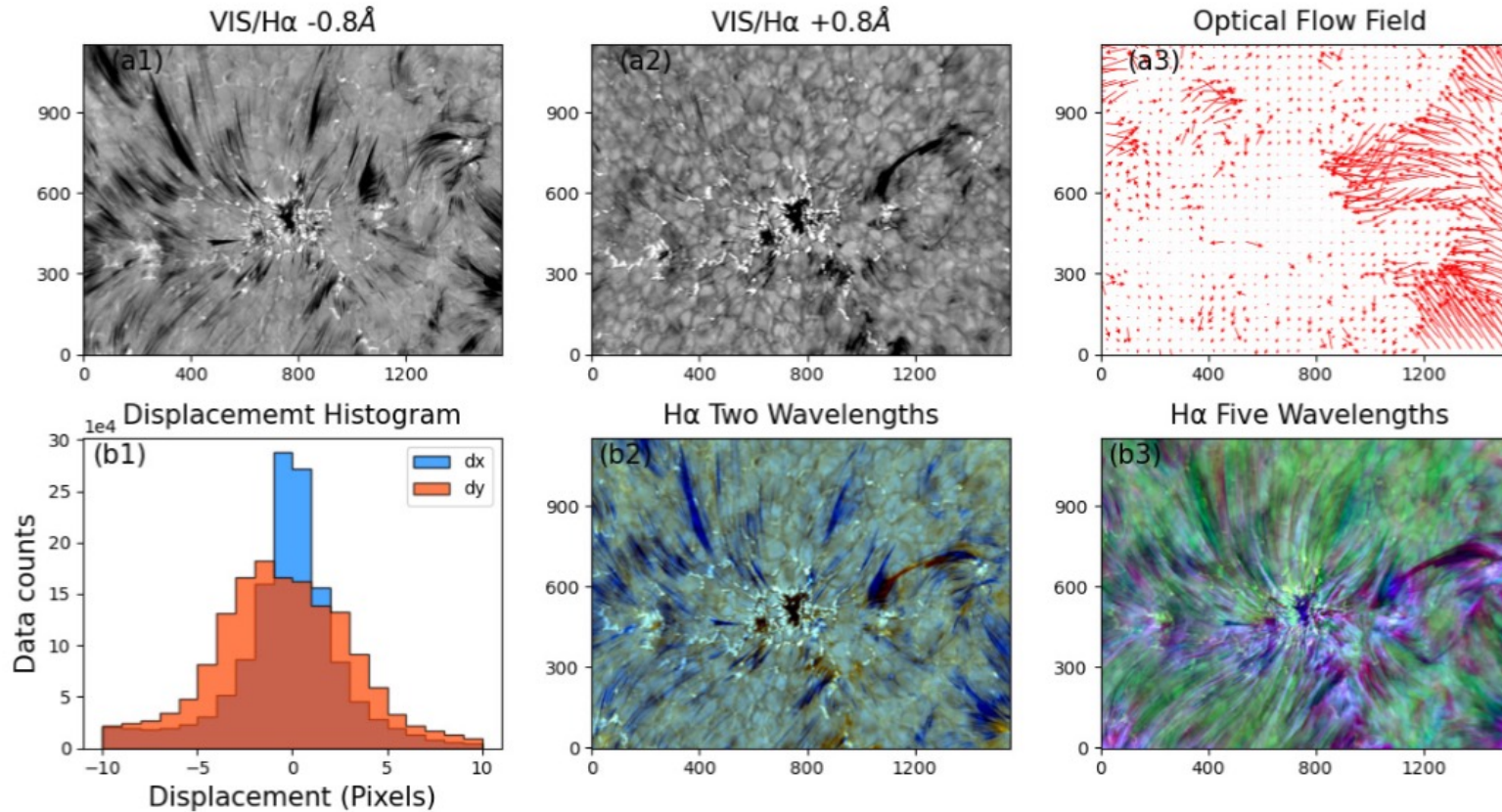
bbso\_tio\_pcscr\_20221002\_201510.fts



# Workflow: Time-sequence Alignment with OF/SIFT



# Imaging Spectroscopic Data Alignment with OF

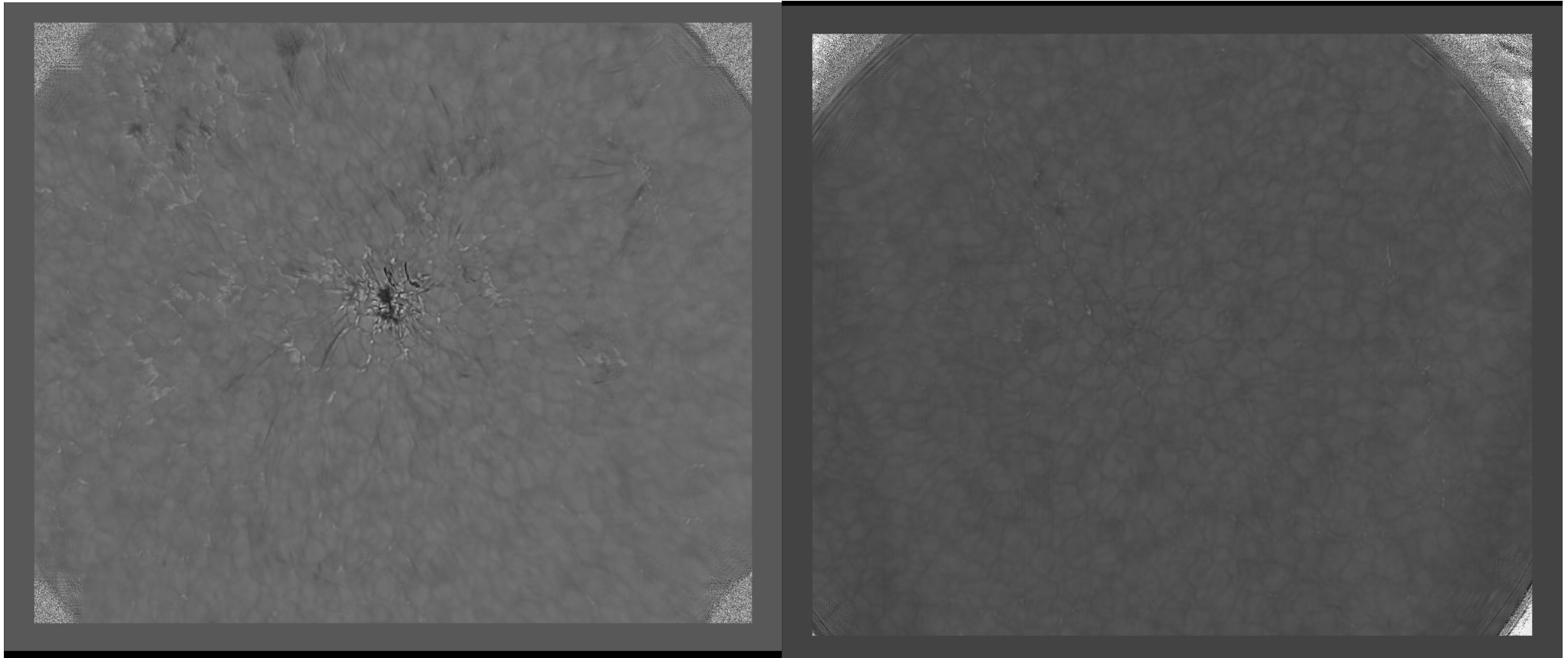


- Most populated displacements;
- Effective points;
- Weighted mean value on effective points as calculated displacement.

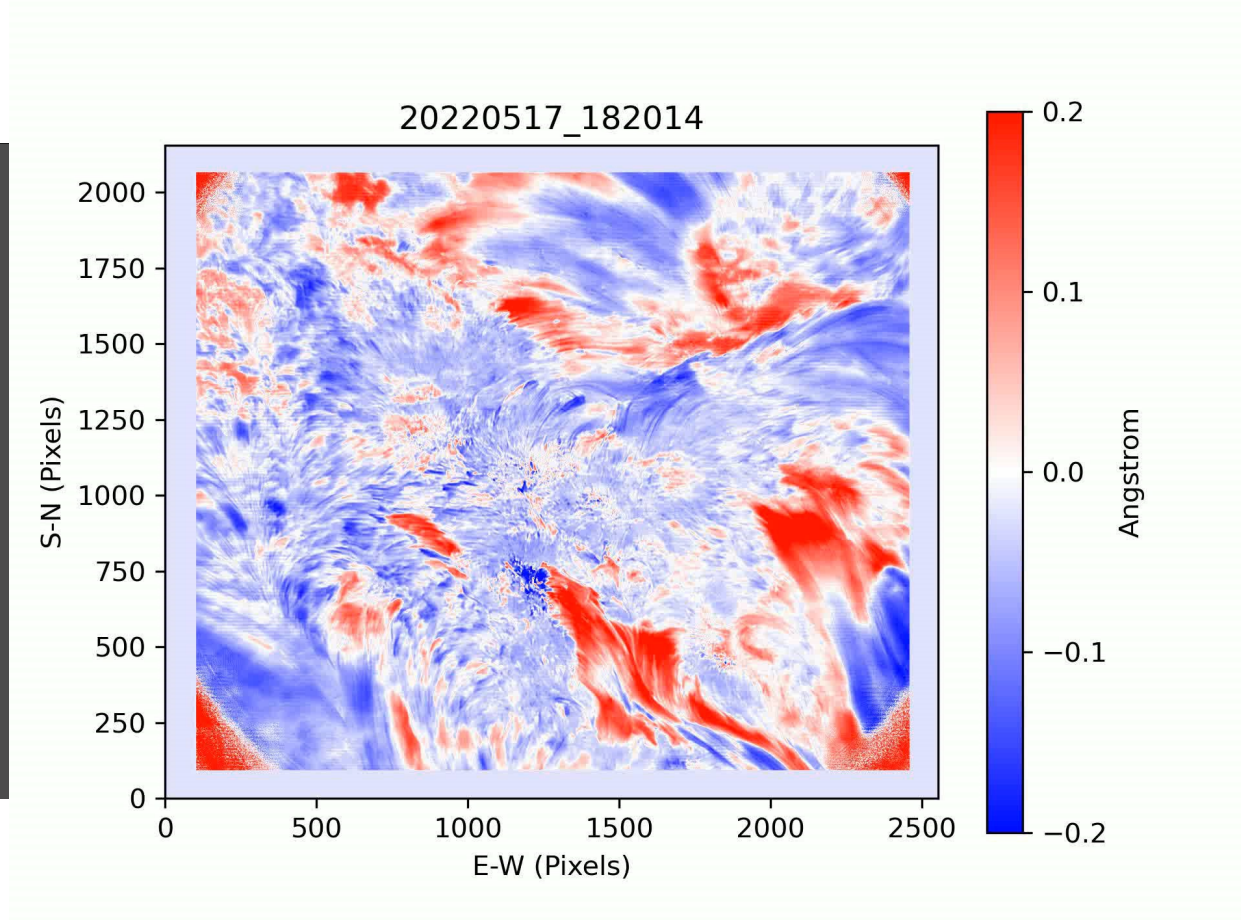
2019-11-04



# Imaging Spectroscopic Data Alignment with OF



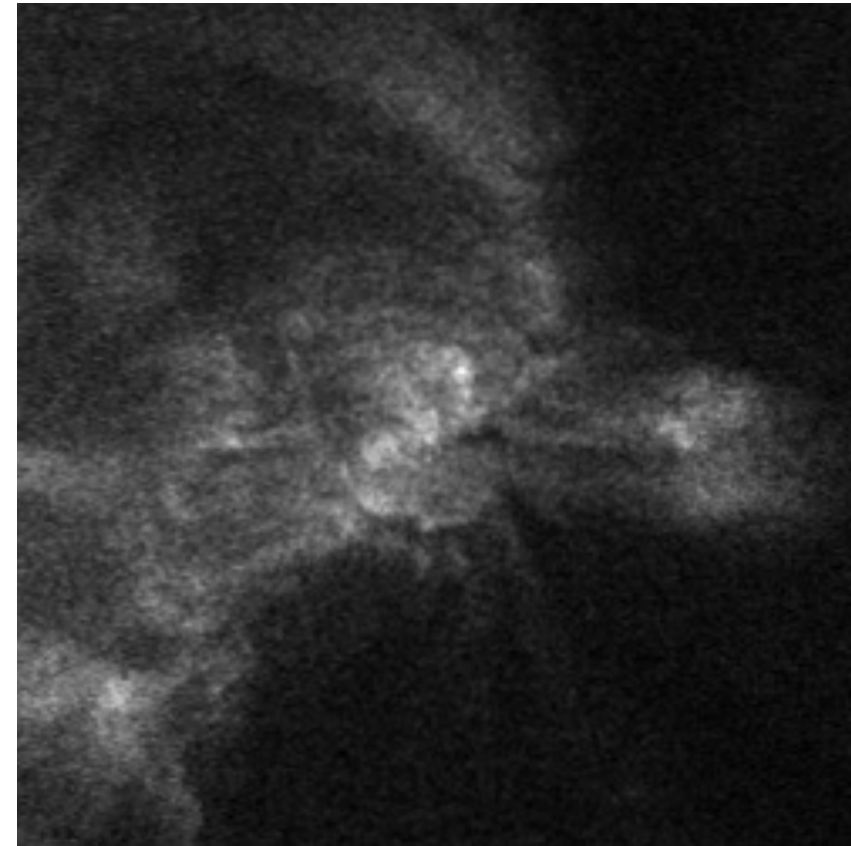
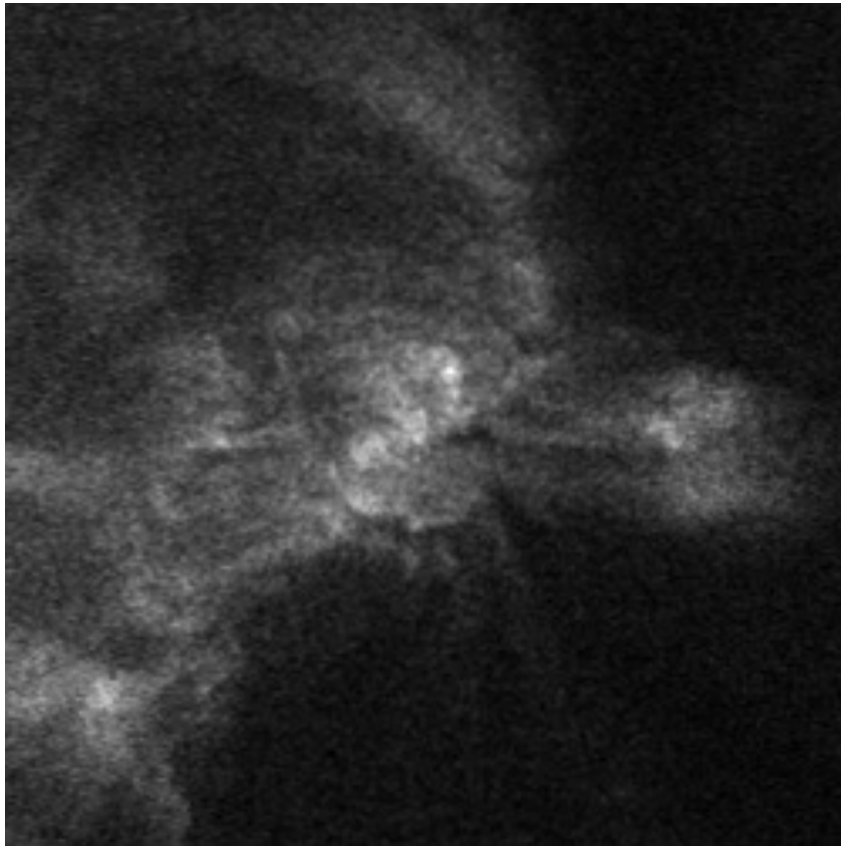
# Imaging Spectroscopic Data Alignment with OF





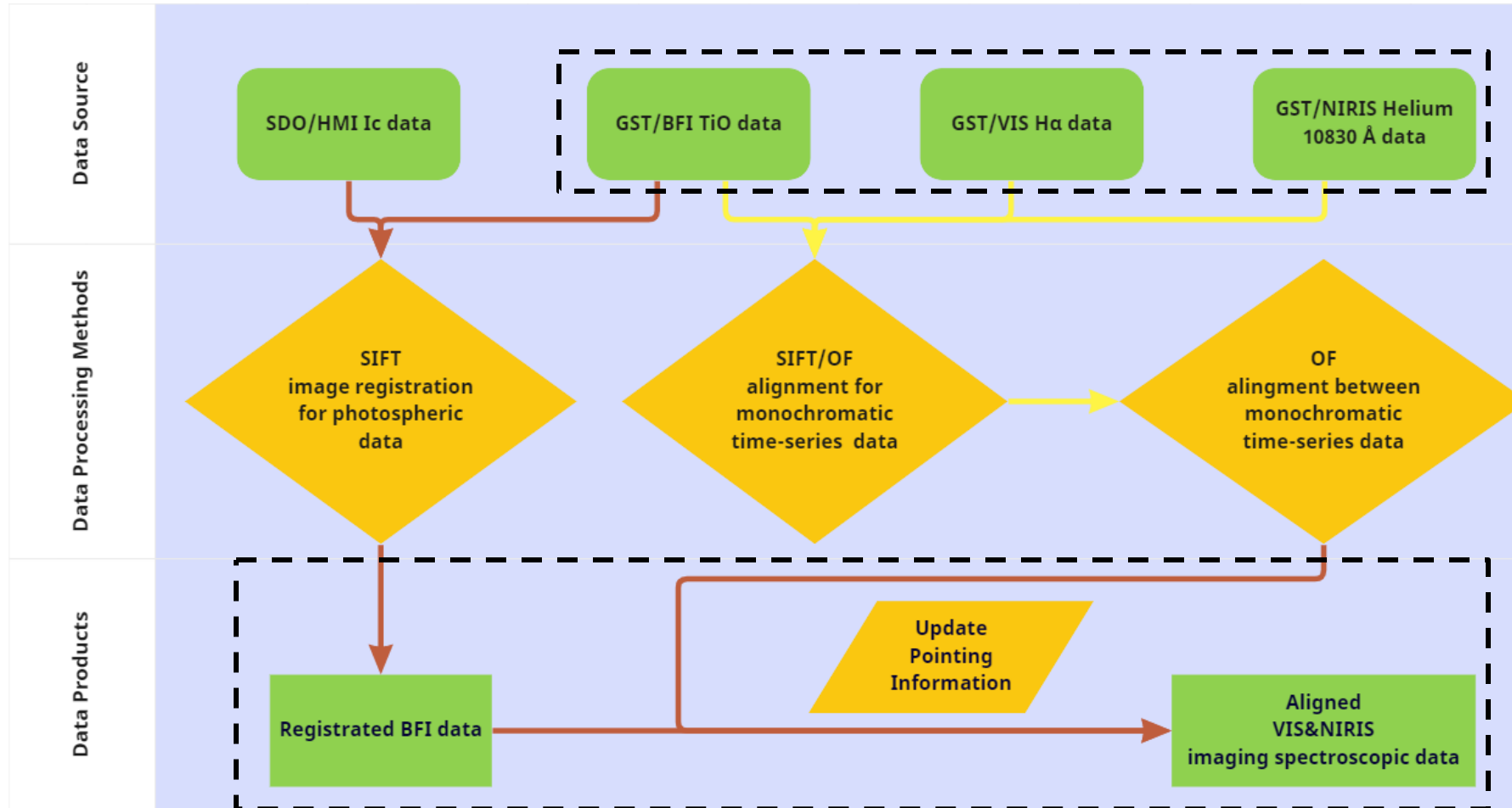


# OF for AIA Sub-pixel Alignment



AIA EUV

# Workflow: Time-sequence Alignment with OF/SIFT



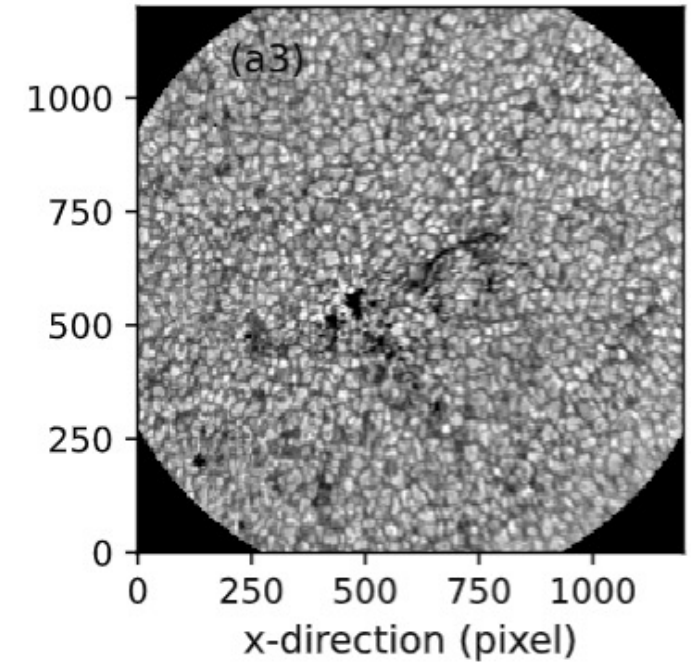
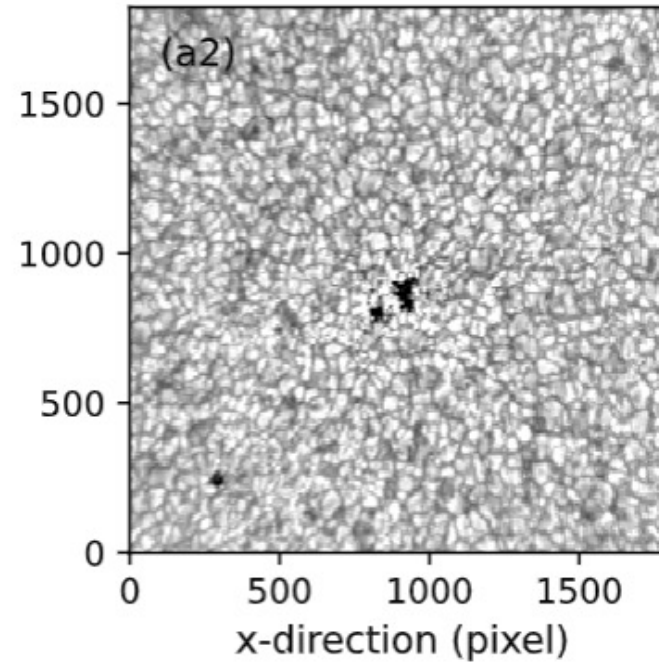
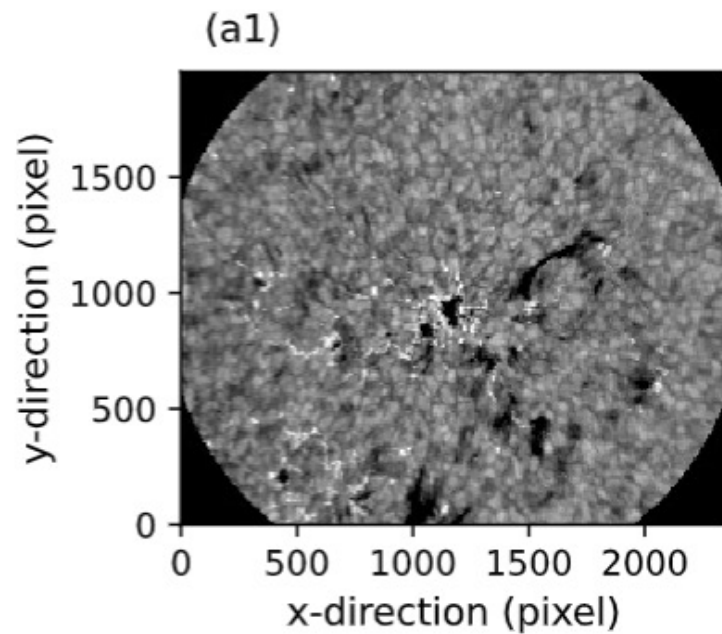
# Image Registration with SIFT II: Between GST Instruments

2019-11-04

VIS/H $\alpha$  +0.8Å

BFI/TiO

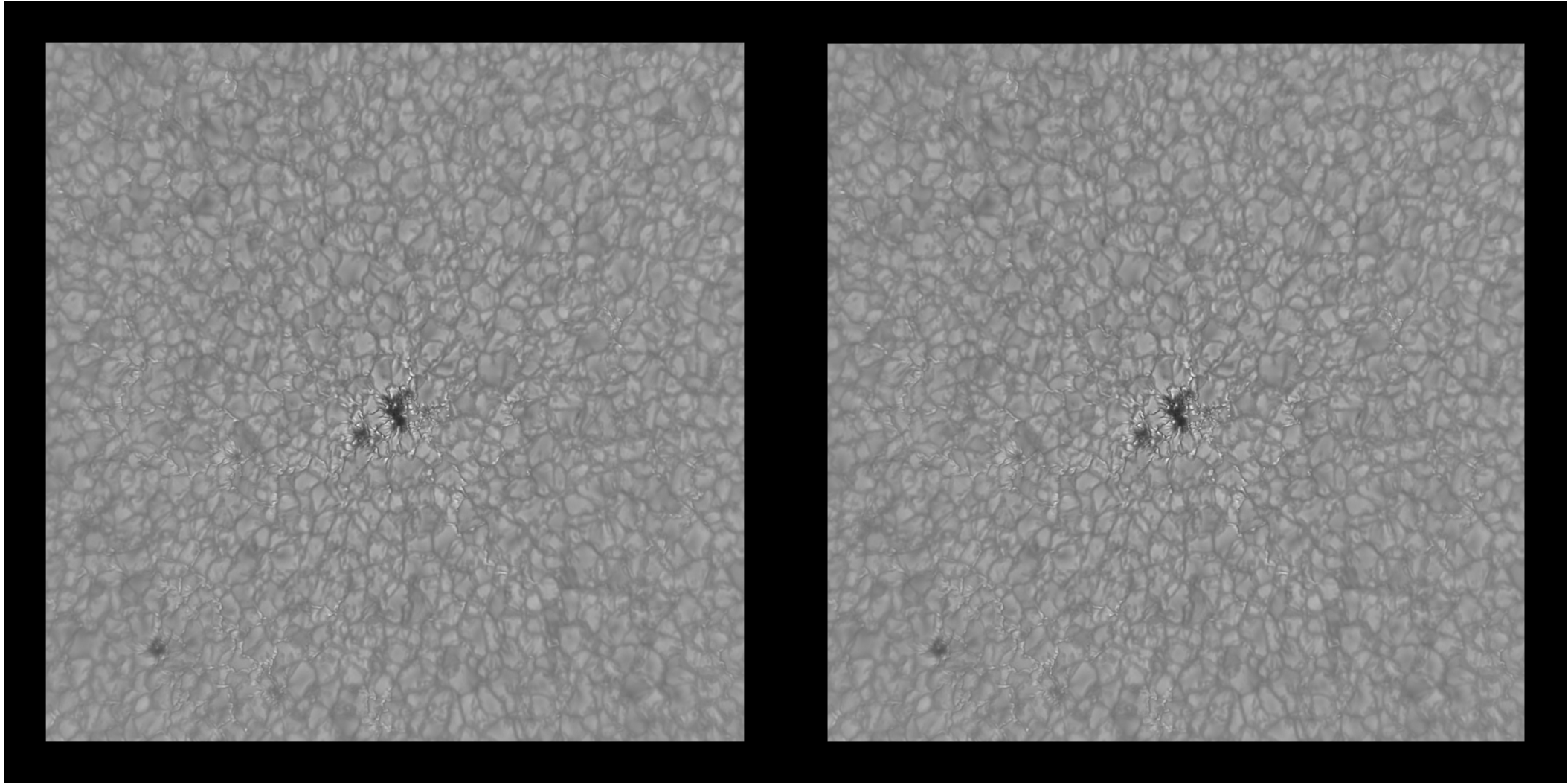
NIRIS/He I 10830 +0.8Å



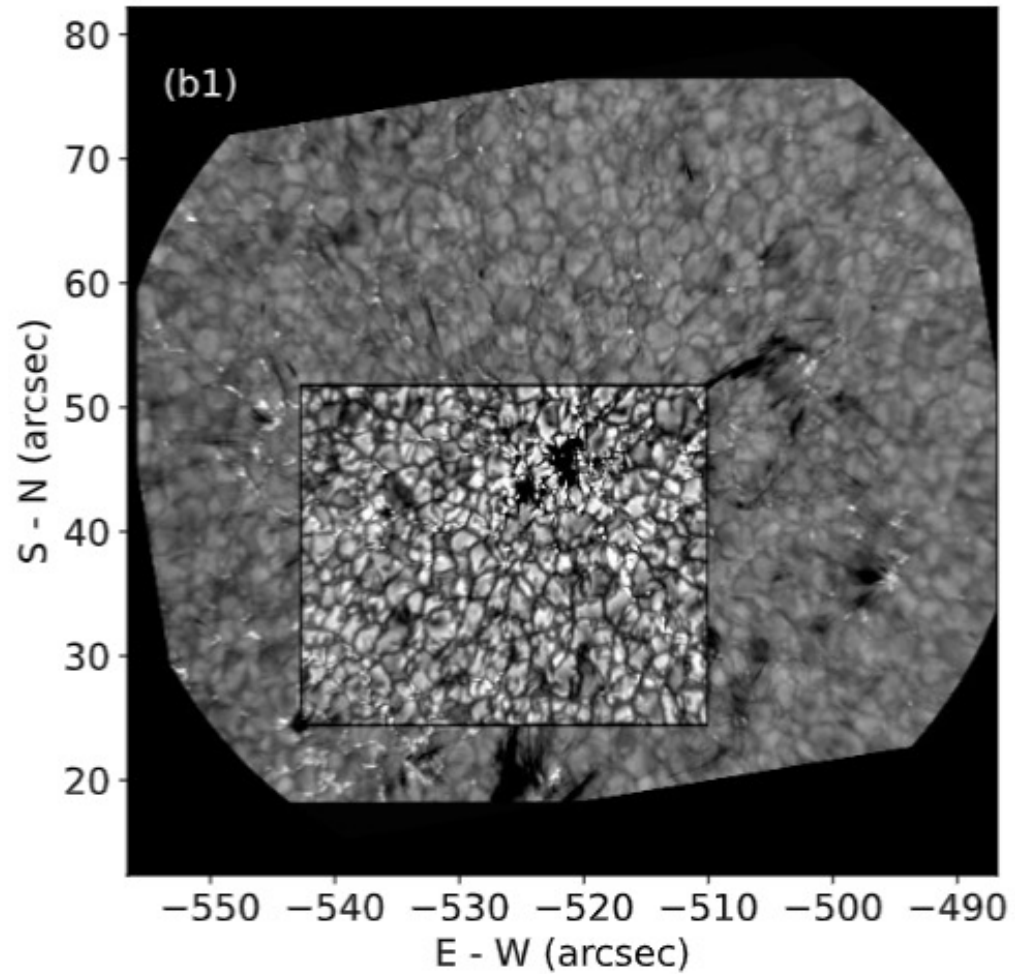


Registration: VIS/H $\alpha$  → BFI/TiO

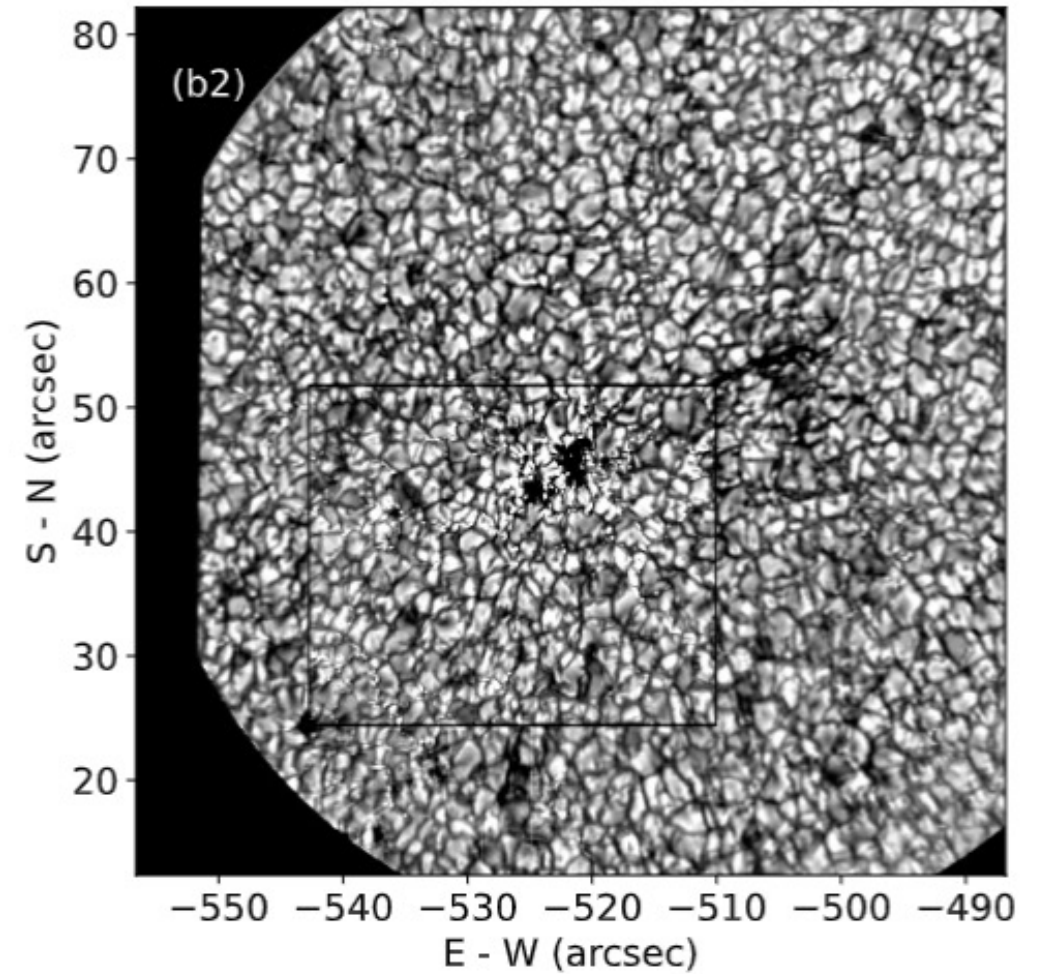
NIRIS/He I 10830 → BFI/TiO



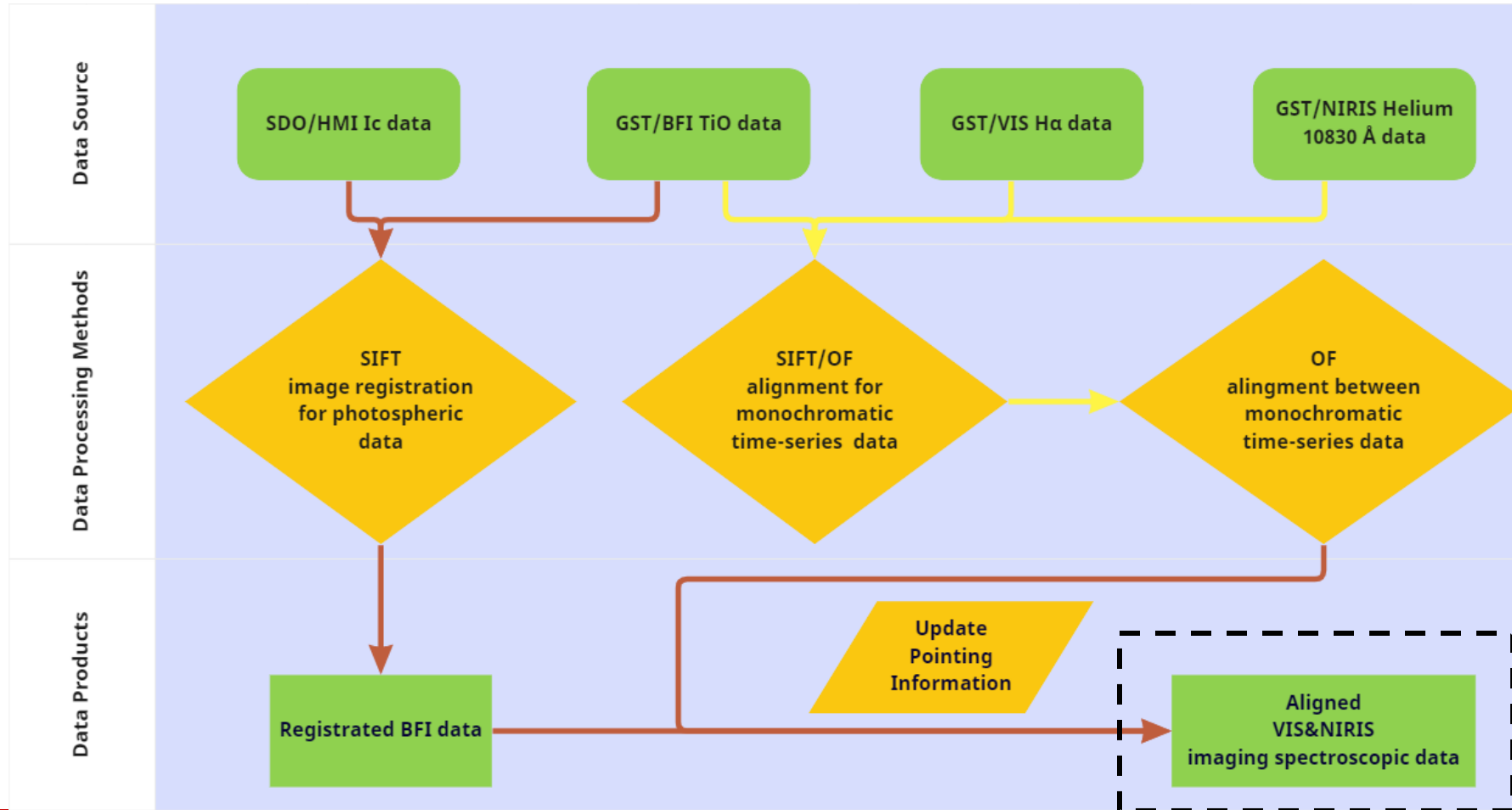
TiO combined with H $\alpha$  +0.8 $\text{\AA}$



TiO combined with He I 10830 +0.8 $\text{\AA}$

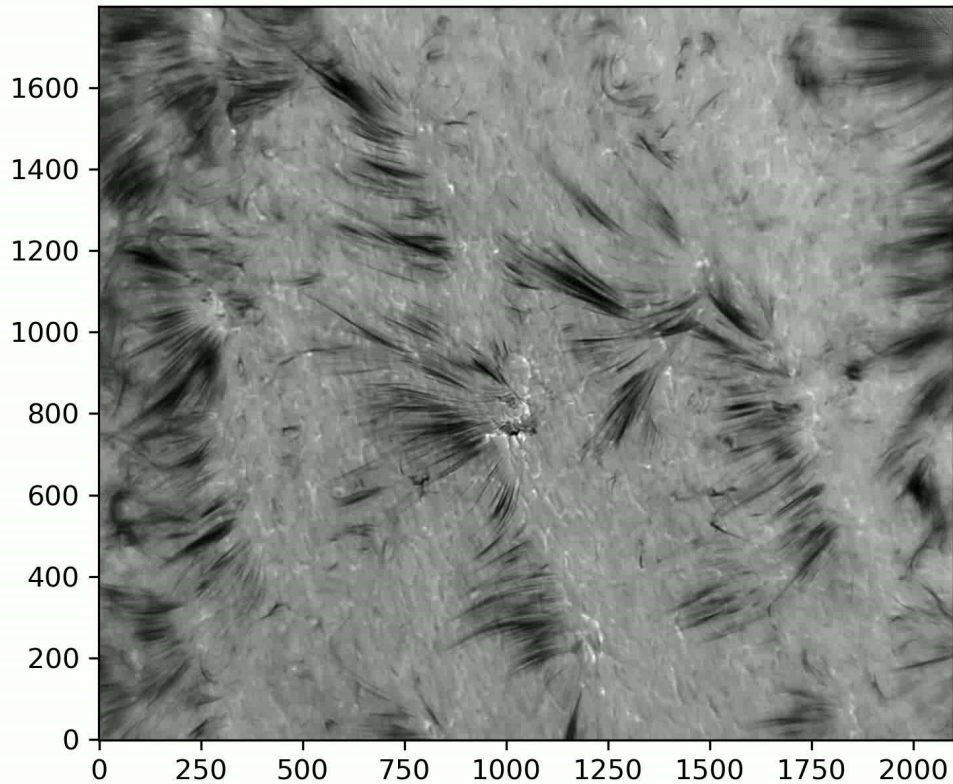


# Workflow Chart

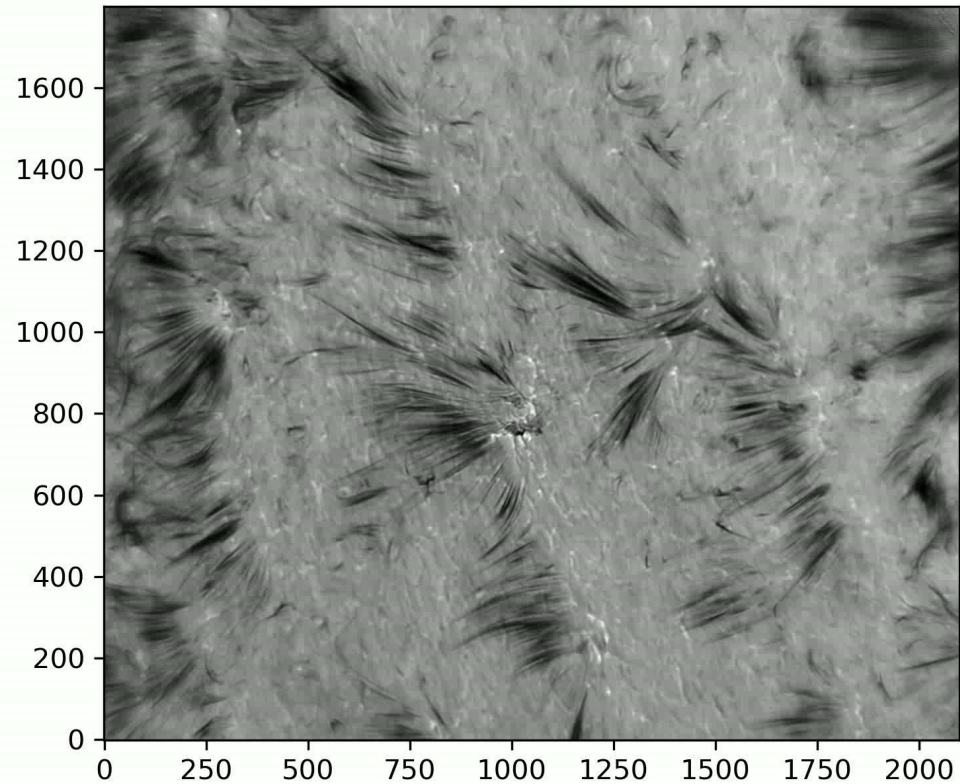


# Kalman Filter: Time Sequence Image De-stretching

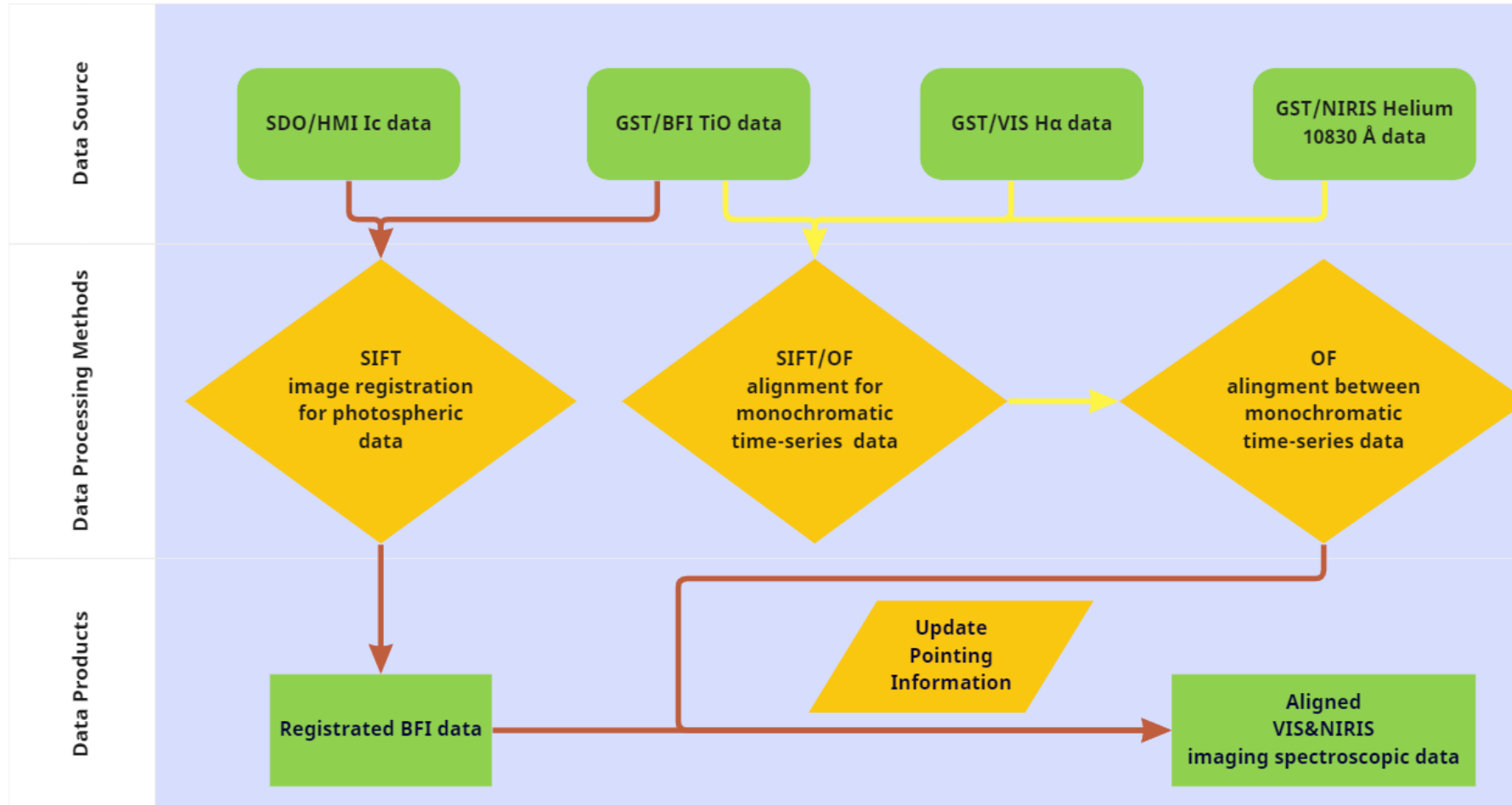
bbso\_hab080\_vissr\_20200513\_174300.fts



bbso\_hab080\_vissr\_20200513\_174300.fts



# GST Imaging Registration and Alignment Workflow







# References:

- *Yang, Xu; Cao, Wenda; Yurchyshyn, Vasyl, “GST Data-processing Workflow: Image Registration and Alignment”, The Astrophysical Journal Supplement Series, Volume 262, Issue 2, id.55, 11 pp. 2022*
- *Ji, Kaifan et al, “An automatic approach of mapping the solar high-resolution image to Helioprojective-Cartesian coordinates system”, Chinese Science Bulletin , Volume 64, Issue 16: 1738 - 1746 2019*
- *Liu, Hui et al, “High-resolution Solar Image Reconstruction Based on Non-rigid Alignment”, Research in Astronomy and Astrophysics, Volume 22, Issue 9, id.095005, 9 pp. 2022*
- *Cai, Yun-Fang et al, “The Co-alignment of Winged H $\alpha$  Data Observed by the New Vacuum Solar Telescope”, Research in Astronomy and Astrophysics, Volume 22, Issue 6, id.065010, 8 pp. 2022*
- *Rempel, M, “Numerical Simulations of Quiet Sun Magnetism: On the Contribution from a Small-scale Dynamo”, The Astrophysical Journal, Volume 789, Issue 2, article id. 132, 22 pp.2014*
- *Rempel, M, “Numerical Simulations of Sunspot Decay: On the Penumbra-Evershed Flow-Moat Flow Connection” The Astrophysical Journal, Volume 814, Issue 2, article id. 125, 14 pp. 2015*