PROBING THE SOLAR WIND USING AKATSUKI RADIO SIGNALS

Keshav Aggarwal[1*], Raj Kumar Choudhary[2], Abhirup Datta[1], Takeshi Imamura[3]

[1]Indian Institute of Technology Indore, Khandwa Road, Simrol, MP
[2]SPL, VSSC, Thiruvananthapuram, Kerala
[3]Graduate School of Frontier Sciences, The University of Tokyo, Kiban-tou 4H7, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan

Abstract

We present an analysis of solar wind dynamics based on Doppler spectral width measurements of X-band radio signals from the Japanese Akatsuki spacecraft. The dataset includes two solar conjunction occultation experiments conducted in 2016 and 2022, capturing the transition from the descending phase of Solar Cycle 24, a period of low solar activity, to the ascending phase of Solar Cycle 25, which exhibited moderate to intense activity. Our study demonstrates the utility of this technique for estimating both slow and fast solar wind velocities across different phases of solar activity. A key focus is the 2022 experiment, which probed the solar corona near coronal holes at heliocentric distances ranging from 1.4 to 10 $R_\odot$. We also investigate the impact of electron density estimates on the accuracy of solar wind speed determinations, underscoring the need for improved electron density modeling to enhance the robustness of such measurements.

Introduction

The solar wind is primarily driven by the high temperatures and magnetic dynamics of the solar corona, where magnetic energy is converted into kinetic energy via MHD waves and open field line topologies that allow plasma to escape, forming high-speed streams. These streams, especially from coronal holes-low-density, magnetically open regions visible in EUV and X-ray as dark patches-can induce recurrent geomagnetic disturbances through Corotating Interaction Regions (CIRs), particularly during solar minima when polar coronal holes dominate. Coronal heating remains a significant contributor to wind acceleration in the 2-10 $R_\odot$ range [4, 3]. Radio occultation (RO), especially using S- and X-band signals, has proven essential in remotely probing the coronal plasma's structure, turbulence, and solar wind properties by measuring phase and amplitude scintillations caused by electron density fluctuations. We utilize X-band (8.41 GHz) RO data from the Akatsuki spacecraft during 2016 and 2022 to estimate solar wind velocities between 1.45 and 10 $R_\odot$, capturing both slow and fast wind streams, including those influenced by equatorial coronal holes during the "Smiley Sun" event in October 2022 [2].

Akatsuki Mission Parameters

Mission Parameters

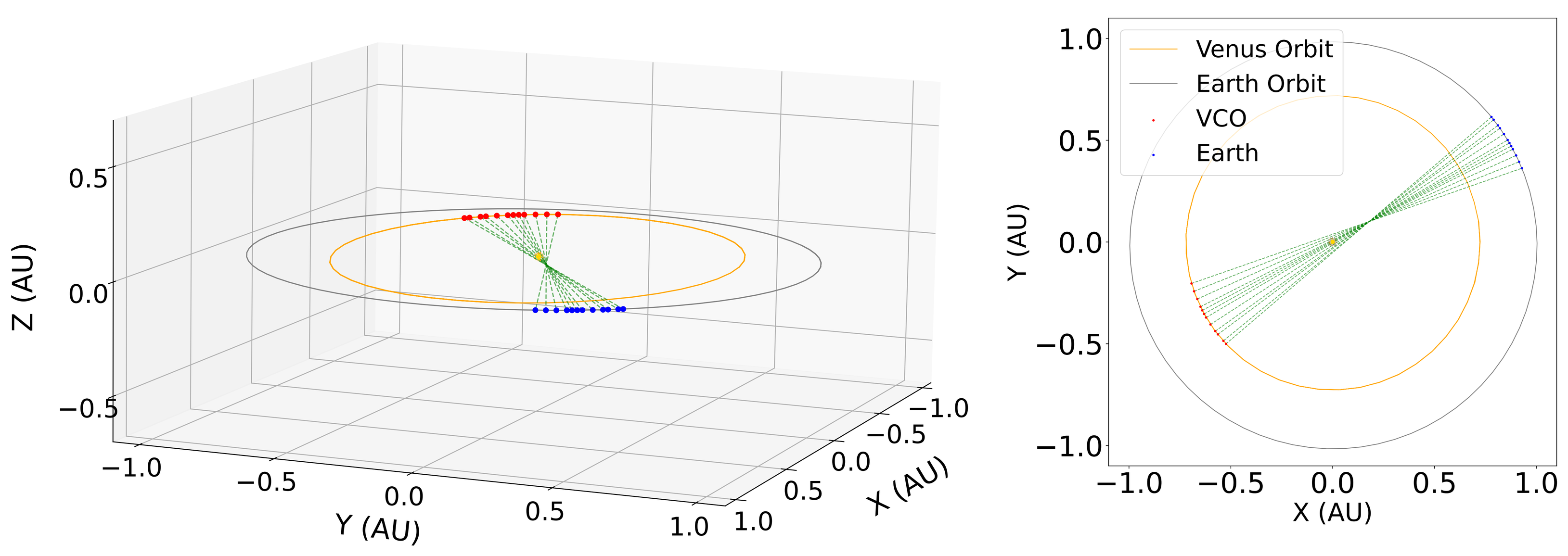
Parameter	Value
Launch Date	20 May 2010
Venusian Orbit Insertion	7 December 2015
Planned Mission Duration	2 years
Duration of Operations	13 years, 11 days
Apoapsis	∼360,000 km
Periapsis	400 km
Orbital Period	∼11 days
Inclination	∼3°

Antenna Parameters

Parameter	Value
Diameter	1.6 m High Gain Antenna
Operating Frequency	8.41 GHz
Power Requirement	20 W DC Power
Beamwidth	±2°
Peak Gain	35 dB

Radio occultation experiment

In this study, we demonstrate the versatility of our technique developed in [1] by applying it to two contrasting observational periods: one characterized by low solar activity and slow solar wind speeds, and another associated with a coronal hole region exhibiting enhanced activity and fast solar wind. Although the spectral width method was originally developed for S-band radio signals, it remains applicable to X-band signals, such as those from the Akatsuki probe, after appropriate adjustments for the 2016 slow solar wind conditions [2]. For the 2022 observations near the coronal hole regions, a scaling factor was applied to the electron density estimates, highlighting the strong dependence of solar wind speed estimates on the local plasma density.



1. Left panel: Schematic representation of Akatsuki-Venus-Sun-Earth geometry during radio occultation experiments. The blue points represent Earth's positions during 22-31 August 2022, while the red points represent positions of the Venus/ VCO with respect to the Sun and Earth during that period. The Left panel shows the geometry in the three-dimensional plain while the right panel shows its top-down view.

The methodology outlined in [1] is adopted here for X-band analysis which is as follows :

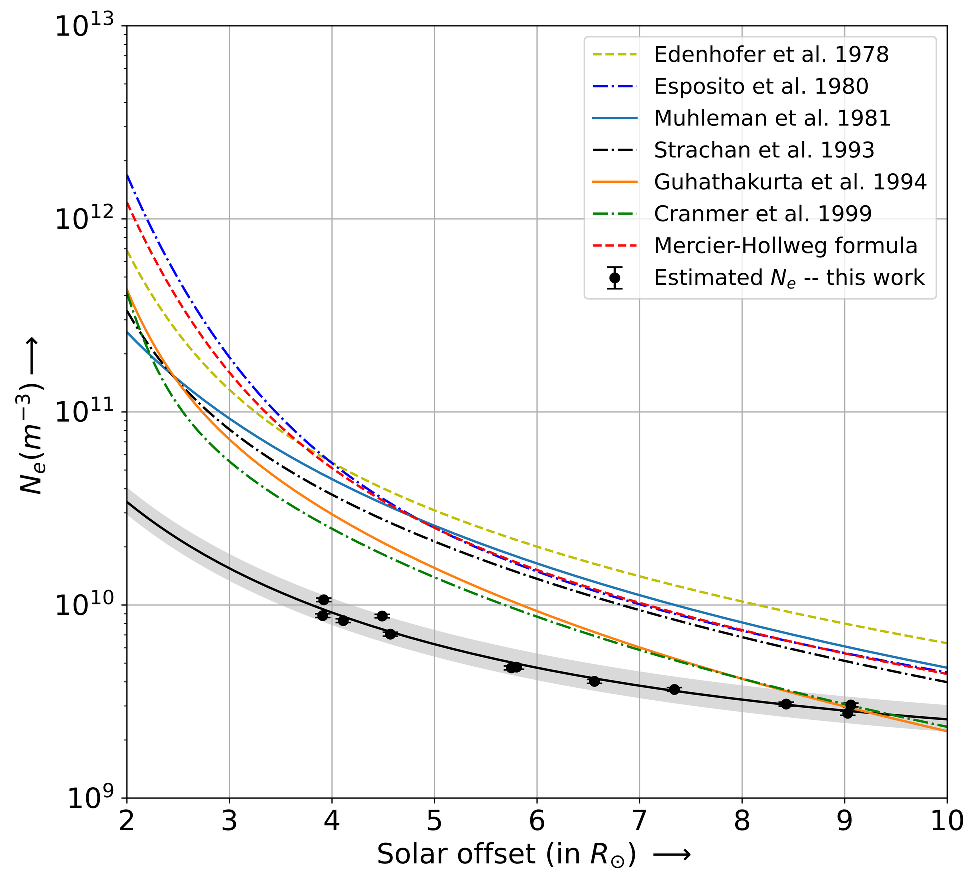
- Calculate the spectral broadening in the received signal and the geometry parameters.
- Assume the density fluctuation spectrum follows a single power law with spectral index $p = 11/3$.
- Estimate electron density N_e using the empirical relation.
- Derive solar wind velocity $v_\perp$ perpendicular to the radio LOS, using the measured spectral bandwidth and estimated N_e.

The solar wind bulk velocity component perpendicular to the LOS can be estimated from the observed spectral broadening of the received signal using the following empirical relation:

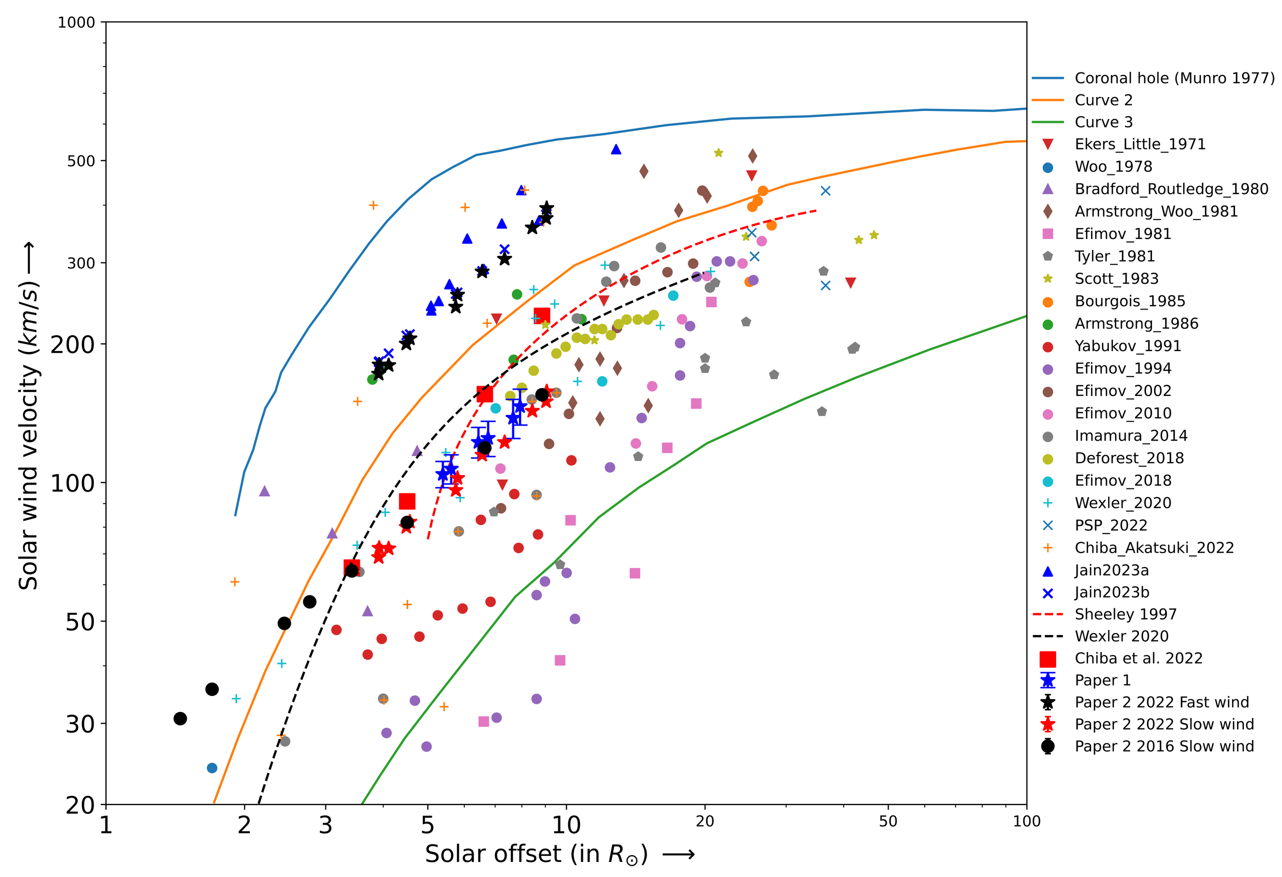
$$v_\perp = k_0 \left[\frac{r \times R_{\mathrm{EP}} \times (1 + R_{\mathrm{SP}})^2}{R_{\mathrm{SP}}} \right] B_S^{\frac{1}{6}} \quad (1)$$

where $v_\perp$ is the solar wind speed component perpendicular to the LOS, B_S is the spectral broadening (in Hz), and r is the solar offset distance—defined as the distance of closest approach to the Sun along the LOS. The constant $k_0 = 1.687$; R_{EP} is the distance from the probe to Earth; and R_{SP} is the distance between the Sun and the probe, expressed in AU.

Results



2. Electron density estimates for the 2022 solar occultation experiment compared against other models in the literature.



3. Our results compared against the solar wind measurements done across a period of more than 50 years, using a variety of methods from in-situ to remote sensing observations.

Conclusions

- Although the spectral width method was originally developed for S-band radio signals, it remains applicable to X-band signals, such as those from the Akatsuki probe, after appropriate adjustments for both the 2016 slow solar wind conditions as well as the 2022 coronal hole regions [1].
- The velocities of solar wind derived in the presented radio occultation study agree with previously reported values (ref to fig 3), and show the acceleration of the solar wind in the Middle Solar Coronal region as well.

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About me:
I am a Ph.D. student under the supervision of Prof. Abhirup Datta at the Department of Astronomy, Astrophysics and Space Engineering (DAASE), Indian Institute of Technology Indore (IIT Indore). I have been awarded the prestigious Prime Ministers Reseach Fellowship (PMRF) for pursuing my doctoral studies. While my present work involves studying the Sun using radio occultation data from the Indian Mars Orbiter Mission, I am interested in planetary and exo-planetary sciences as well.