Measuring the Auroral Ionosphere: Evaluation of Petite-Ion Probe RPA Performance on Multiple Rocket Missions

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Abstract

Observations of ambient ions in the auroral ionosphere can provide a more complete understanding of the underlying physics. In-situ observations of the aurora are often conducted with sounding rockets, which require an instrument package that can fit a small platform and be replicated for multiple subpayloads. Petite-Ion Probes (PIPs) are small retarding potential analyzers (RPAs) that determine thermal ion plasma parameters by using a swept screen voltage to select energies of ions entering the detector and reaching the anode. Thus, the PIP's data consists of a series of current vs voltage (IV) curves over time. Using the known PIP geometry and trajectory, PIP voltage sweep and payload attitude solution, we can model IV curves for a PIP on a payload charged to an assumed potential (Vs) in an assumed Maxwellian plasma, with some assumed ion temperature (T_i) and density (n_i) (Fraunberger et al. RSI, 2020). We use the Levenberg-Marquardt nonlinear least-squares minimization algorithm in the LMFit python library to find the values of ni, Ti and Vs that minimize the difference between the modeled and measured IV curves at a given time for an assumed relative velocity. Additionally, (near-)simultaneous IV curve measurements from two PIPs, separated azimuthally by a fixed angle, can be used to solve for the flow vector, given constraints from the scalar parameters. Thus, scalar and flow vector plasma parameters (T_i, n_i and payload potential) can be derived from PIP measurements.
Three recent sounding rocket missions carried PIPs: the May 2021 Kinetic-scale energy & momentum transport experiment (KiNET-X) launched from Wallops, the December 2021 Cusp Region Experiment 2 (C-REX-2) launched from Andoya, and the March 2022 Loss through Auroral Microburst Pulsations (LAMP) mission launched from Poker Flat. Each rocket carried eight main-payload-mounted PIPs onboard. KiNET-X also had two small, deployable subpayload instrument packages (Bobs) with two pips each.
Here we present the preliminary results from these three rocket missions as well as demonstrate the process of determining scalar and flow vector plasma parameters by fitting IV curves to combined simultaneous measured PIP IV curves with the KiNET-X data. Finally, we will discuss how to get the most information out of the PIPs measurements while minimizing the uncertainty in the optimized fitting process. This is considerably more difficult for PIPs on Bobs than for main-payload-mounted PIPs as a Bob's attitude must be determined separately and only two PIPs are carried on a Bob. However, the usefulness of multi-point measurements for many missions encourages us to reduce the uncertainty in PIPs measured plasma parameters so that we can more accurately interpret future Bob-carried PIPs' results, and support possible future multi-point sounding rocket missions.

Introduction

Motivation

- Determine thermal properties of a plasma's ions:
  - ion temperature (T_i)
  - ion density (n_i)
  - flow (v_{flow}) [= ExB]
- These are sensitive diagnostics of many aspects of the ionospheric plasma environment, including: ExB motion, sheath potential and ion inertial length.

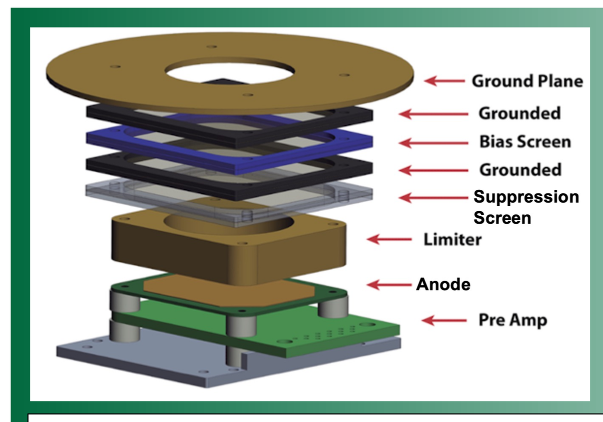


Figure 1. PIP diagram from (Roberts et al., 2017). (Note that present PIPs have a square aperture, not the pictured circular one.)

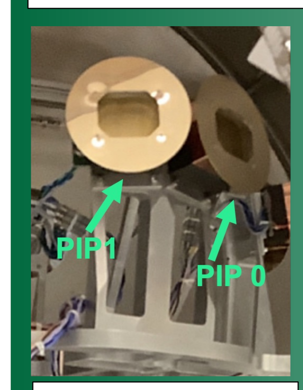


Figure 2. PIP pair mounted on deckplate.

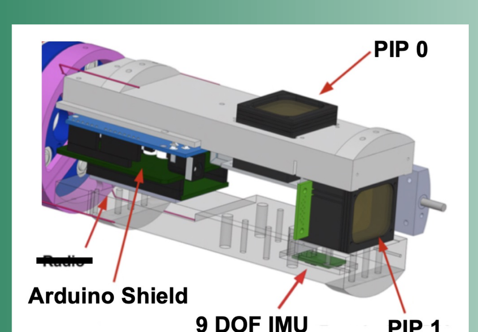


Figure 3. Diagram of PIP-Bob front-end assembly from (Roberts et al., 2017)

Instrument Design

- A Petite-Ion-Probe (PIP) is a small retarding potential analyzer (RPA) that measures anode current (I) from incoming ion flux as a function of screen voltage (V).
  - Voltage of screen is swept from 5V to 0V in 28 steps over 22ms (45 sweeps/second)
  - Ions reaching anode produce a current
  - Pre-amp board converts the measured current to a voltage, offset by 1V, and transmits data to shield
- Shield package:
  - A processor, consisting of an Arduino Uno with a custom "shield" board, connected to an IMU and two PIPs (designated PIP0 and PIP1)
  - Provides in-flight PIP & IMU control and data handling
- Sounding Rocket Mission Integration:
  - On the main payload, PIP0 and PIP1 are mounted at a fixed azimuth from each other to obtain the time-synchronized measurements necessary to determine (vector) flow.
  - A shield package can also be installed on an ejectable, called a PIP-Bob (Fig. 3)

PIP Data Analysis

- PIP data consists of a measured anode current vs the sweep voltage (IV) curve at each timestamp in datafile
- IV curves provide **coupled** information on:
  - ion density (n_i)
  - ion temperature (T_i)
  - payload potential (V_s)
  - flow velocity ($\mathbf{v}_{flow}$)
- Fig. 4 is a very rough indication of these plasma parameters effects on an IV curve.
- **Non-trivial** to determine and separate coupled thermal plasma parameters.
- Solution: forward model PIP IV curves to measured ones using the python LMFit library and PIP-axes attitude solution (Fraunberger et al., 2020).

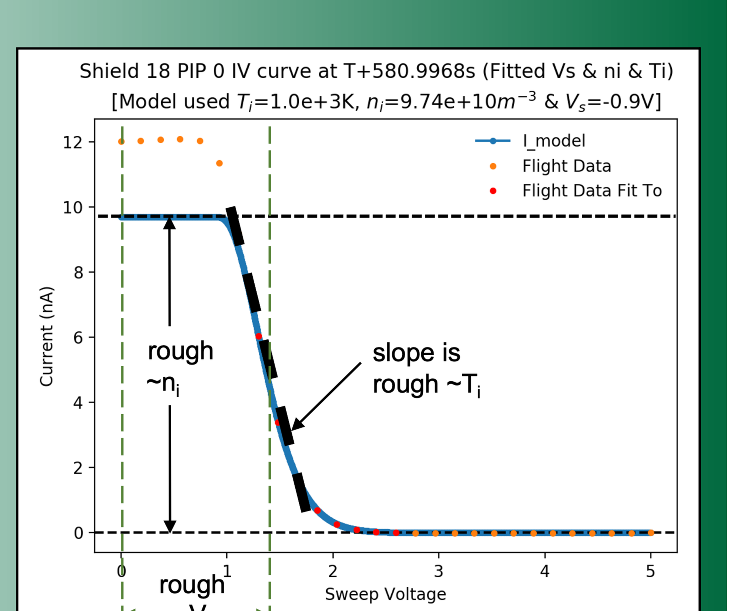


Figure 4. Annotated example of a measured and fitted IV curves.

PIP Attitude Solutions

- Need PIP's orientation with respect to ambient plasma in the East-North-Up (ENU) frame
  1. Express $\hat{q}_{PIP} = \cos\theta\,\hat{x}_{assembly} + \sin\theta\left(\cos\varphi\,\hat{y}_{assembly} + \sin\varphi\,\hat{z}_{assembly}\right)$, for q=x,y,z.
  2. Find the Direction-Cosine-Matrix (DCM) $\vec{M}$ at each time for the entire flight.
     - Main payload DCMs provided by NSROC for the flight.
     - PIP-Bob DCMs must be calculated from PIP-Bob IMU data.
  3. Rotate each PIP axis vector to the ENU frame: $\hat{q}_{PIP,ENU} = \vec{M}\,\hat{q}_{PIP}$

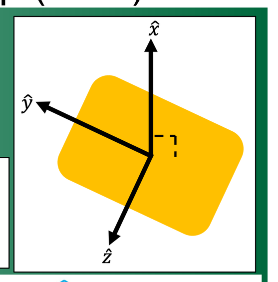


Figure 5. PIP axes (looking down on anode).

Determination of PIP-Bob DCMs

1. Calibrate magnetometer B-field data (i.e. decouple axes) with IGRF
2. Get spin (ψ), coning (θ) and precession ($\phi=\phi_{true}$-$\Delta\phi$) angles from measured B-field components.
3. Find $\Delta\varphi$ offset that minimizes the difference of the measured B-field from IGRF.
4. Construct the DCM from these Euler angles: ϕ_{true}(=ϕ-$\Delta\phi$), θ and ψ

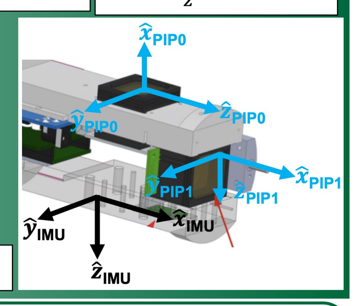


Figure 6. PIP-Bob's assembly & PIP axes.

Obtaining Angles from IMU Data

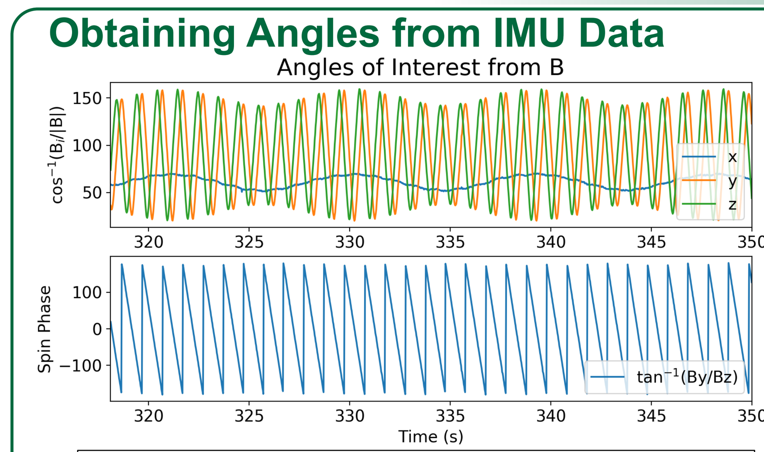


Figure 7. Angles determined for KiNET-X PIP-Bob16.

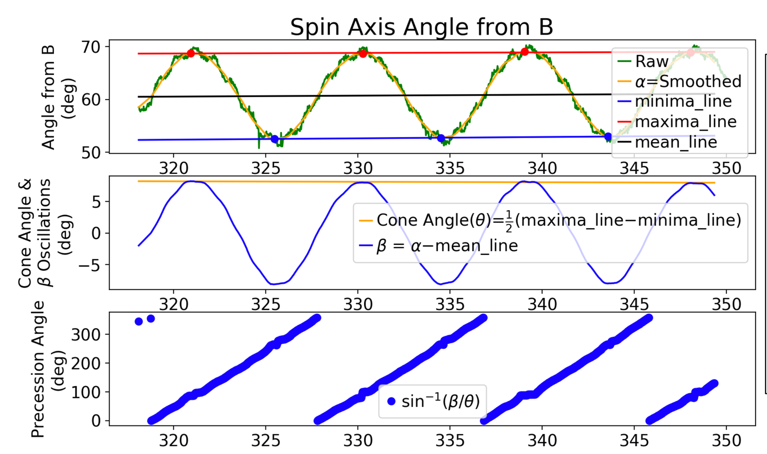


Figure 8. Coning and precession angles for KiNET-X PIP-Bob16.

Forward Modeling PIP Current

Model PIP Current

- General RPA anode current $I = \eta eAF \Leftrightarrow I = \eta e \int_0^h \int_0^w \int_{v_{z1}}^{v_{z2}} \int_{v_{y1}}^{v_{y2}} \int_{v_{x1}}^{v_{x2}} v_x f(\vec{v}-\vec{v}_D)\,dv_x\,dv_y\,dv_z\,dy\,dz$

- Corrections to RPA current equation for PIP from (Roberts et al., 2017):

Payload Charging In-Flight

- Payload sheath potential (V_s) further limits the parallel velocity distribution.

$$v_{x1} = v_c = \sqrt{2e(V_b+V_s)/m}$$

Sub-Sonic Impact

- Perpendicular velocity (v_y, v_z) distribution limited by PIP geometry & v_x

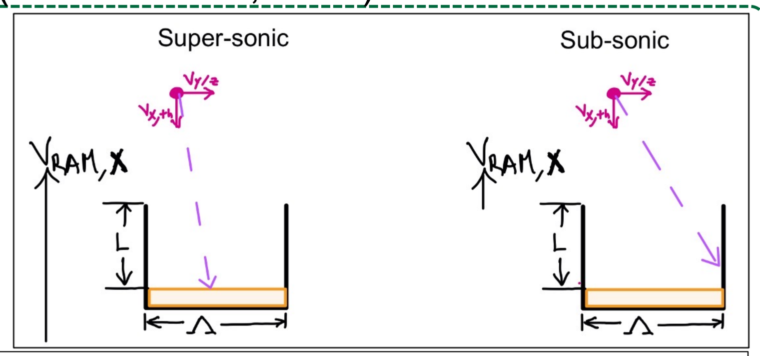


Figure 9. Illustration of the trajectory (purple) of a particle entering a PIP. (Based on figure in (Roberts et al., 2017).)

⇒ Model PIP current measured at a screen bias voltage V_b:

$$I = \eta e \int_0^h \int_0^w \int_{-z\frac{v_x}{L}}^{(h-z)\frac{v_x}{L}} \int_{-y\frac{v_x}{L}}^{(w-y)\frac{v_x}{L}} \int_{\sqrt{2e(V_b+V_s)/m}}^{\infty} v_x f(\vec{v}-\vec{v}_D)\,dv_x\,dv_y\,dv_z\,dy\,dz$$

PIP Data Fitting

- Goal: find $f(\vec{v}-\vec{v}_D)$ that gives best-fit curve to data using LMFit (Fraunberger et al., 2020).
- Modeling Assumptions:
  - Maxwellian distribution of O+ ions
  - Subtract any current offset in IV curve tail

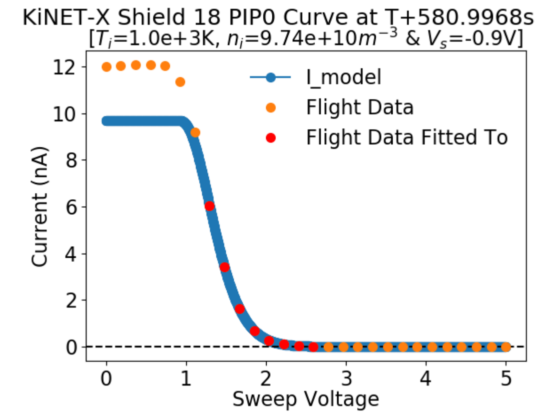
$$\vec{v}_D = \sum_{q=x,y,z} \hat{q}_{PIP}\left(-\hat{q}_{PIP,ENU}\cdot\left(\vec{v}_{flow,ENU}-\vec{v}_{RAM,ENU}\right)\right)$$

$$I_{fit}[V_b] = \eta e n_i \left(\frac{m}{2\pi k_B T_i}\right)^{\frac{3}{2}} \int_0^h \int_0^w \int_{v_{z1}}^{v_{z2}} \int_{v_{y1}}^{v_{y2}} \int_{\sqrt{\frac{2e}{m}(V_b+V_s)}}^{\infty} v_x \exp\left(-\frac{m}{2k_B T_i}|\vec{v}-\vec{v}_D|^2\right) dv_x\,dv_y\,dv_z\,dy\,dz$$

Scalar Fits

$$residual = \left|\frac{I_{true}[V_{b,min}:V_{b,max}] - I_{fit}[V_{b,min}:V_{b,max}]}{I_{error}}\right|^2$$

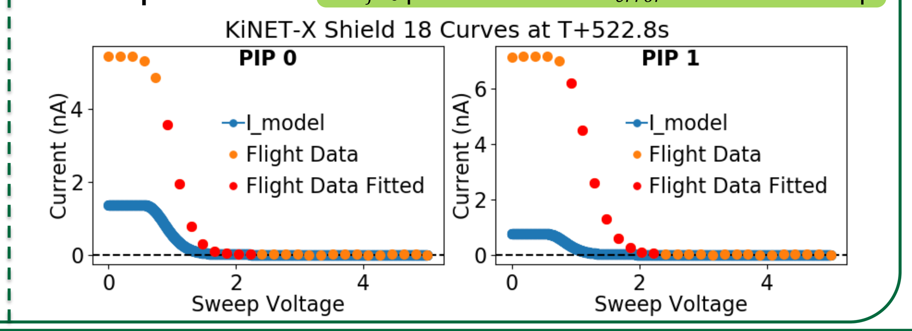
- Set $\mathbf{v}_{flow}$= 0 or constant
- Find n_i, T_i & V_s that minimize residual



Flow Fits

- Set n_i, T_i & V_s values with another data set.
- Find $v_{flow,East}$, $v_{flow,North}$ & $v_{flow,Up}$ that minimize the residual for a PIP-pair

$$\sum_{j=0}^{1}\left|\frac{I_{pipj}[V_{b,min}:V_{b,max}] - I_{fitj}[V_{b,min}:V_{b,max}]}{I_{error}}\right|^2$$



PIP Observations from Missions

Description of Missions

- KiNET-X (Wallops, May 2021):
  - PIPs on main payload deckplate
  - two PIP-Bobs ejected
  - two Barium releases from rocket.
- CREX-2 (Andoya, December 2021): PIPs on main payload boom
- LAMP (Poker Flat, March 2022): PIPs on main payload deckplate

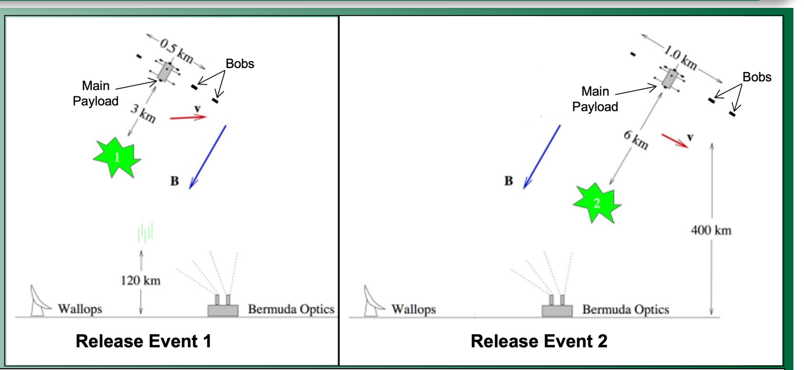
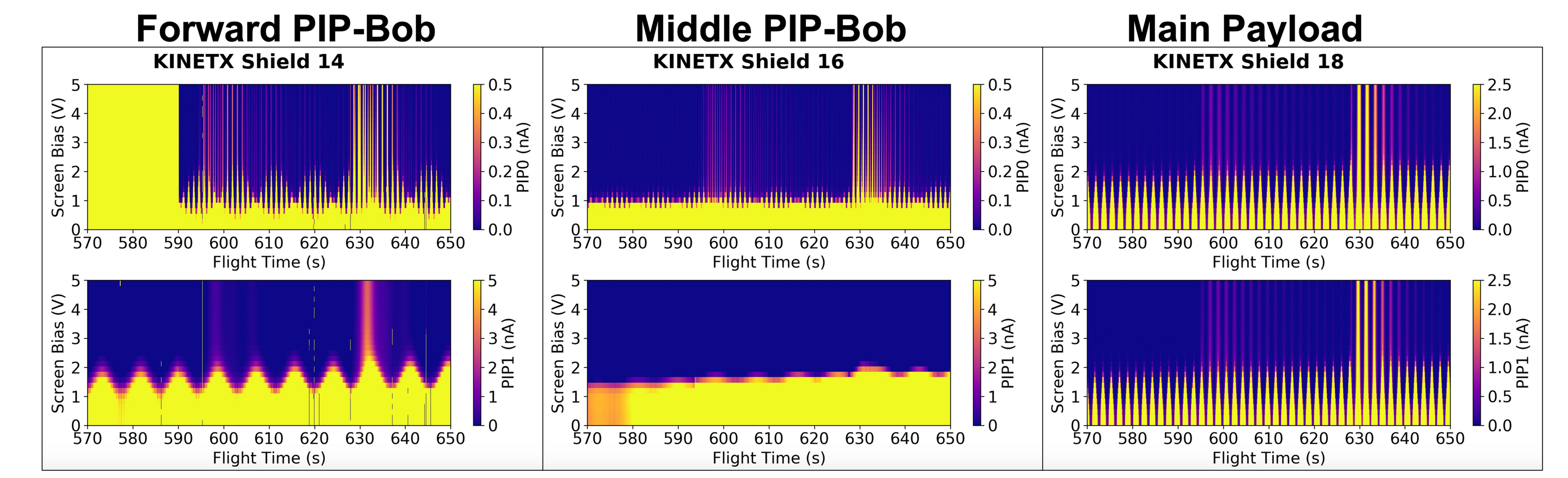


Figure 10. KiNET-X instrumentation & release geometry. (Modified version of figure from P. Delamere.)

KiNET-X Multipoint PIP Measurements

Figure 11 KiNET-X distributed PIP measurements.



Main Payload Data vs Attitude

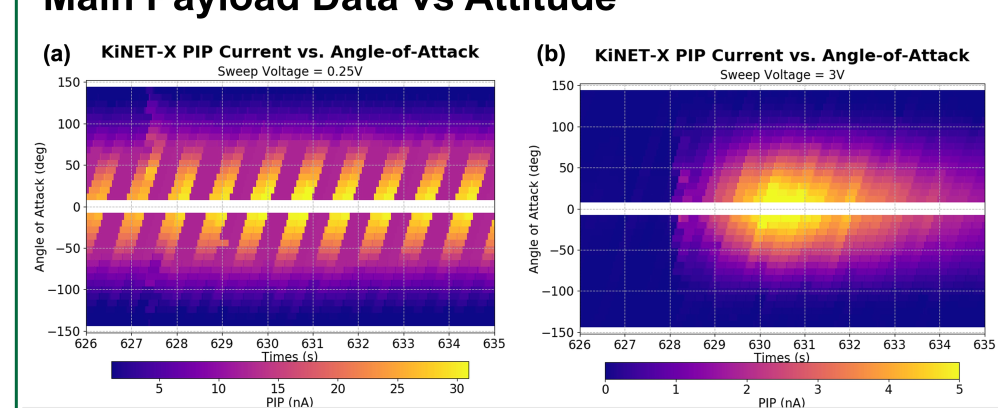


Figure 12. PIPograms for 2nd Barium release (T+600) at screen bias (a) 0.25V and (b) 3V. (AoA grid: −152° to 160° in 8° bins).

Link 1: PIPograms from other missions.

Fitted PIP Data

Link 2: Flow fit plots.

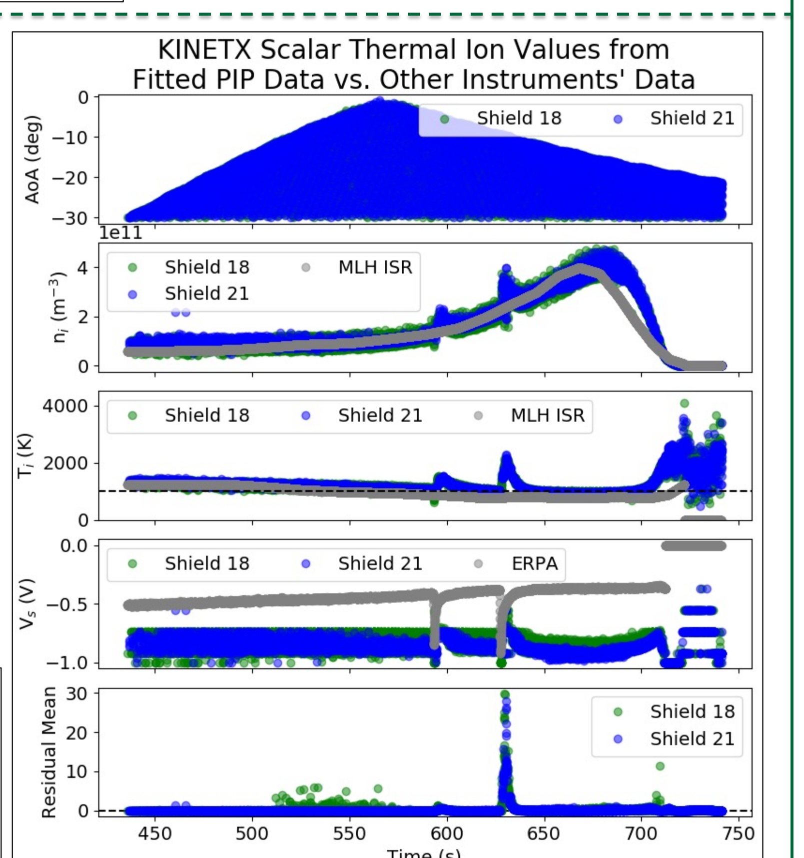


Figure 13. Scalar fit of ion density (n_i), ion temperature (T_i) and payload potential (V_s) to Shield 18 and 21 data along with altitude-interpolated ion temperature and density (n_i = n_e) from Millstone Hill ISR slant beam (collected near T0), and payload potential (V_s=5T_e[eV]) from onboard ERPA. (Note only plot fitted data with −30° ≤ -|AoA| and 0 ≤ mean residual ≤ 100.)

Future Work

- Improve flow fitting algorithm.
- Finish the PIP-Bobs attitude solution
- Start scalar and flow fitting to the KiNET-X PIP-Bob, CREX-2 and LAMP data.
- Investigate the scientific implications of these KiNET-X data.

References and Acknowledgments

Fraunberger, Lynch, et al, "Auroral Ionospheric Plasma Flow Extraction using Subsonic Retarding Potential Analyzers", Rev Scientific Instr., 2020, DOI: 10.1063/1.5144498.

Roberts, T. M., Lynch, K. A., et al, "A small spacecraft for multipoint measurement of ionospheric plasma" Rev. of Scientific Instr., 2017, 88(7):073507.

NASA LCAS Sounding Rocket Program; NSROC Personnel at Wallops Island

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