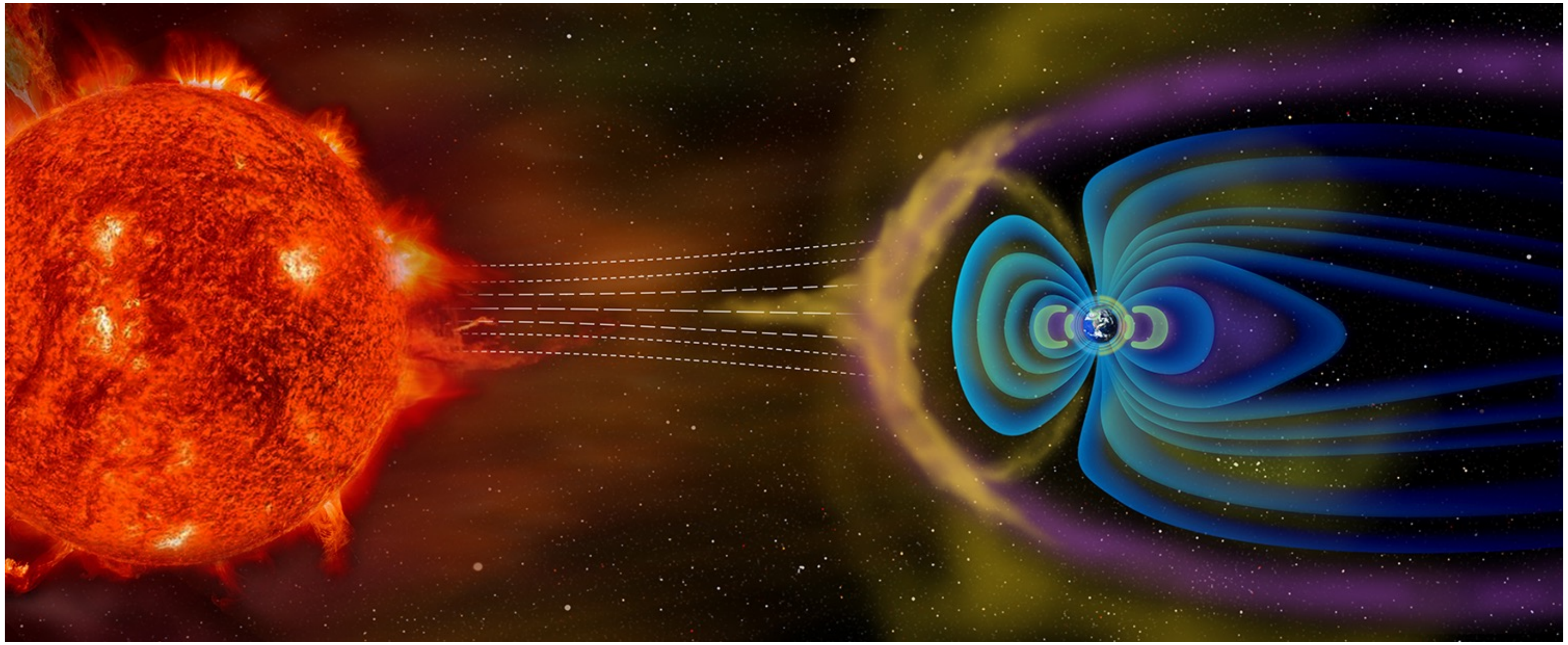

Image Credit:
NASA

Plasma and Field Instrumentation

Michael Hartinger

July 20, 2023

Heliophysics Summer School 2023: Observational Heliophysics

Goal for Today

- Broad overview of space plasma instrumentation used to measure plasma and fields
    - Not a comprehensive overview! 50 minutes could easily be devoted to each instrument type
    - Focus on common concepts including data levels, noise, etc.
- Common tools and procedures used to work with all instruments
- Show of hands: Who is a modeler/theorist?

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- Show of hands: Who is an observer?

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- Common tools and procedures used to work with all instruments
- Show of hands: Who would like to build instruments / be an instrument PI?

Further reading

Impossible to cover all relevant instruments – each one could fill one or more lectures – instead, I'll focus on two types of instruments as examples, and suggest the following references for details on other instruments:

- AGU Monograph: Measurement Techniques in Space Plasmas: Fields (eds R.F. Pfaff, J.E. Borovsky and D.T. Young)
- AGU Monograph: Measurement Techniques in Space Plasmas: Particles (eds R.F. Pfaff, J.E. Borovsky and D.T. Young)
- ISSI Scientific Report: Calibration of Particle Instruments in Space Physics (eds M. Wuest, D.S. Evands and R. von Steiger)
- Numerous instrument papers for specific missions. I'll show several figures today from instrument papers related to NASA's THEMIS mission.

Heliophysics Missions

Heliophysics Mission Fleet

Heliophysics missions are strategically placed throughout our solar system, working together to provide a holistic view of our Sun and space weather, along with their impacts on Earth, the other planets, and space in general. NASA's heliophysics mission fleet includes 19 operating missions using 26 spacecraft, 13 missions in development, 1 mission under study, a robust sounding rocket program and a variety of CubeSat missions.

- ESA = European Space Agency
- JAXA = Japan Aerospace Exploration Agency

*Numbers in parentheses indicate how many spacecraft each mission includes.

*Objects Not to Scale

● UNDER DEVELOPMENT

- AWE (ISS)
- Carruthers Geocorona Observatory
- ESCAPADE (2)
- EUVST (JAXA)
- EZIE (3)
- GDC (6)
- HelioSwarm (9)
- HERMES (Gateway)
- IMAP
- MUSE
- PUNCH (4)
- SunRISE (6)
- TRACERS (2)

● PRIMARY OPERATION

- Parker Solar Probe
- Solar Orbiter (ESA)

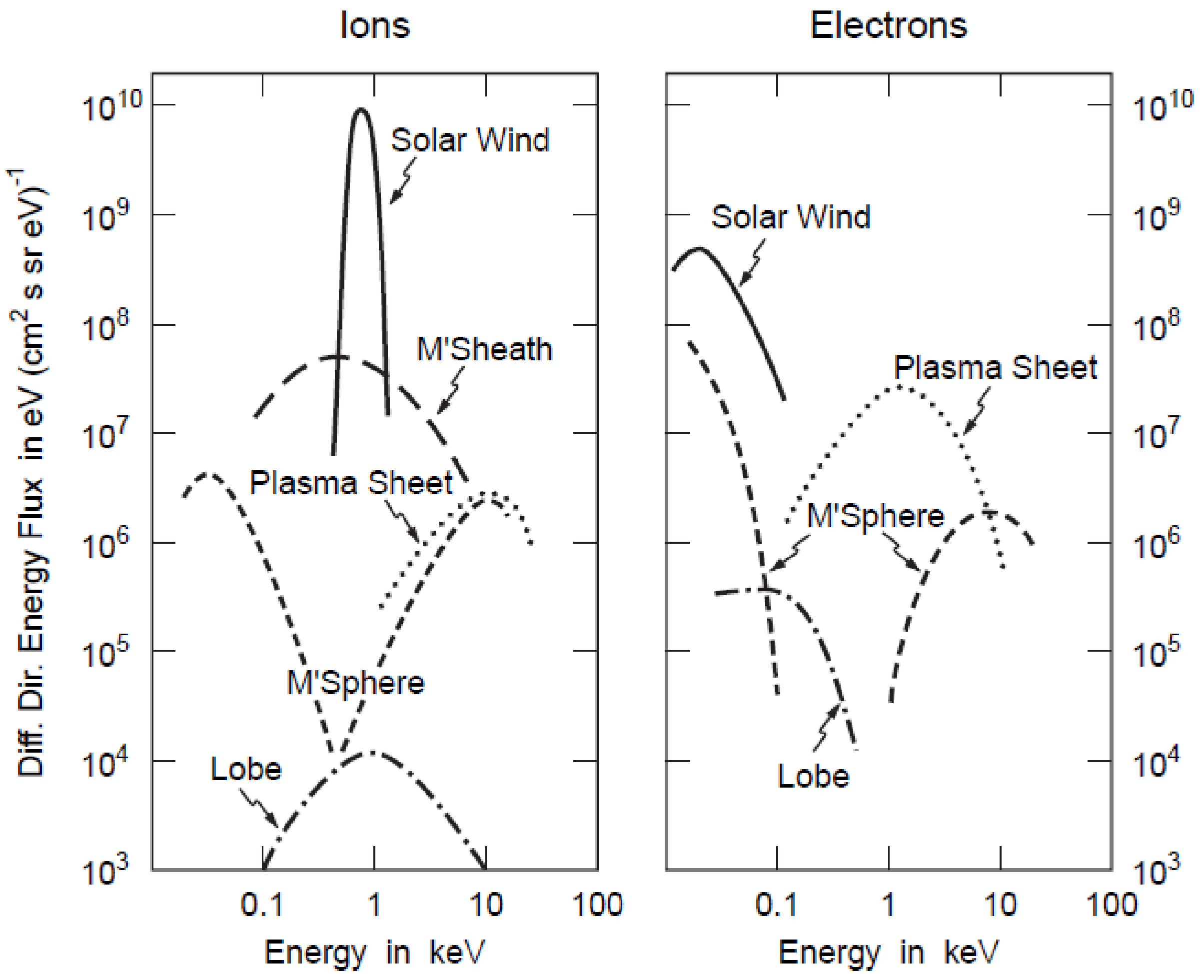
● EXTENDED OPERATION

- ACE
- AIM
- GOLD (SES-14)
- Hinode (JAXA)
- IBEX
- ICON
- IRIS
- MMS (4)
- RAD (Curiosity)
- SDO
- SOHO (ESA)
- STEREO
- THEMIS-ARTEMIS (2)
- THEMIS (3)
- TIMED
- Wind
- Voyager (2)

science.nasa.gov/heliophysics

Instrumentation Across the Heliophysics System Observatory

- Numerous satellite missions with different scientific goals operating in very different environments
- Instrumentation is driven by the scientific goals of each mission
- There are always tradeoffs. Power, telemetry, weight, cost, etc are all drivers for the choice of instrumentation. Some instruments work better in different environments (high/low Beta, etc)
- Given these tradeoffs and the different operational environments, it's no surprise there are a vast range of instrumentation used to measure plasma and fields

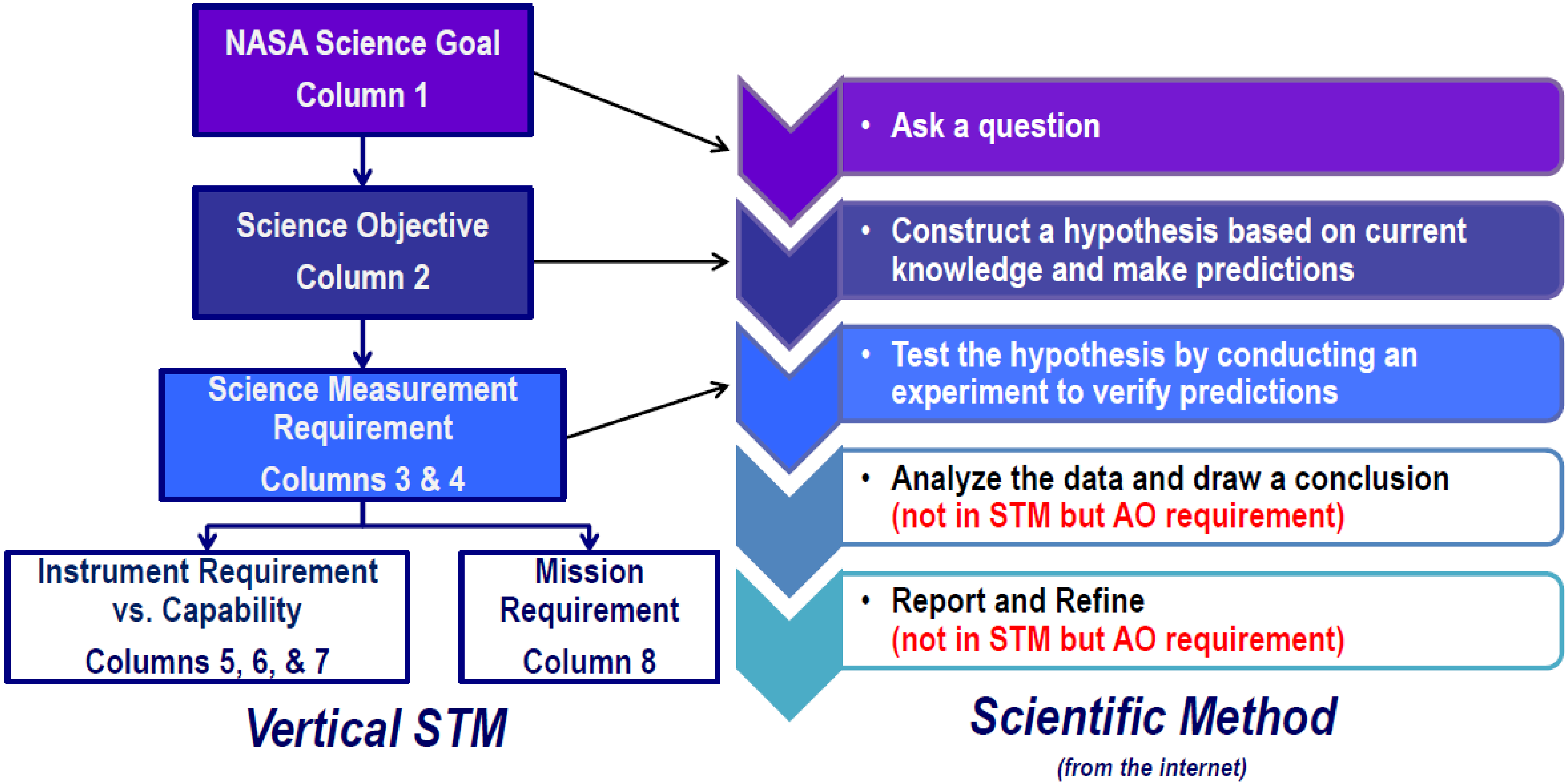


[From Wuest et al., 2007; Cluster mission proposal]

Instrumentation Across the Heliophysics System Observatory

Scientific Method: systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses. (*Oxford English Dictionary*)

- Important to trace from scientific objectives to measurement requirements to instrument requirements and top-level measurement requirements
- NASA often uses the "Science Traceability Matrix" – **future PI's take note!**



NASA Science Goal
Column 1

Science Objective
Column 2

Science Measurement Requirement
Columns 3 & 4

Instrument Requirement vs. Capability
Columns 5, 6, & 7

Mission Requirement
Column 8

Vertical STM

- Ask a question
- Construct a hypothesis based on current knowledge and make predictions
- Test the hypothesis by conducting an experiment to verify predictions
- Analyze the data and draw a conclusion (not in STM but AO requirement)
- Report and Refine (not in STM but AO requirement)

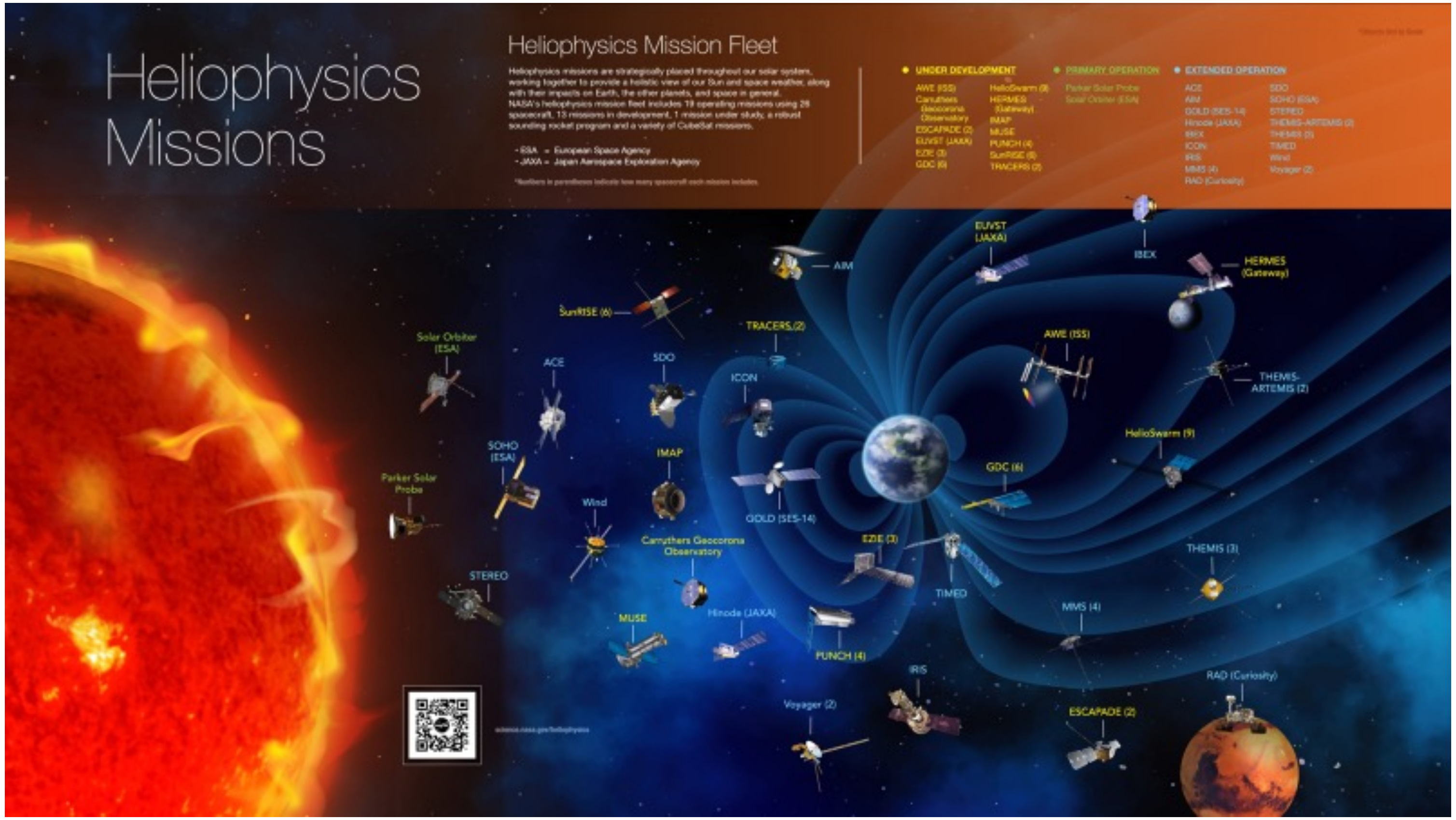
Scientific Method

(from the internet)

[From "The Science Traceability Matrix", NASA PI Launchpad workshop, Sabrina Feldman]

Magnetic Field Instruments

- Magnetic fields are a vital parameter for understanding space plasmas
- If direct measurements are available in the plasma, we can use them to characterize the plasma (highly/weakly magnetized), understand charged particle motions, determine plasma wave properties…
- On the following slides, I’ll introduce a few techniques for measuring magnetic fields, but also use them as an example to highlight issues that are common with other instruments



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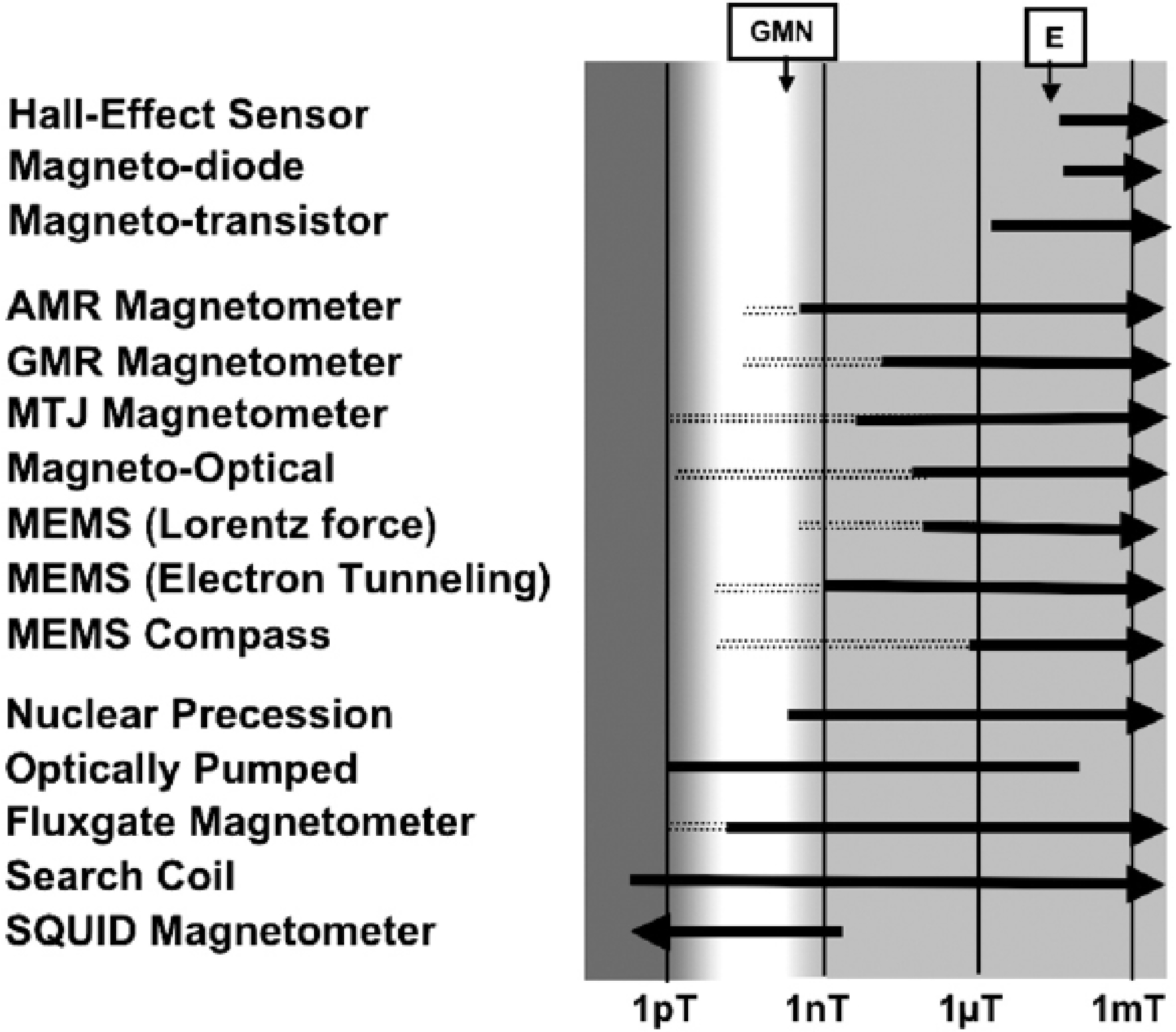
[NASA]

Tools to measure magnetic fields: magnetometers

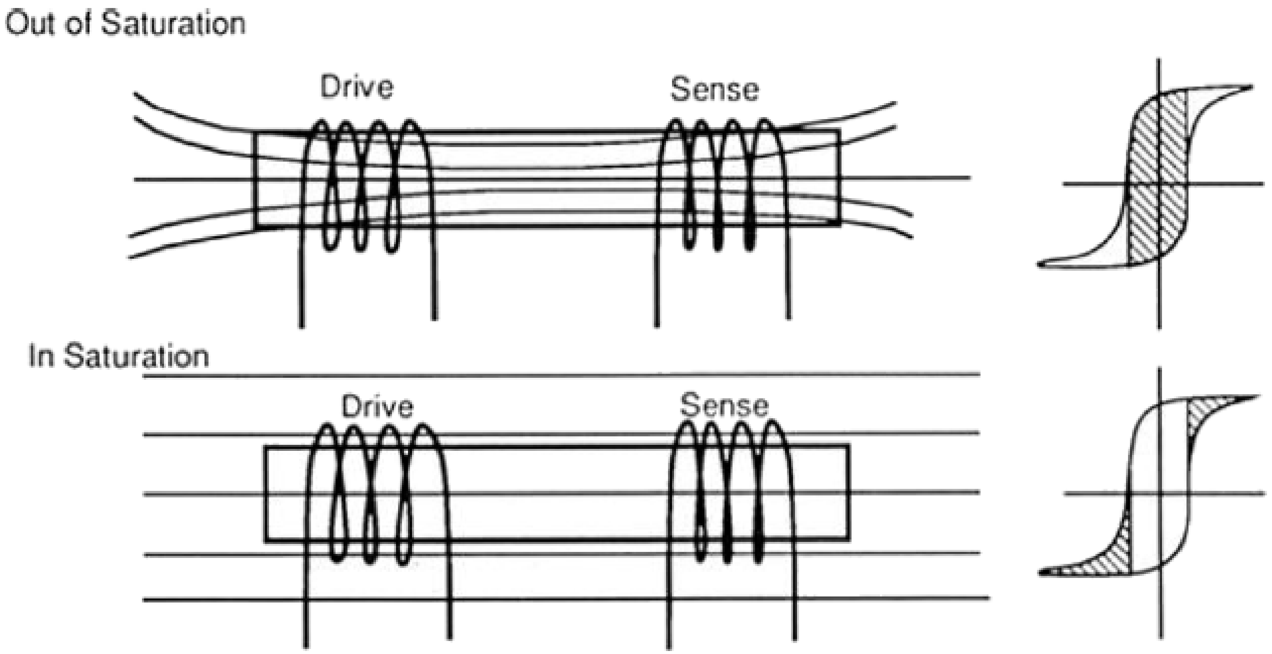
- Magnetometers – instruments to measure the magnetic field – come in many styles and are used for many applications: space weather/space plasma diagnostics (what I'll focus on), magnetotellurics, defense applications,…
- Two types of magnetometers that I'll focus on: fluxgate magnetometers and search coil (induction) magnetometers. There are many other types (e.g., proton precession, helium vapor)
- There are large networks of fluxgate and search coil magnetometers on the Earth's surface, and they've been flown on many satellites near the Earth, Moon, and across the solar system
- Widely used on spacecraft due to small size, low power requirements, accuracy



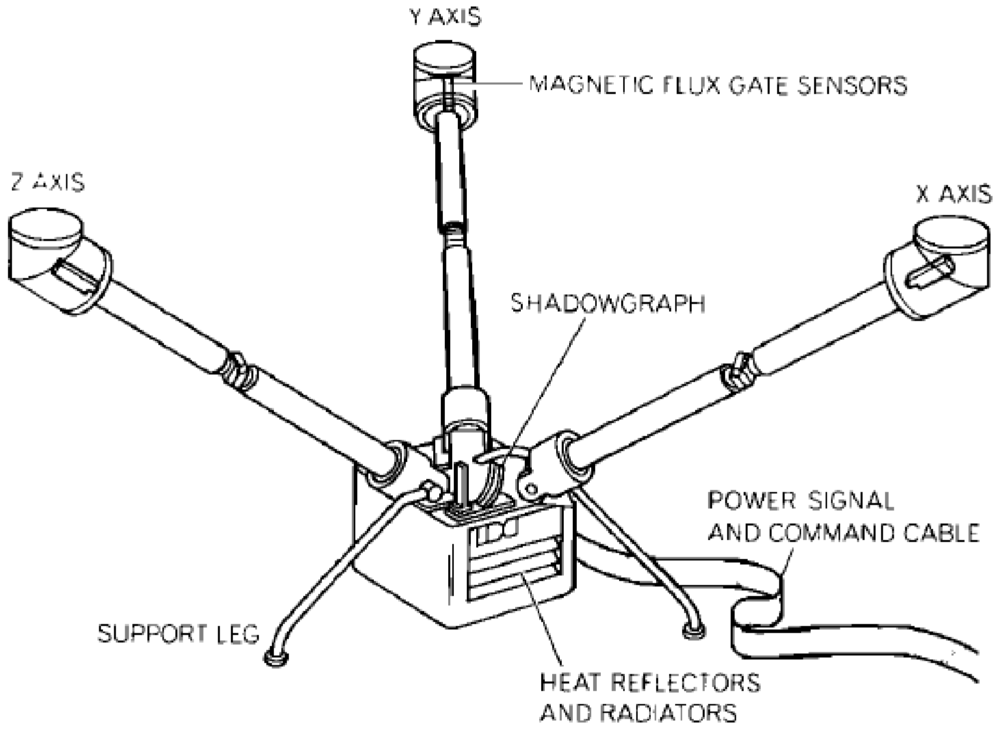
[Lens and Edelstein, 2006]

Fluxgate magnetometer: the basics

- Ferromagnetic material wound with two coils, “Drive” and “Sense”. A sinusoidal current is applied in the “Drive” coil
- Coil reaches saturation every half cycle – if no ambient magnetic field, odd harmonics are induced in the sense coil – if there is an ambient magnetic field, even harmonics also detected and the voltage associated with these harmonics is proportional to the ambient magnetic field → a measurement of the magnetic field
- Wide range of designs for fluxgates: size, power, core material,…
- Wide range of applications: spacecraft and ground, high and low temperature

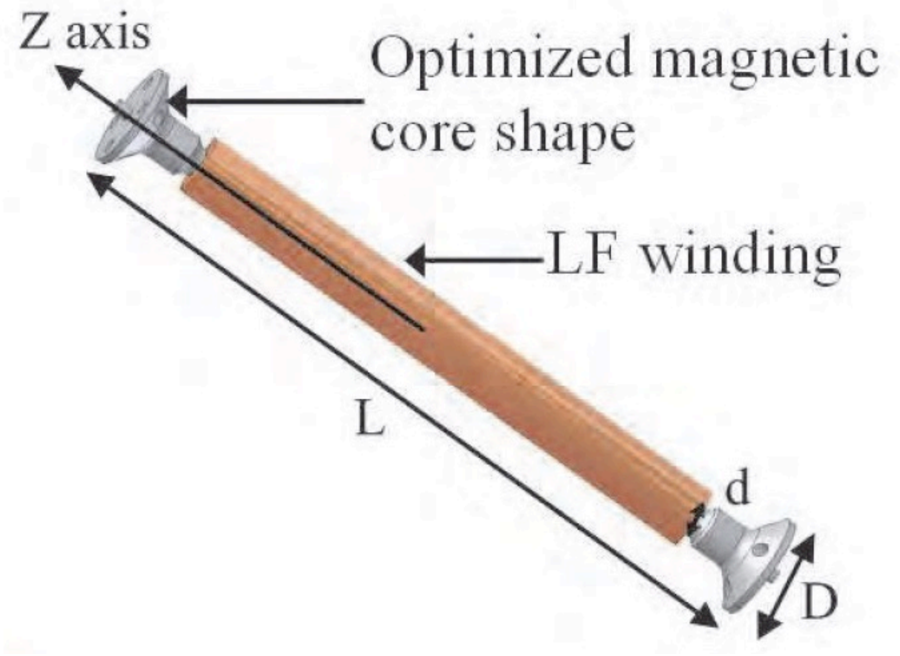


[Lens and Edelstein, 2006]

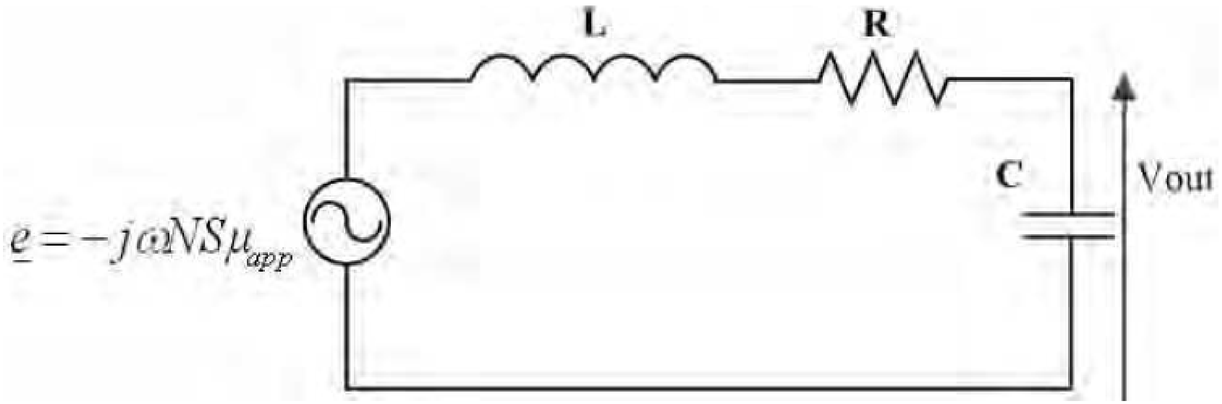


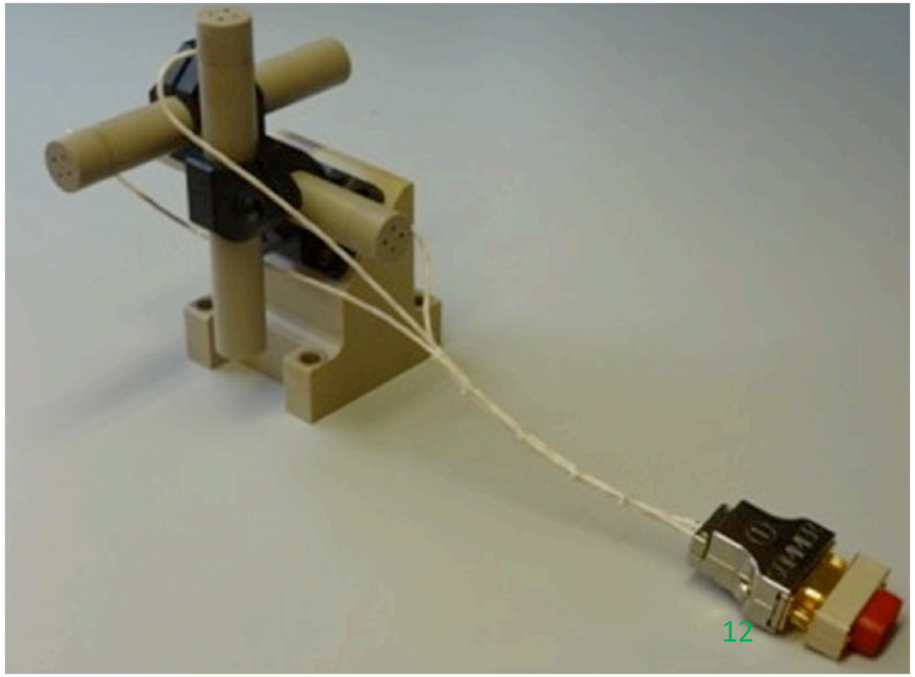
[Dyal and Parkin, 1971]

Search coil magnetometer: the basics



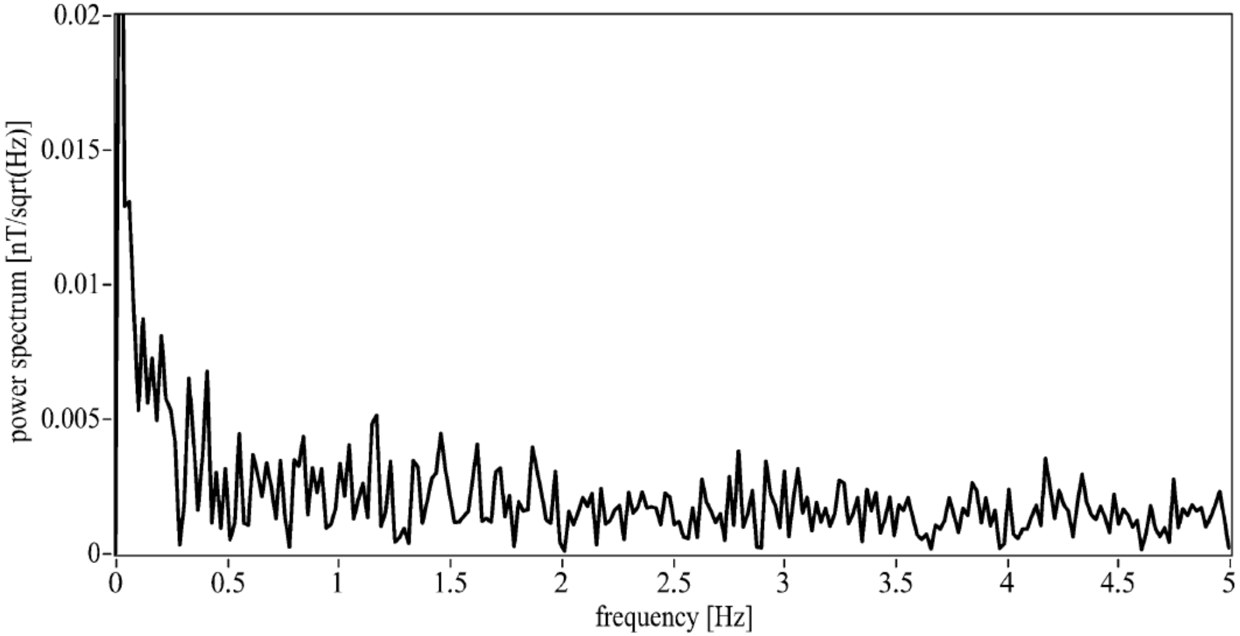
- Works on the principle of magnetic induction (Faraday's Law): time varying magnetic flux trough a coil sensor is proportional to voltage in the sensor
- The coil itself is basically just wire wrapped around a variety of materials – for spacecraft, there is usually a magnetic core to boost sensitivity
- There are a vast range of shapes, sizes, and applications for search coil magnetometers, depending on the application: frequency of interest, sensitivity needed, mass/power requirements,...
- A very basic design is shown at the bottom from Coillot and Leroy, [2012], where the number of turns of wire and other parameters affect the measured flux
- Other designs include "diabolos" or flux concentrators at the end of the coil (at right) to help boost the measured signal





[MMS satellite search coil that is 10 cm long, from LeContel et al 2016]

Common issues: noise



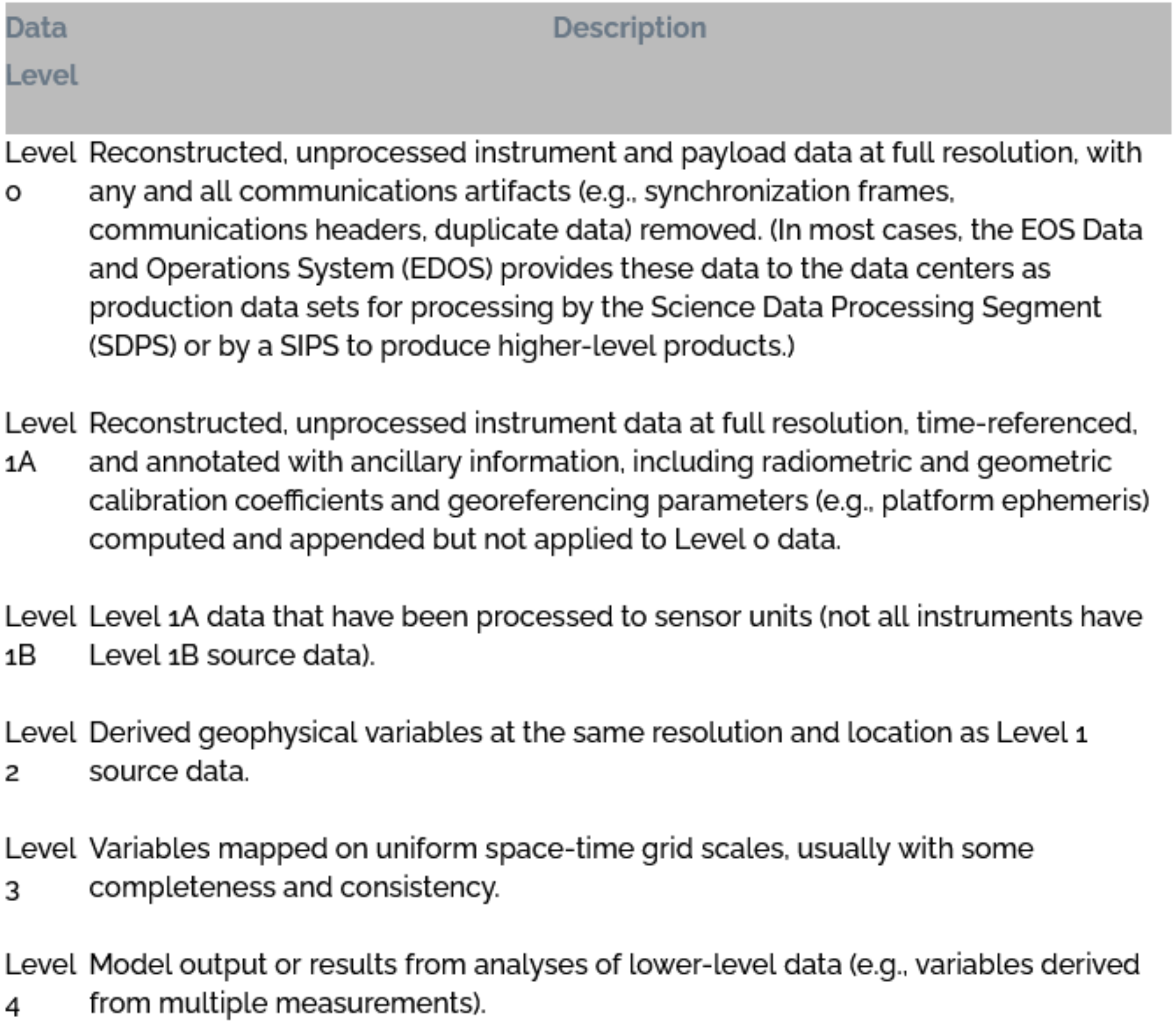
[Auster et al., 2008]

Fig. 2 Noise spectrum of a 13 mm ring-core as used for Themis

- Magnetometers and other plasma and fields instruments are affected by a variety of noise sources that are often frequency dependent
- For example, there’s noise inherent to the instrument that can be well characterized through laboratory tests
- There’s also noise from the electronics onboard the spacecraft, and magnetic fields from the spacecraft itself – these are sources of that can obscure the signals of interest
- “magnetic cleanliness” is very important when designing spacecraft flying magnetometers
- The weaker the signal of interest, the more important it is to know the noise spectrum

Common issues: data levels

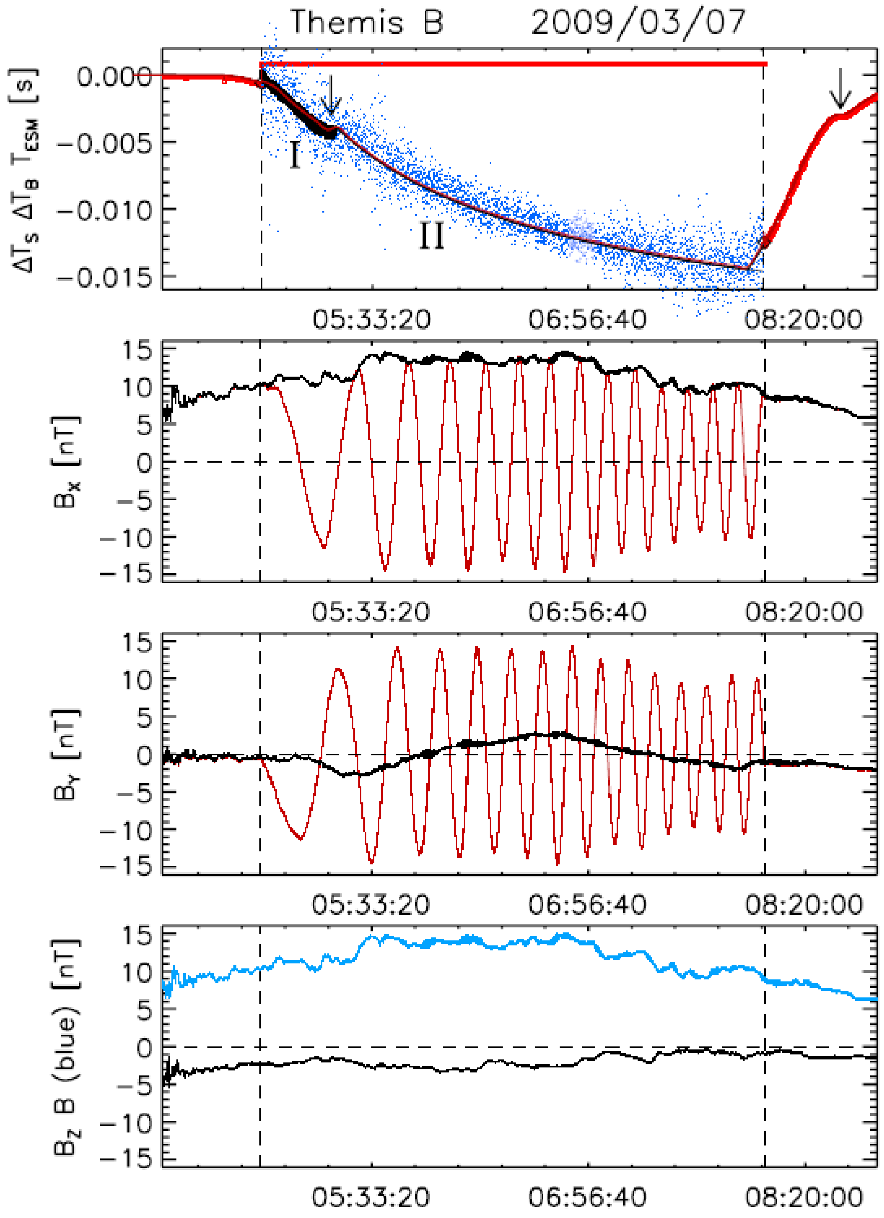
- Example at right from NASA’s Earth Observing System Data and Information System, but analogies can be made to Heliophysics instrumentation
- Example from magnetometer on spinning spacecraft:
  - Level-0 = voltages with arbitrary timestamps
  - Level-1 = calibrated magnetic field measurements in units of nT in spinning satellite frame
  - Level-2 = calibrated magnetic field measurements in units of nT in geocentric inertial frame, various coordinates
- Unless you’re an instrument designer/operator, you’ll likely never interact with Level-0 data
- Can you think of some examples of Level-1 data for other instruments?



Data Level	Description
Level 0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e.g., synchronization frames, communications headers, duplicate data) removed. (In most cases, the EOS Data and Operations System (EDOS) provides these data to the data centers as production data sets for processing by the Science Data Processing Segment (SDPS) or by a SIPS to produce higher-level products.)
Level 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to Level 0 data.
Level 1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B source data).
Level 2	Derived geophysical variables at the same resolution and location as Level 1 source data.
Level 3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
Level 4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Common issues: unwanted signals from data processing

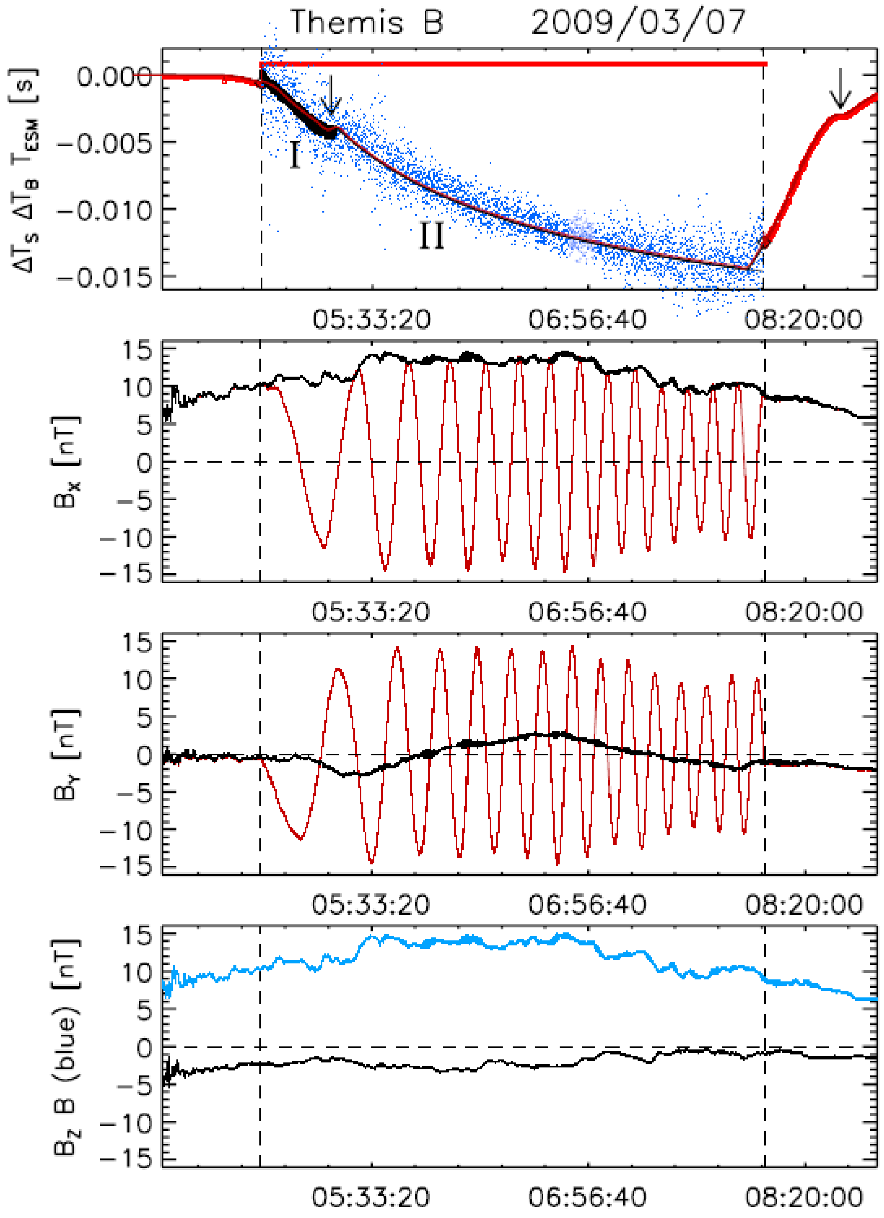
- Data processing steps required to advance from Level-0 to Level-1 and Level-2 can introduce unwanted signals into the higher-level data
- These arise from many sources, including the need to use supporting attitude information from the spacecraft that may not always be available or may be corrupted



[Georgescu et al., 2011]

Common issues: unwanted signals from data processing

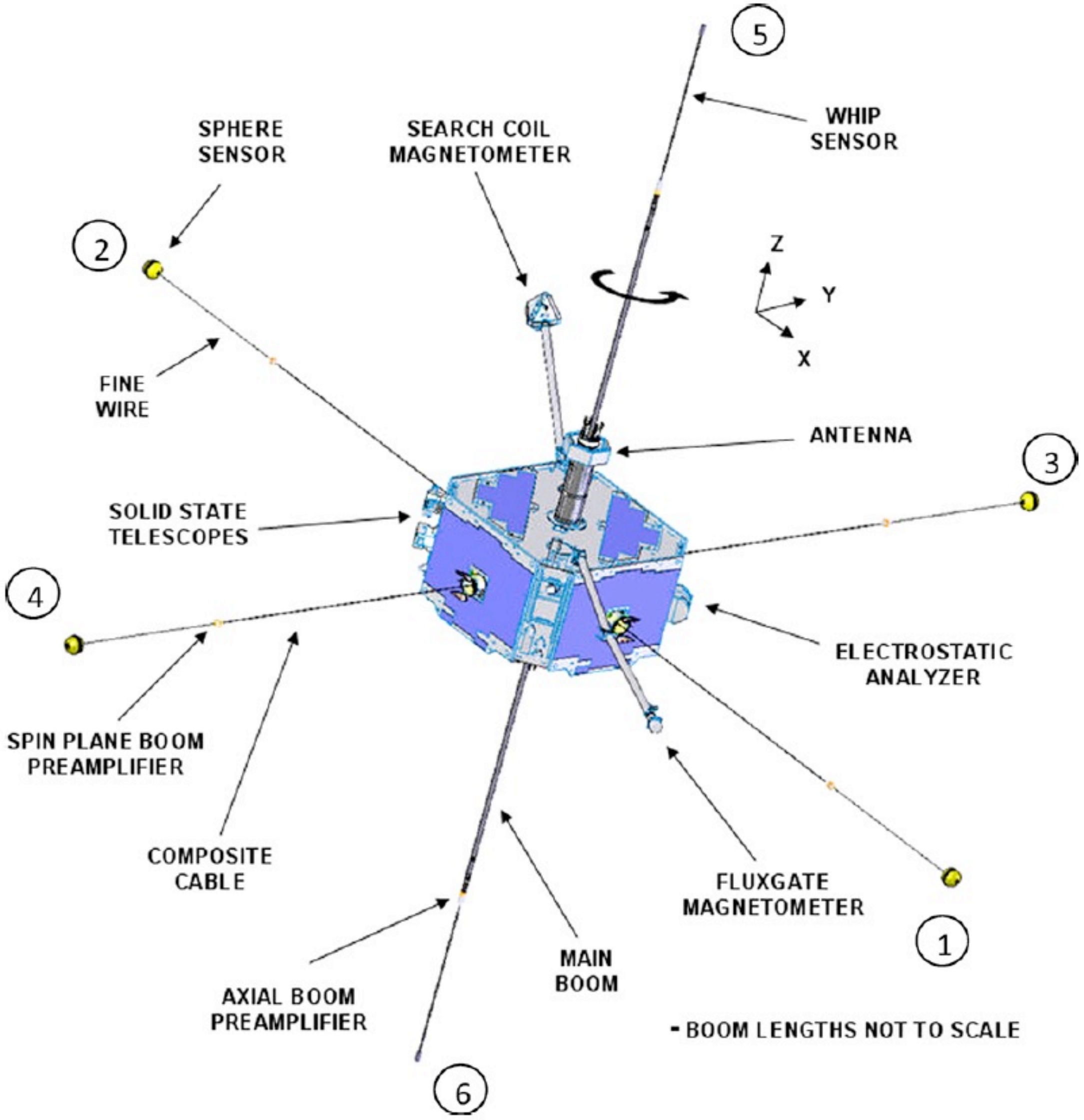
- Data processing steps required to advance from Level-0 to Level-1 and Level-2 can introduce unwanted signals into the higher-level data
- These arise from many sources, including the need to use supporting attitude information from the spacecraft that may not always be available or may be corrupted
- Example for a spinning spacecraft:
    - Transforming magnetic or electric field measurements from the spinning frame to a geocentric inertial frame requires attitude information
    - A sun sensor is often used for attitude information, but this doesn't work when a satellite is in eclipse and can't see the Sun
    - Errors in attitude information and knowledge of spinphase → spurious signals in despun magnetic field data
    - This can be corrected with a model of the spin period, but this might not be done in automated L2 data generation



[Georgescu et al., 2011]

Summary of magnetic field measurements

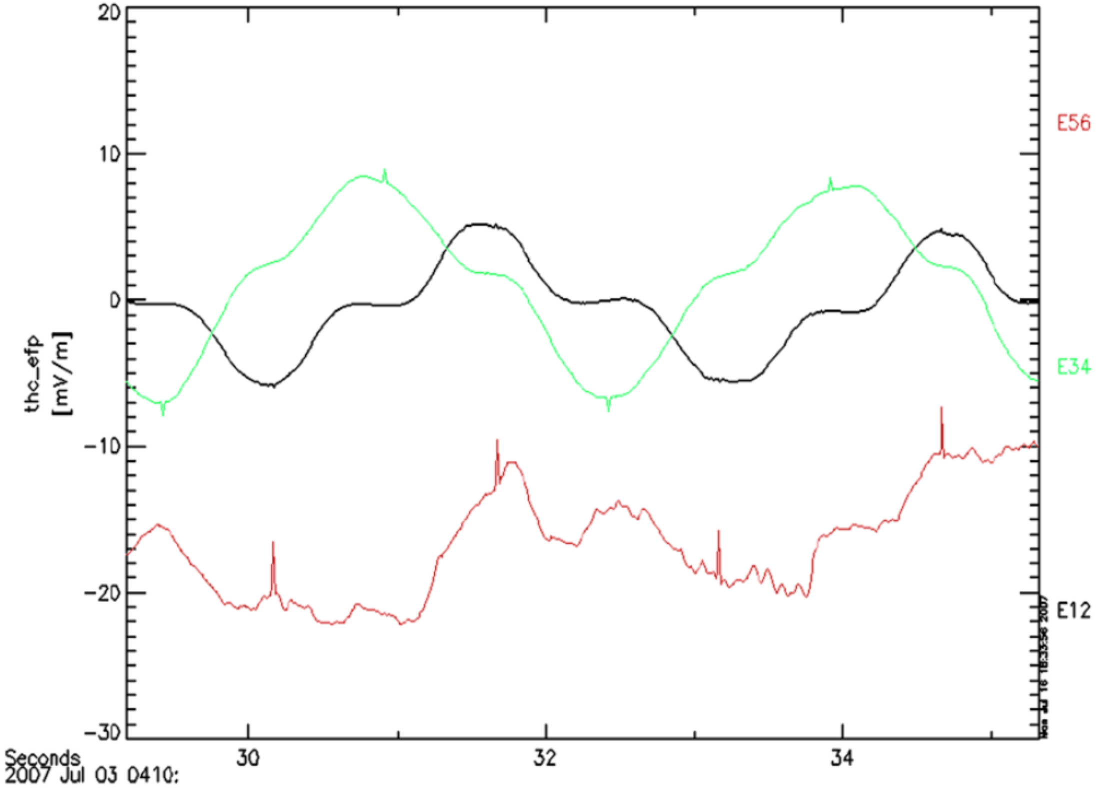
- Magnetometers are versatile measurements used for a range of mission objectives
- They come in many types and sub-types
- Common issues: noise and unwanted signals from data processing
- Common solutions: read the metadata, read the instrument paper, talk to the instrument team



[Schematic of THEMIS spacecraft from Bonnell et al., 2008]

Electric field measurements

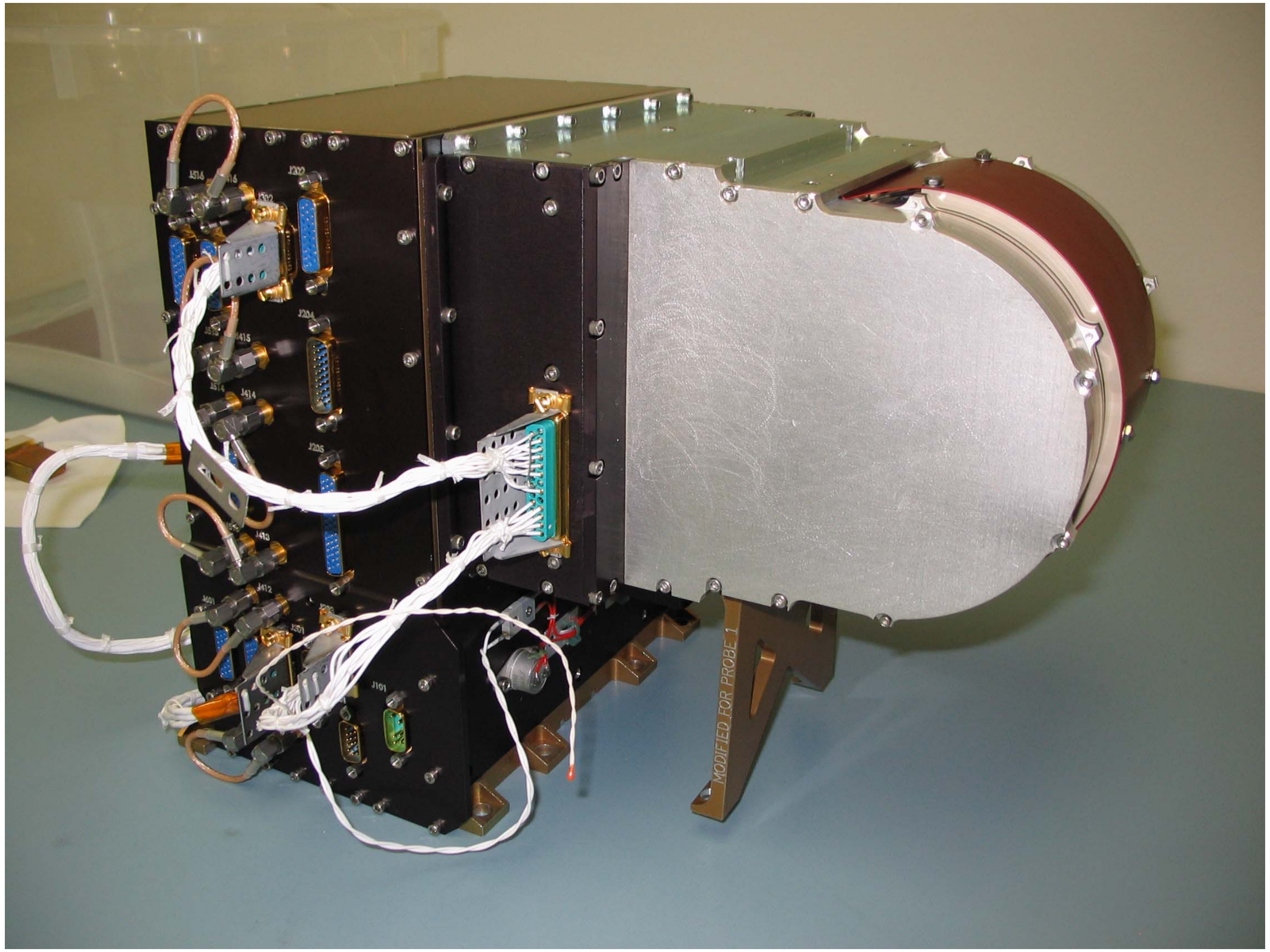
- There's not enough time to cover electric field instruments
- Here's a brief summary of three ways of measuring electric fields:
    - **Double probes** provide direct potential measurements
    - **Electron drift instruments** rely on measuring ExB drift of emitted electrons to get E normal to B
    - **Particle detectors** that provide velocity moments can be used to infer E normal to B under some assumptions
- Like magnetic field instruments, these instruments are also affected by various sources of noise (e.g., electrostatic wake of spacecraft, example at right) and unwanted signals related to data processing
- Also like magnetic field instruments, these instruments can be tailored to the region/plasma regime of interest



[Example of spacecraft wake event on THEMIS double probe instrument, EFI, Bonnell et al., 2008]

Electrostatic Analyzers: An Example Particle Instrument

- Electrostatic analyzers (ESA) are widely used to measure particle distributions throughout the heliosphere
- They can be used to quantify particle flux at different energies, calculate higher order moments such as velocity, density,…
- On the following slides, I'll introduce a few techniques for measuring charged particles with ESA's, but also use them as an example to highlight issues that are common with other instruments



[THEMIS satellite ESA, Source: NASA]

Electrostatic Analyzer: An Example Particle Instrument

- Electrostatic analyzers (ESA) perform a differential selection in particle energy
- An electric field between two curved plates guides the flight path of the particle
- Energy-dependent drift path/radius → differentiation in energy
    - Radius of path = mv^2 / qE
    - Dependence on q also provides a charge selection – i.e., ESA's automatically separate ions from electrons
- At the end of their drift path, the number of particles of different energies are counted with various techniques
    - Example: THEMIS ESA uses microchannel plate detectors

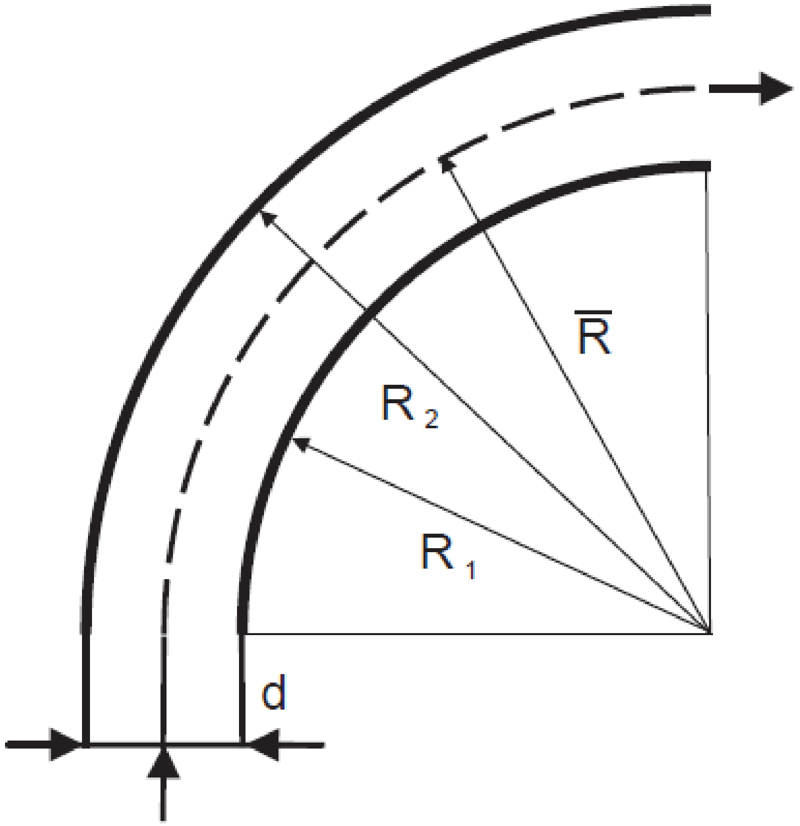
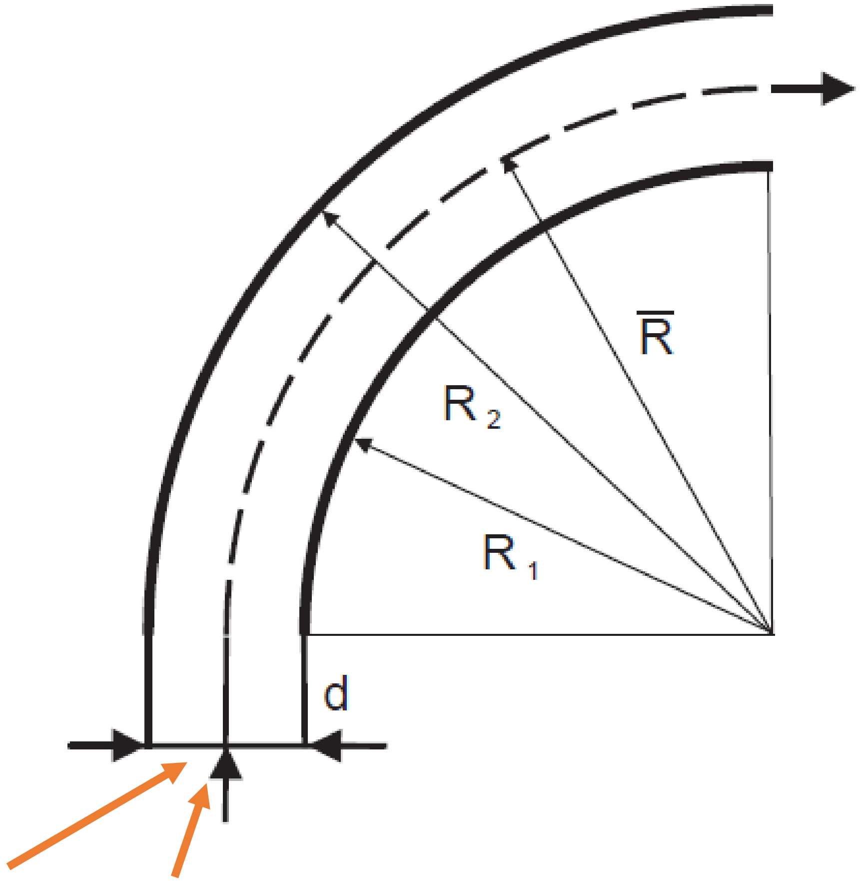


Figure 2.27: Cylindrical electrostatic analyzer.

[Wuest et al 2007]

Electrostatic Analyzers: An Example Particle Instrument

- Significant customization of ESA's is possible depending on whether the satellite is spinning or not, the plasma distribution of interest, operational environment
- Major types of ESA geometries and refinements
    - Cylindrical ESA's – less complicated setup, more difficult to measure full 3D distribution function due to narrow acceptance, but can be done with spinning spacecraft, multiple ESA etc.



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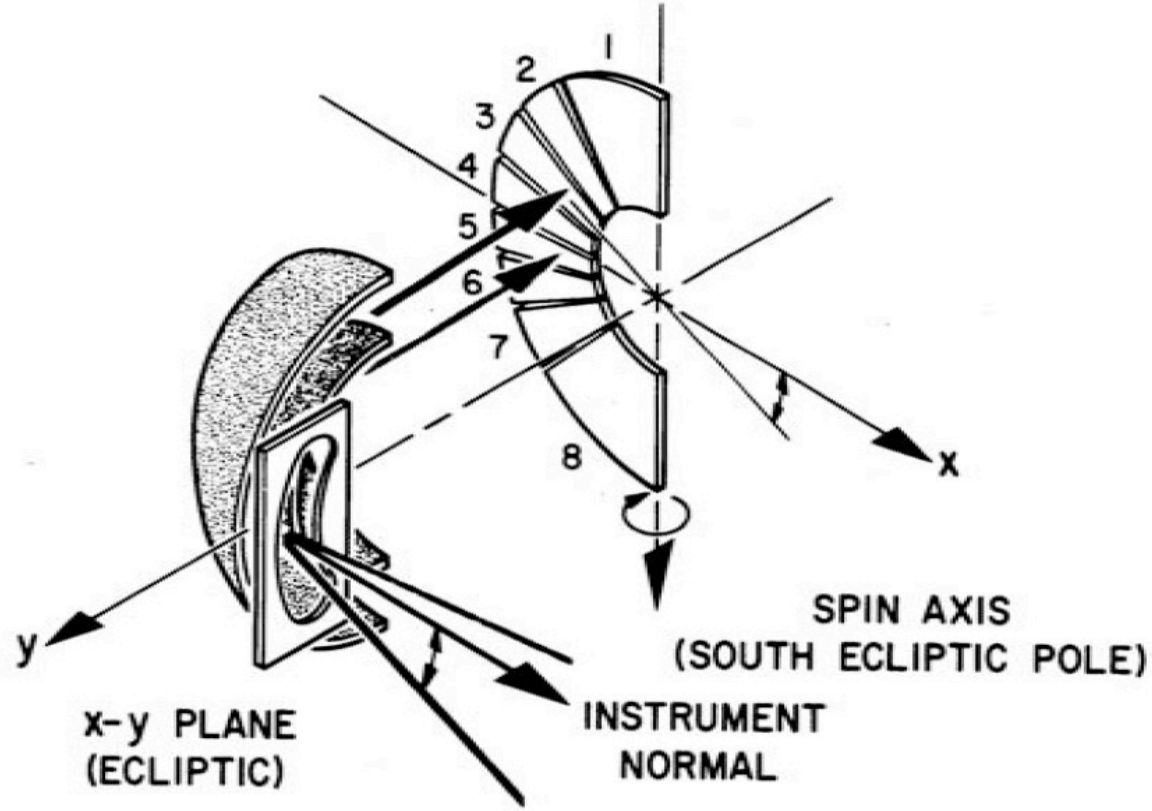
    - Spherical ESA’s (quadrispheric, hemispheric) – extends detector to two spherical surfaces to allow for trajectories more like great circle paths, can sample 2D particle distributions



[Wuest et al 2007, from Scarf et al., 1996 – for ESA flown on Pioneer-6 spacecraft]

Electrostatic Analyzers: An Example Particle Instrument

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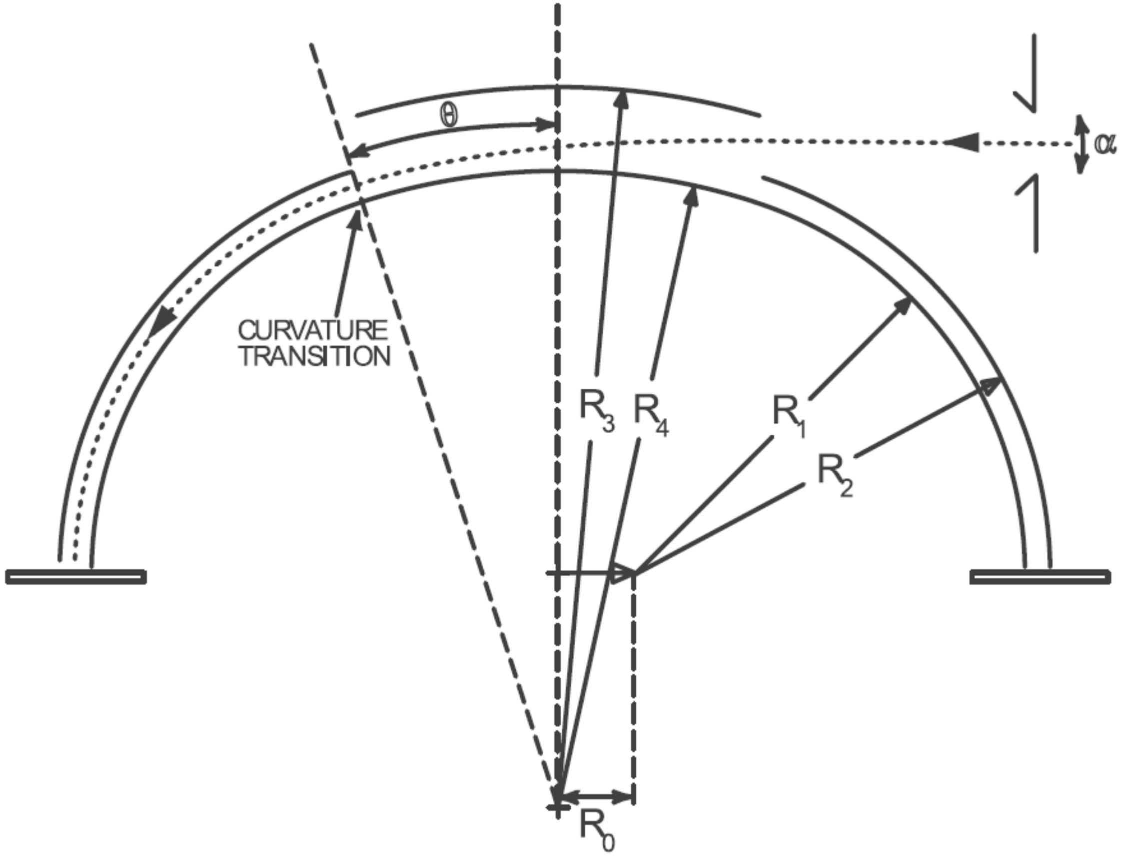
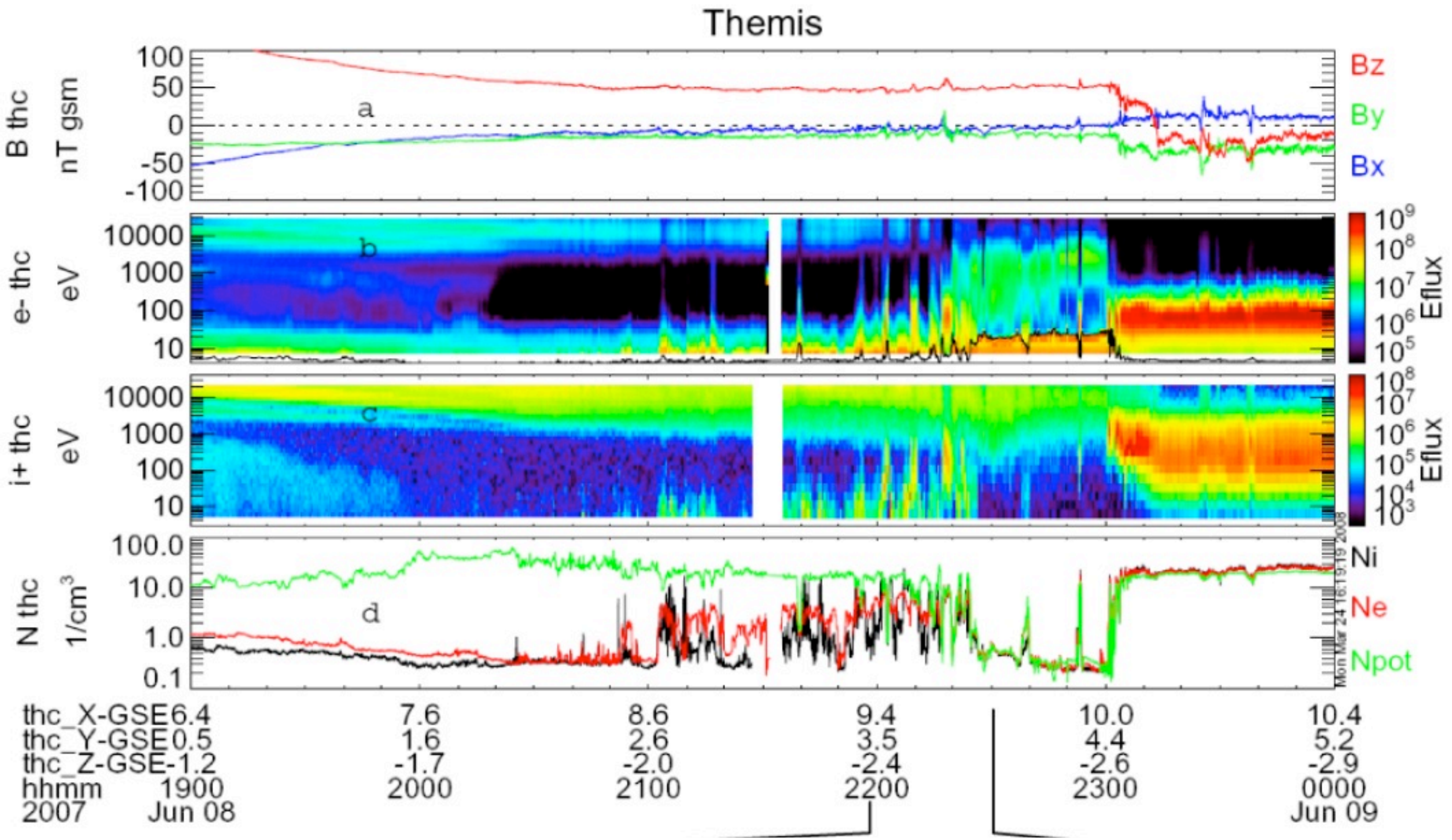
- Major types of ESA geometries and refinements
    - Cylindrical ESA's – less complicated setup, more difficult to measure full 3D distribution function due to narrow acceptance, but can be done with spinning spacecraft, multiple ESA etc.
    - Spherical ESA's (quadrispheric, hemispheric) – extends detector to two spherical surfaces to allow for trajectories more like great circle paths, can sample 2D particle distributions
    - Top-Hat ESA's – small analyzer section placed on top of deflection plates to help guide the particles into the plates → can scan wider range of angles



[Wuest et al 2007 Figure 2.33, from Carlson and McFadden 1998]

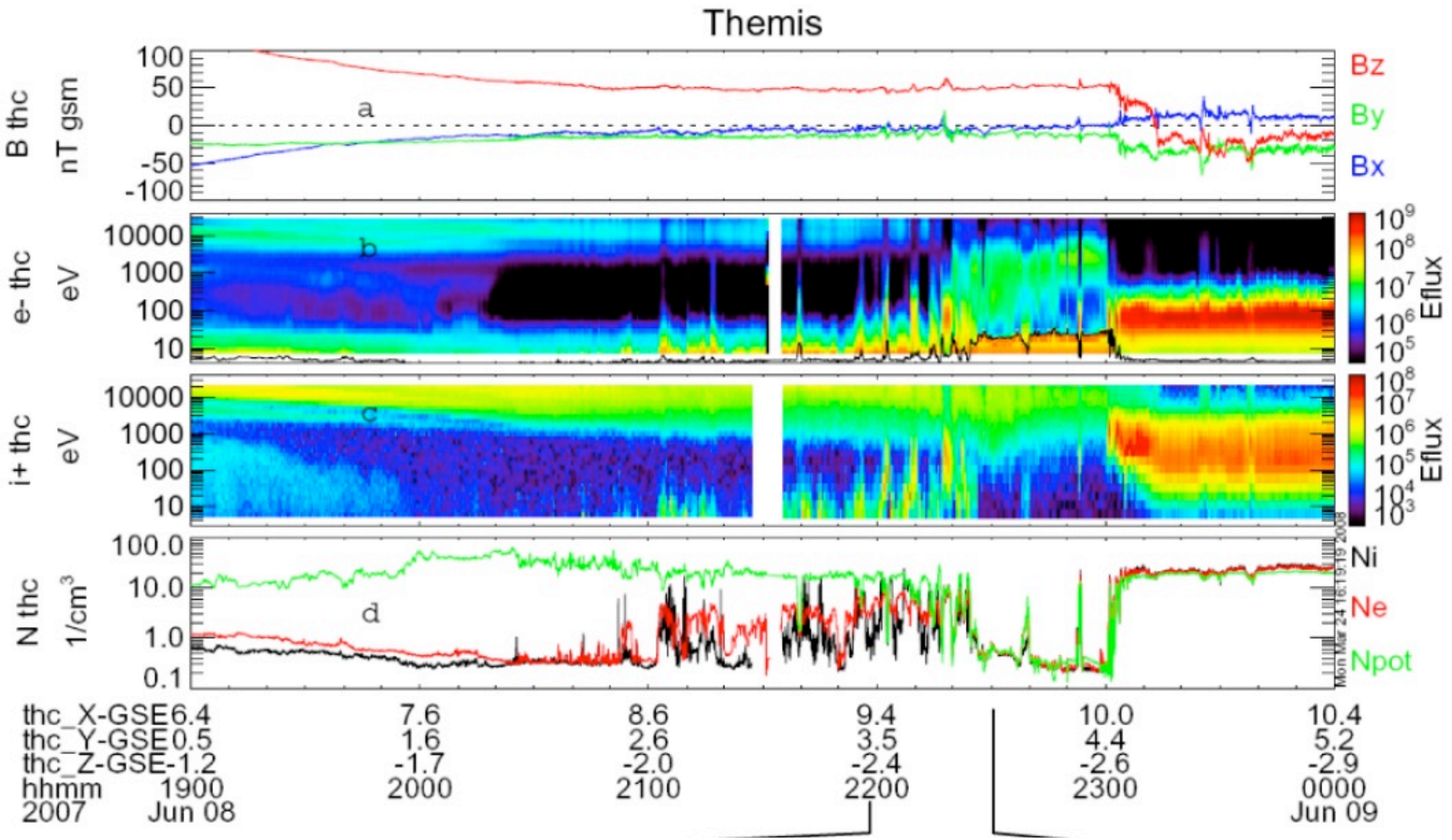
Common issues: detector range



[McFadden et al., 2008]

- ESA’s, like other instruments, are only designed to cover a certain range of energies, angles, frequencies, etc.
- Can you think of examples of how this might impact moments of the particle distribution (e.g., density, velocity)?

Common issues: detector range

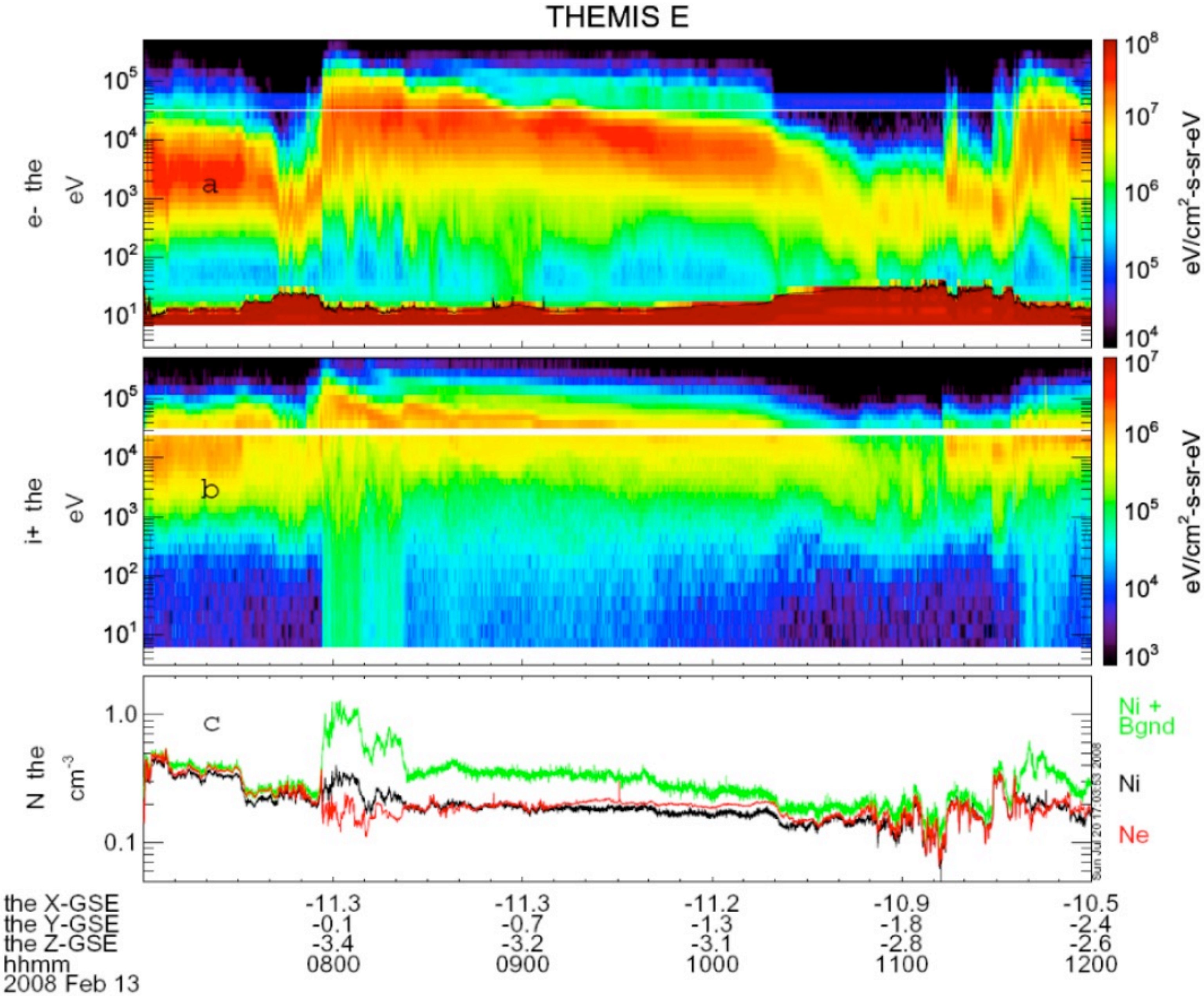


[McFadden et al., 2008]

- ESA’s, like other instruments, are only designed to cover a certain range of energies, angles, frequencies, etc.
- Can you think of examples of how this might impact moments of the particle distribution (e.g., density, velocity)?
- Example: THEMIS ESA is not designed to capture low energy plasmasphere population. This is reflected in a significant underestimate of the density moment in the plasmasphere and related cold plasma structures, based on comparisons with other density diagnostics (spacecraft potential inferred density)

Common issues: unwanted signals from environment

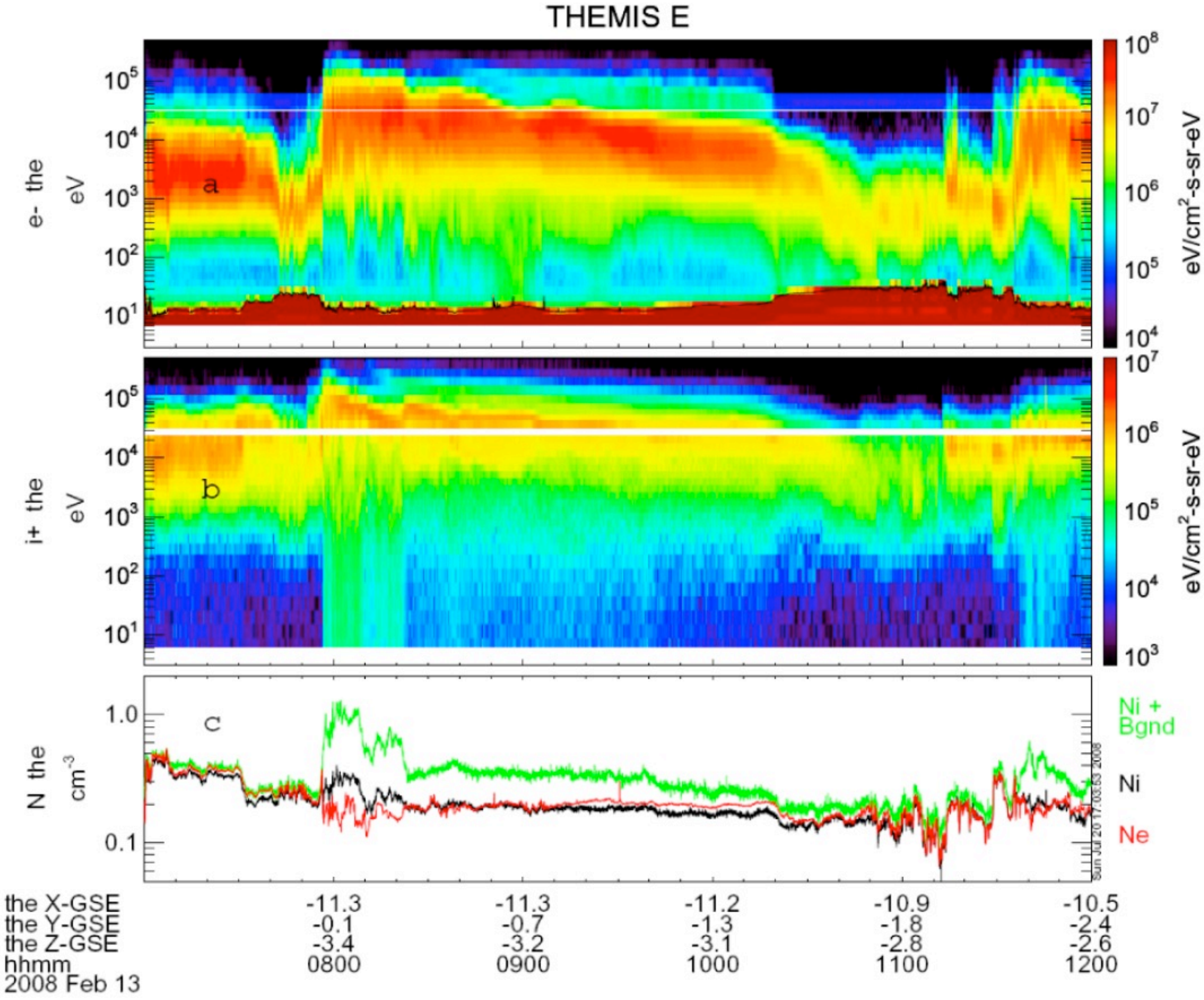
- ESA’s can pick up many undesired signals, including penetrating radiation
- Can you think of examples of how this might impact moments of the particle distribution (e.g., density, velocity)?



[McFadden et al., 2008]

Common issues: unwanted signals from environment

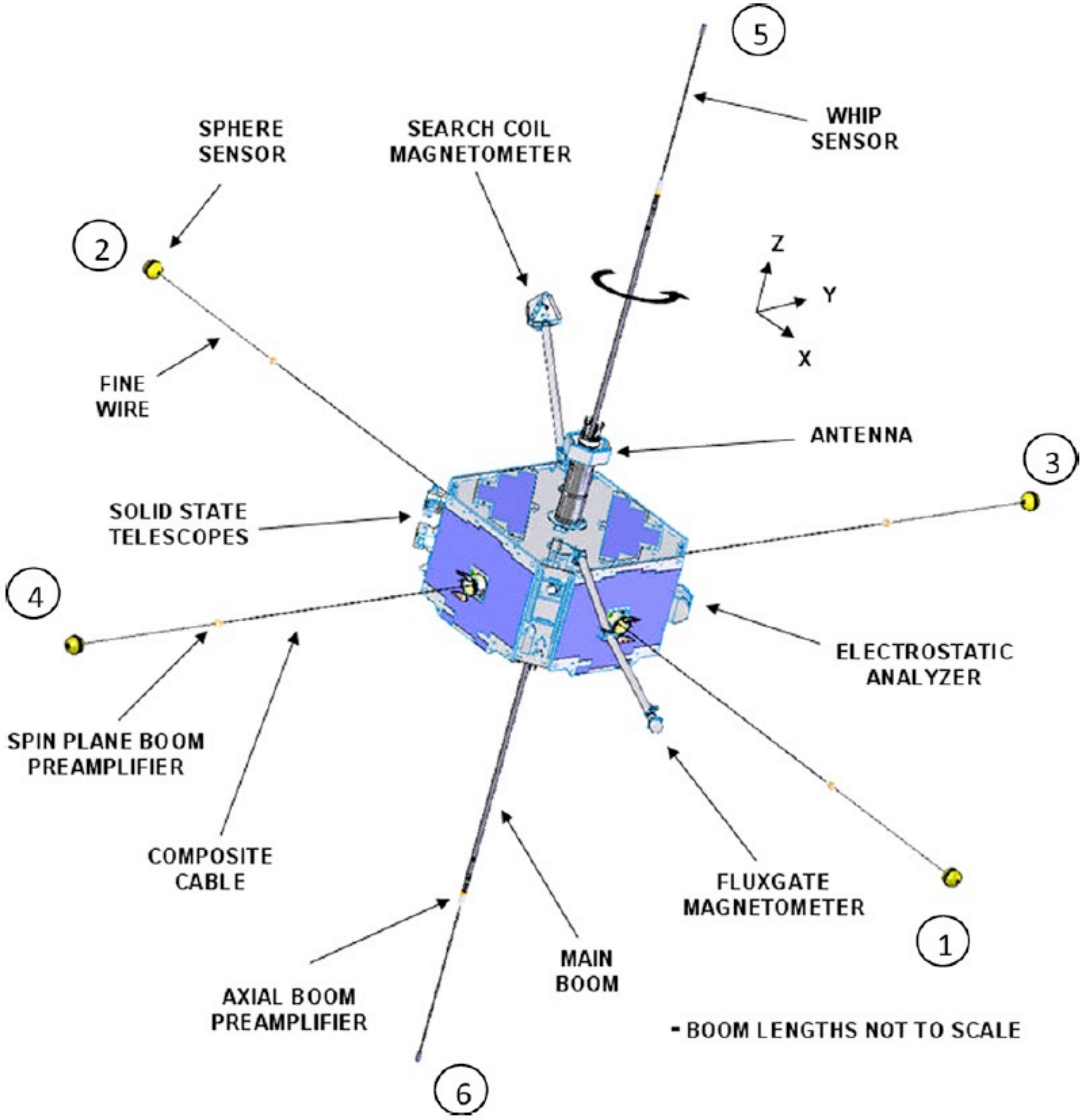
- ESA's can pick up many undesired signals, including penetrating radiation
- Can you think of examples of how this might impact moments of the particle distribution (e.g., density, velocity)?
- Example: When in an environment with significant energetic electron population, ion sensor records spurious counts due to Bremsstrahlung x-rays and/or secondary electrons can also produce spurious counts. This is reflected in, for example, a larger than expected ion density moment



[McFadden et al., 2008]

Summary of ESA’s

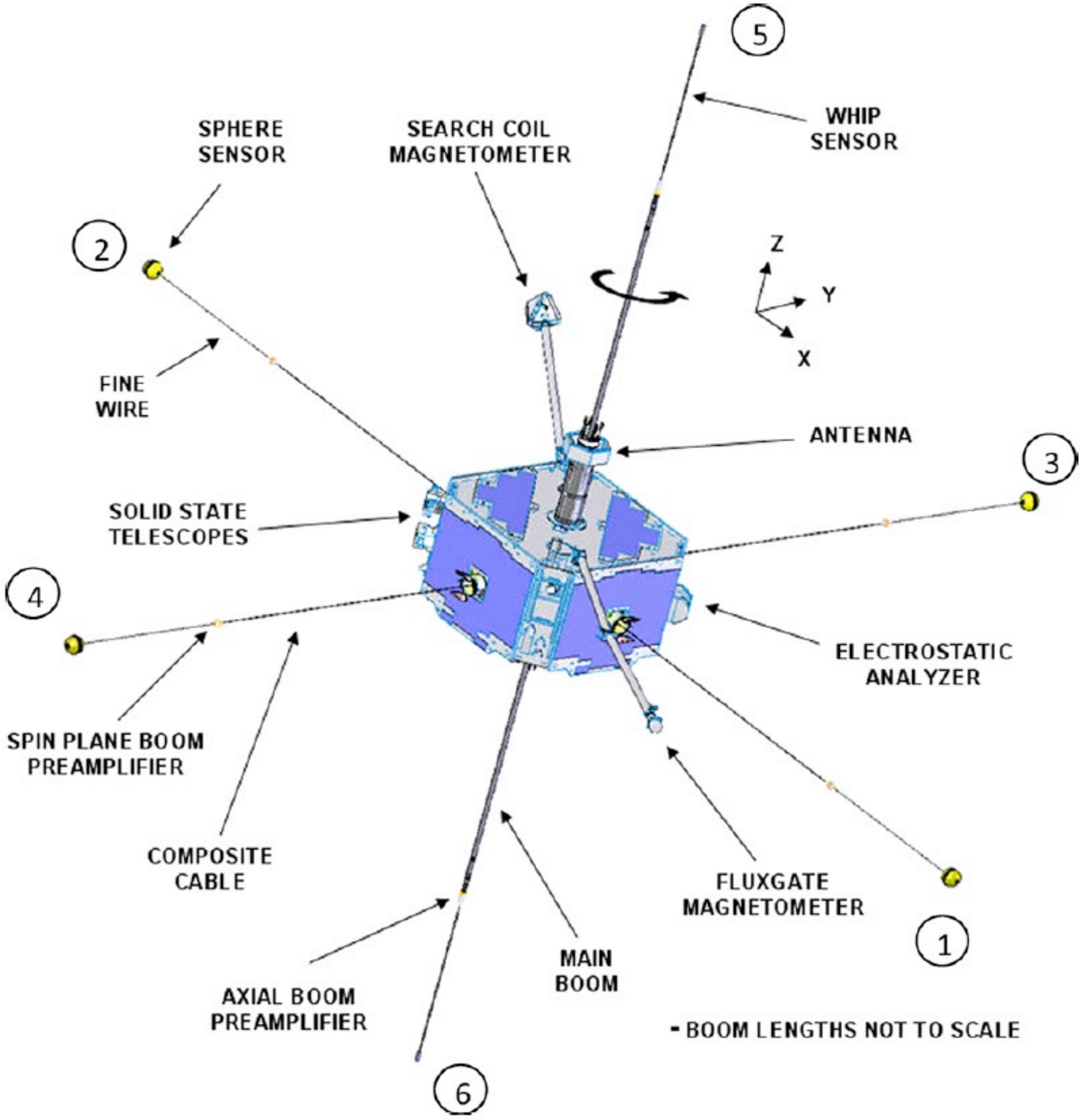
- Like magnetometers, ESA’s are versatile instruments used for a range of mission objectives
- Also like magnetometers, they come in many types and sub-types
- Common issues: detector range and unwanted signals from environment
- Common solutions: read the metadata, read the instrument paper, talk to the instrument team



[Schematic of THEMIS spacecraft from Bonnell et al., 2008]

Other particle instruments

- There’s not enough time to cover all particle instruments today
- Here’s a brief summary of many other types of particle measurements. Keep in mind there’s significant customization/sub-types not reflected in this list, and there are sometimes mixtures of instruments:
    - **Langmuir probes**
    - **Retarding potential analyzers**
    - **Magnetic spectrographs**
    - **Energetic neutral atom imagers** (remote sensing technique)
    - **Faraday Cups**
    - **Solid-state detectors**
    - **Plasma wave instruments** (infer density from characteristic frequencies)



[Schematic of THEMIS spacecraft from Bonnell et al., 2008]

Summary

- Brief overview of two widely used instruments in Heliophysics missions: magnetometers and electrostatic analyzers
- Used these as examples to cover several topics relevant to all instruments: data levels, noise, unwanted signals from data processing, instrument range of performance, unwanted signals from ambient plasma
- Please see other references (next slide) for further reading that covers other instruments as well as deeper dives into magnetometers and electrostatic analyzers
- **Note for future PI/instrument designers:** you have a lot of choices, but remember to always carefully trace from science objectives to measurements to instrumentation – see materials from NASA PI Launchpad workshop
- **Note to modelers/theorists/data analysts:** Data comes in many levels with many possible issues unique to the instrument/satellite mission/mode of operation/region of interest. Check for possible issues for the specific data product you're using by checking metadata, talking with instrument PI, etc

Further reading

- AGU Monograph: Measurement Techniques in Space Plasmas: Fields (eds R.F. Pfaff, J.E. Borovsky and D.T. Young)
- AGU Monograph: Measurement Techniques in Space Plasmas: Particles (eds R.F. Pfaff, J.E. Borovsky and D.T. Young)
- ISSI Scientific Report: Calibration of Particle Instruments in Space Physics (eds M. Wuest, D.S. Evands and R. von Steiger)
- Numerous instrument papers for specific missions. I drew heavily from the THEMIS mission instrument papers today:

Auster, H.U., Glassmeier, K.H., Magnes, W. *et al.* The THEMIS Fluxgate Magnetometer. *Space Sci Rev* **141**, 235–264 (2008). https://doi.org/10.1007/s11214-008-9365-9

Bonnell, J.W., Mozer, F.S., Delory, G.T. *et al.* The Electric Field Instrument (EFI) for THEMIS. *Space Sci Rev* **141**, 303–341 (2008). https://doi.org/10.1007/s11214-008-9469-2

Georgescu, E., Plaschke, F., Auster, U., Fornaçon, K.-H., and Frey, H. U.: Modelling of spacecraft spin period during eclipse, Ann. Geophys., 29, 875–882, https://doi.org/10.5194/angeo-29-875-2011, 2011.

McFadden, J.P., Carlson, C.W., Larson, D. *et al.* The THEMIS ESA Plasma Instrument and In-flight Calibration. *Space Sci Rev* **141**, 277–302 (2008). https://doi.org/10.1007/s11214-008-9440-2

McFadden, J.P., Carlson, C.W., Larson, D. *et al.* THEMIS ESA First Science Results and Performance Issues. *Space Sci Rev* **141**, 477–508 (2008). https://doi.org/10.1007/s11214-008-9433-1