Solar Activity Investigation (SAI): a 6U CubeSat mission concept

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Introduction

- The Solar Activity Investigation (SAI) mission would provide a key step in developing the multi-spacecraft interplanetary constellation that is needed to understand and predict Space Weather events, such as flares and Coronal Mass Ejections (CMEs) and their impact on terrestrial and interplanetary systems, and particularly on astronaut safety

- SAI is a single-instrument 6U CubeSat, carrying a compact Doppler/magnetograph (CDM), which produces images of the line-of-sight velocity (ie, Doppler shift) and magnetic field in the Sun's photosphere

- **Magnetic field and Doppler measurements provide critical insight into the processes that drive space weather events**

What do we need to know about Space Weather?

- In response to concerns about potential impacts on terrestrial infrastructure, and robotic and human assets in space, Space Weather plays a dominant role in heliophysics research
  - Potential impacts range from disruption of national power grids to variations in low earth orbit satellite drag to dangerous radiation doses for astronauts, and many others.
- Space Weather studies are complex because they require the study of the Sun, the solar wind and heliospheric magnetic field, the geomagnetic field, and Earth's ionopshere and thermosphere as a coupled system
  - Parts of **the basic science needed for a predictive capability** are not well enough understood
  - In many areas, **we lack the necessary observations**: We sample the interplanetary medium very sparsely, and have an incomplete remote view of the sun.
  - The few cases where multi-point or multi-vantage point measurements have been made,(ISEE, Cluster, THEMIS, Stereo etc.) make it clear how much insight we are missing, and show the challenges in filling in the measurement gaps
- **The remedy for this is a distributed measurement system, analogous to that used for terrestrial weather, with multiple s/c in heliocentric orbits**
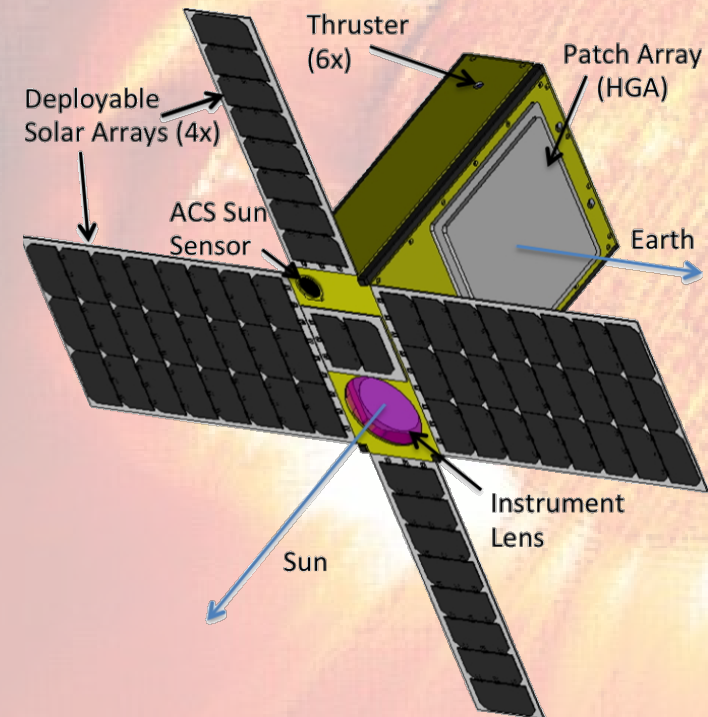
How can we make the required measurements?

- **Distributed measurements**, both in-situ and remote sensing, are required.
  - This requires multiple spacecraft operating simultaneously beyond Earth orbit
- Using conventional spacecraft, this is prohibitively expensive
  - Even with the reduced recurring cost that comes from producing multiple identical spacecraft, this is an intractable problem
- A solution is to use smaller, less expensive, (and perhaps initially less capable) spacecraft
  - For example, we don't need the performance of the SDO mission to monitor solar magnetic fields beyond earth orbit, or the performance of MMS for in-situ solar wind measurements
- **Given the recent explosion in CubeSat development, they are an obvious choice to begin filling this need, making them potential weather buoys for Space Weather research**

First steps in building a Space Weather constellation

- All the necessary spacecraft capabilities are available now.
  - CubeSat power, communications, attitude stability, and propulsion systems have already been developed
  - They will certainly be improved in the future, but the basic capabilities are in place
  - A number of missions are under development that could contribute to this endeavor, and the NASA EM-1 Launch vehicle will deposit 11 CubeSats beyond earth orbit in 2019
- Our proposed contribution is the Solar Activity Investigation (SAI), which uses a 6U CubeSat to take solar photospheric Doppler and magnetic field images, from beyond Earth orbit
- **SAI is a science mission, and the SAI CubeSat would be the prototype of a key building block for a constellation of solar imaging CubeSats, which will ultimately give us a 4π view of the solar atmosphere**

Solar Activity Investigation science

- SAI would provide a second vantage point to Earth, for observing line-of-sight velocity and magnetic fields in the Sun's photosphere

  - Enables stereoscopic helioseismology to probe deep solar structure, improving our understanding of what drives solar variability

  - Enables stereoscopic magnetic field measurements and enhanced measurement of horizontal flows , improving our understanding of how solar magnetic active regions evolve

  - Enables magnetic field measurements over a larger fraction of the sun's photosphere, improving models of the heliospheric magnetic field and its connection to Earth

Thruster (6x)

Patch Array (HGA)

Deployable Solar Arrays (4x)

ACS Sun Sensor

Earth

Instrument Lens

Sun

Driving mission requirements

- To effectively co-analyze SAI data with data from instruments in earth orbit, SAI Doppler images require a comparable velocity sensitivity to avoid introducing additional noise (<13 m/s per pixel over 60s)

- Data should be collected with a cadence of 60s (8.3 mHz), so as to capture the entire frequency range of interest (the p-mode frequency range)

- To track features as small as 3 mega meters (Mm) requires a spatial resolution of 3"

- CDM's diffraction limited performance (2.7") requires image jitter to be ≤1.2" to meet this requirement.

- To Nyquist sample the solar image with 2.7" resolution requires a 1500 x 1500 pixel focal plane, and to accommodate the s/c pointing control of ≈0.1° requires a > 1790 x 1790 pixel imager
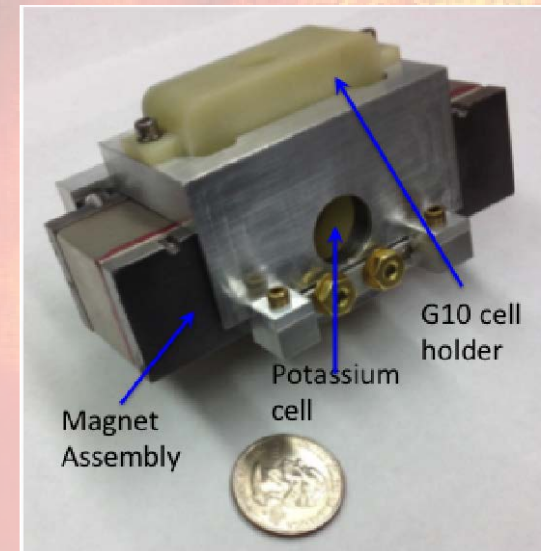
The Compact Doppler Magnetograph (CDM)

The CDM can meet its requirements and be packaged in a 6U form-factor by using a magneto-optical filter (MOF) (*Cacciani and Fofi, 1979, Tomczyk et al. 1995*), which provides two narrow, stable pass-bands, and has a large etendue, minimizing the optics volume.

The MOF is composed of a heated glass cell, containing potassium vapor, held between two crossed linear polarizers, and in a strong magnetic field. Close to absorption lines in the potassium vapor, light travelling through the cell has it's polarization rotated, allowing two narrow passbands to pass the 2nd polarizer.

The CDM uses the K 770nm line to image the same line in the sun's atmosphere. We can use information from CDM's two passbands to infer Doppler shifts in the solar line, and light from this line is polarized by the Zeeman effect – CDM measures this polarization to image the photospheric magnetic field

G10 cell holder

Potassium cell

Magnet Assembly

A compact MOF, prior to vacuum testing

Compact MOF accommodation specifications
Mass: Filter section   500g
Mass: Wing selector, (not shown) 1040g
Max power   3.0W

CDM optical design, and spacecraft accommodation

The CDM can be accommodated within a highly functional 6U CubeSat, with both mass and volume margin

MOF cells

Steering Mirror

Relay Optics

MOF Filter Section

MOF Wing Selector

Objective Lens

Focal Plane

2048x2048 pixel Focal plane

SAI schematic

70mm aperture
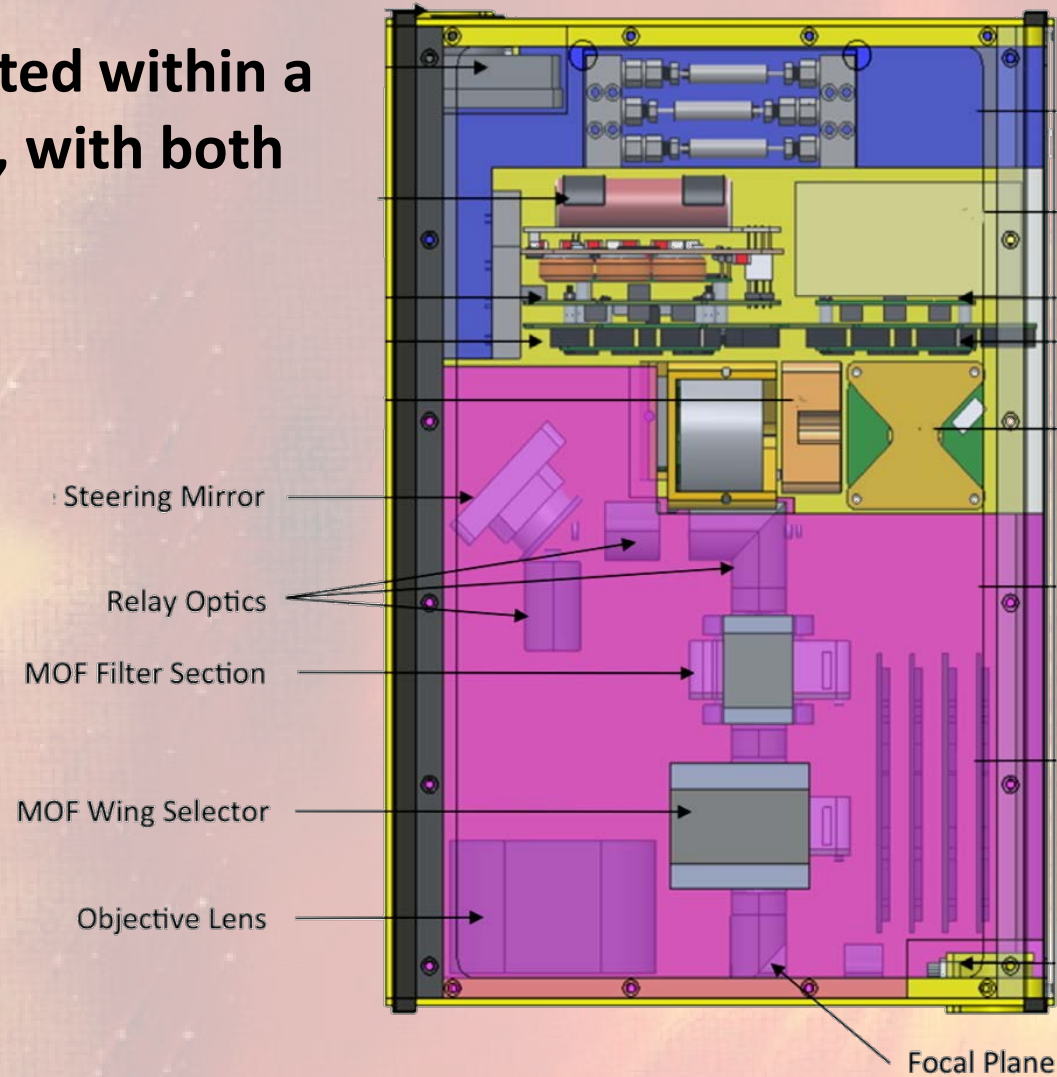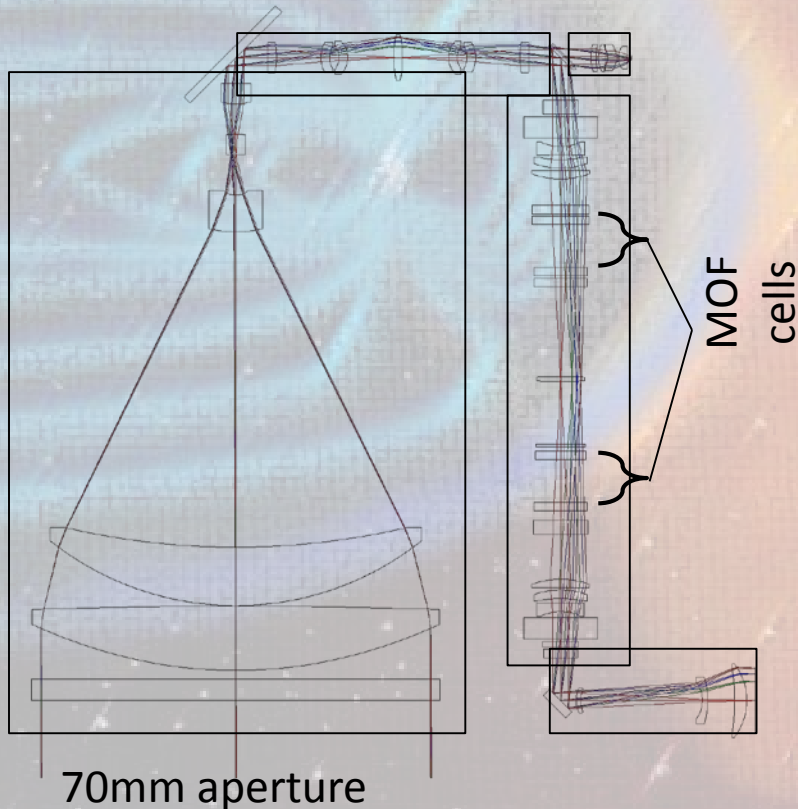
CDM data products

A) A raw filter image, through one MOF passband, each measurement set uses 4 filter images (2 senses of circular polarization, and two MOF passbands, to produce a Doppler shift image (a Dopplergram) and line-of-sight magnetic image (magnetogram)
B) The resulting magnetogram
C) The resulting Dopplergram.
D) A magnified Dopplergram showing velocity structure in the sun's photosphere, from which we can extract information about flows and waves
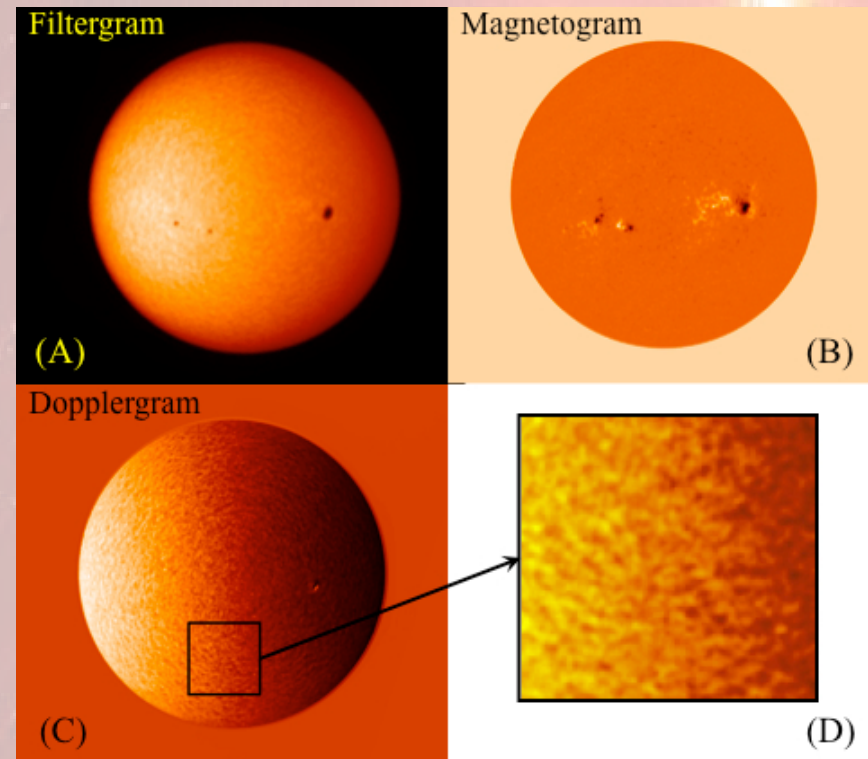
Doppler and magnetic image data from a prototype CDM, taken at the Jet Propulsion solar/magnetics lab

Operations concept

- SAI was proposed (unsuccessfully) to be launched on EM-1, NASA's 1st heavy launch vehicle test
  - This led to an operations concept based on a slow drift away from Earth
- While still in the Earth's vicinity, data rates reach 100kbps, however, in the current design, by 0.5AU the rate is 1 kbps.
  - This led to a campaign based approach, similar to Solar Orbiter, with data collected in 10-day segments, and returned to Earth slowly. Maximum DSN usage would be one 8 hour pass per day to a 34m antenna (≈130 total) After it's prime mission, SAI would continue to collect magnetograms at a low cadence (several), as it continued to drift.
- In the next design iteration, we will accommodate some of the improvements made for MarCO to boost the data rate (by ≈x5), but we will still follow a similar approach
  - This would allow us to trade DSN time vs data volume vs range to earth, vs science gain

SAI requirements and capabilities

- SAI's measurement requirements are challenging, with attitude stability and communications producing the most difficulty. However, **we have developed a detailed mission concept that would achieve our science requirements, within the range current CubeSat capabilities**

  - Driving requirements
    - s/c pointing accuracy (0.1°)
    - s/c pointing knowledge (0.1°)
    - s/c stability (jitter)over 60s (10")
    - Focal plane jitter over 60 (1")

    - Data storage (128 Gbits)
    - Onboard data editing/compression
    - Communications (1 -100 kbps)

  Proposed solution
  Inst. FP 0.1° > than sun's image
  allows slow image drift
  limited by reaction wheel noise
  FSM gives x10 s/c performance

  Data storage (>10 days) & analysis
  High performance FPGA
  Iris DSN transponder/ 22 dB antenna

Key capabilities – Attitude control/image stabilization

- Main components: three isolated reaction wheel assemblies (RWAs), two sun sensors, a star camera, a cold-gas propulsion system for momentum dumping, and a fast steering mirror (FSM) for image stabilization

  - Requirements – 0.1° s/c pointing knowledge and control, 10" s/c stability over 60s, 1.2" focal plane image stability over 60s

  - Performance modeled, including s/c and FSM dynamics, noise sources and solar torques. The control system in the model uses flight control algorithms. FSM sensor input is a solar-illuminated quad cell

  - Performance was 1" over 60s and is dominated by RWA noise, and FSM – CubeSat coupling, a consequence of SAI's very low mass

Key capabilities – Communications

- Components: Iris V2.1, CubeSat Deep Space Network (DSN) Compatible X-Band transponder, a 22 dBi gain antenna patch array.

- Capabilities: 1kbps at 0.5 AU from Earth, (2 W RF power, and a 34 M DSN antenna). Navigation support (Doppler data), and ranging.

  - Iris V2.1 coupled with a more recent antenna design developed for the Mars CubeSat One (MarCO) mission (2018 Launch) could provide ≈8kbps from 0.5 AU to a DSN 35m antenna
  - The Iris V2.1 transponder can provide a 1 kbps uplink, and up to 25.6 kbps downlink.
  - In development are higher power, and Ka-Band versions of IRIS, with Downlink rates up to 8.2 Mbps.
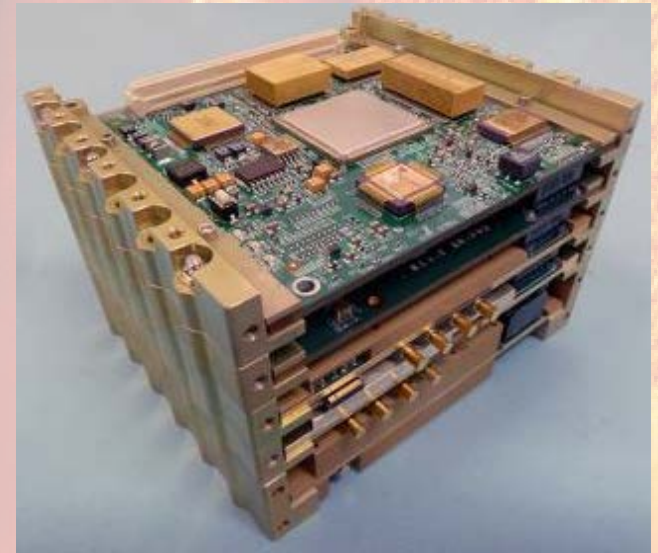
Iris V2.1 Transponder

SAI spacecraft design summary

Design Parameter	Requirement	Implication
Orbit	Heliocentric	Uses Iris V2 Deep Space Radio and Deep Space Network (DSN)
Initial Mission Science Data Return	25600 Mbit	Iris V2 Deep Space Radio and 16GB data storage on board
Power – Science – Downlink	24.1 W 30.1 W	Deployable panels for 44W EOL power
CubeSat attitude Stability	10 arc-sec/min	3 reaction wheels, 2 sun sensors,
Spacecraft attitude Knowledge	0.1 deg	
Spacecraft attitude Control	0.1 deg	
Payload volume	3U	6U form factor CubeSat is required
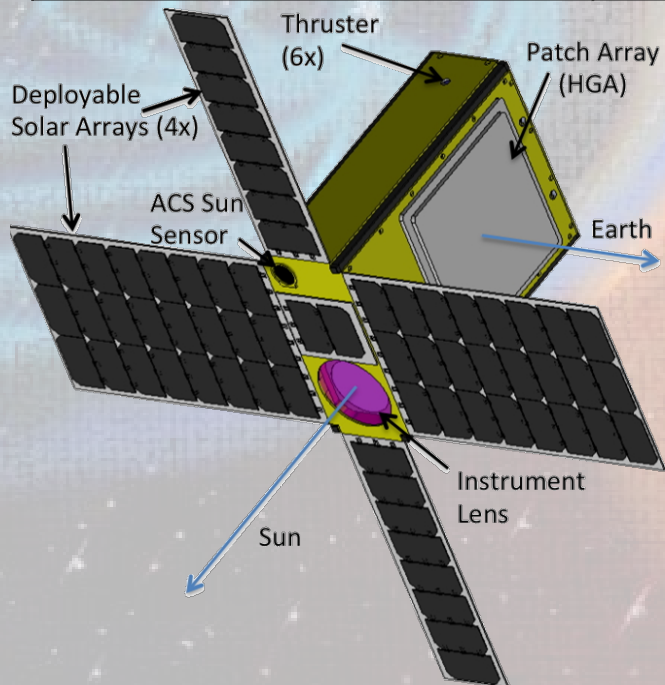
Design Parameter	Requirement	Capability	Margin
Mass	11.13 kg	13.67 kg	19%
Volume	5.25U	6U	12.5%
Power – Science – Downlink	24.1 W 30.1 W	45.6 W 44.1 W	45% 32%
Data Storage	78900 Mbit	128000 Mbit	70%
Downlink	12756 Mbit	13902 Mbit	8.3%
Telecom Pt/No	31.87 dB-Hz	36.86 dB-Hz	4.99 dB
Coarse Attitude Knowledge	0.1 degree	0.1 and better	--
Coarse Attitude Control	0.1 degree	0.1 and better	--
Focal plane stability	1.2" over 60s	1" over 60s	20%

Conclusions

- Space Weather studies present a difficult challenge – how do we understand and predict such a complex, coupled system?
  - We must have distributed, multi-spacecraft measurements
  - CubeSat missions are required to address the challenge

SAI would be a critical step in developing the required key measurement capabilities for a Space Weather constellation

- CDM path forward – multi-pronged
  - Ongoing ground based measurements (currently at South Pole)
  - Proposed balloon mission SONETTO (next talk)
  - SAI CubeSat mission…