Interplanetary scintillation measurements of the solar wind: A complementary tool for STEREO studies of the inner heliosphere

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Probing the 3-D heliosphere - the present

In-situ

- Absolute measurement of parameters at known time and location
- No way of distinguishing spatial and temporal variations (without multiple spacecraft)
- Measurements of solar wind parameters (V, N, "T", composition) made directly
- Limited coverage:
  - No measurements inside 60 R
  - Only one set of high-latitude measurements

Direct measurements of solar wind parameters, but poor spatial coverage

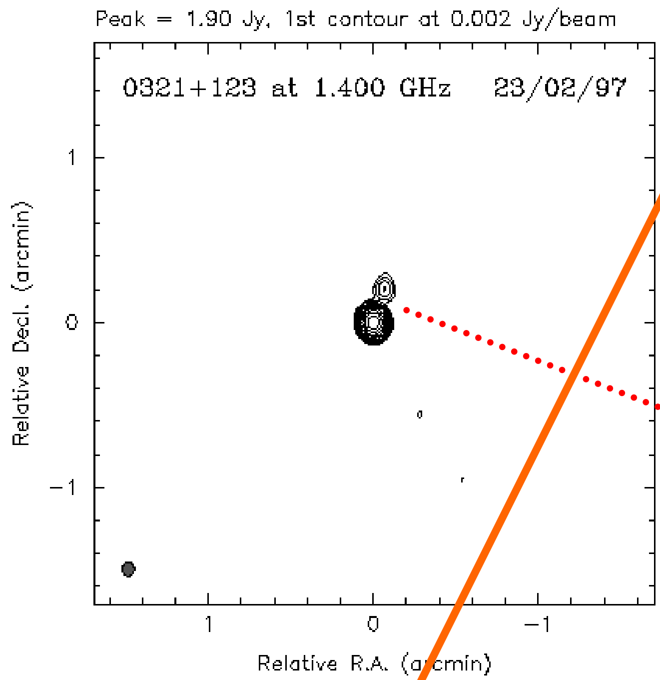
Remote-sensing

- Measurements integrated along extended ray-path
- Difficulty in resolving contributions from different parts of the ray-path
- Solar wind parameters must be derived from observed parameters:
  - sensitivity to assumptions made or model used
- Very good spatial coverage:
  - Can observe solar wind at any latitude
  - Observations available covering a wide range of distances from the Sun

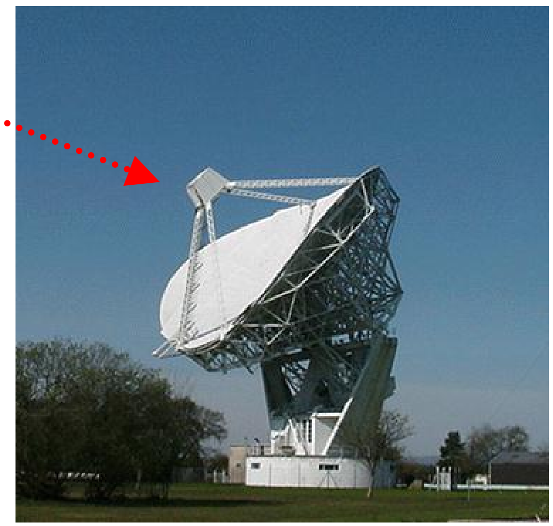
Good coverage of inner heliosphere, but needs care in interpretation

Temporal resolution often worse than in-situ measurements

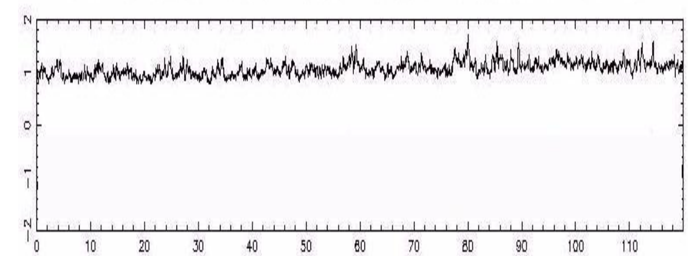
Interplanetary scintillation (IPS)

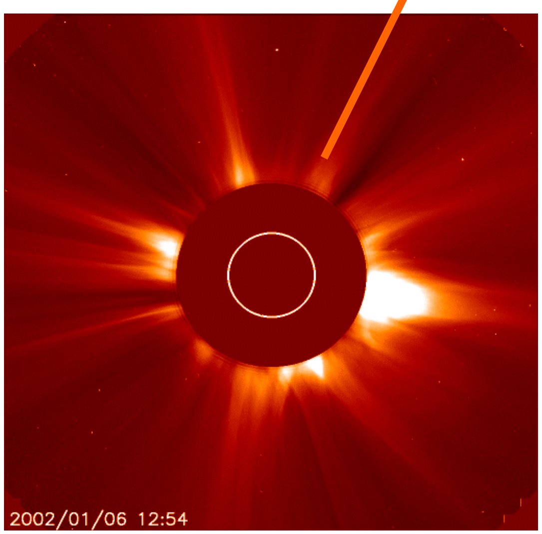


- Compact radio source observed when it lies close to the Sun in the sky
- Phase changes introduced by turbulent-scale density irregularities in solar wind (~100 km)



- Phase changes gradually converted to amplitude variation by constructive and destructive interference



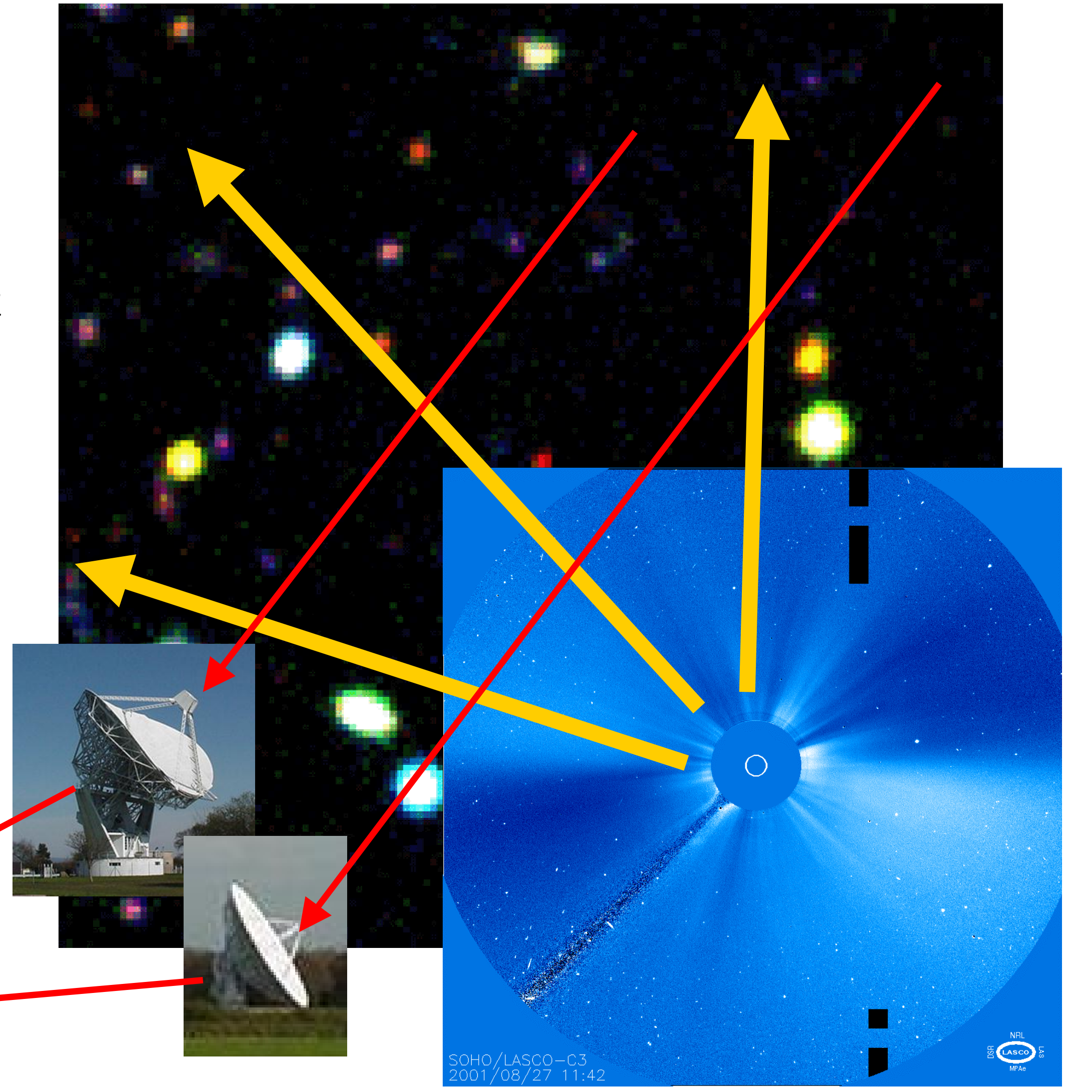


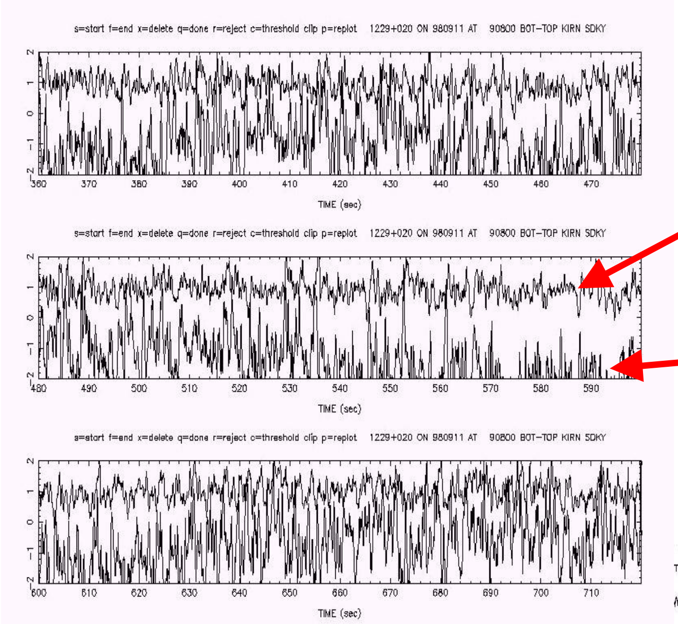
- RMS variation in power roughly $\propto N_e^2$
- Spectrum of IPS can be used to estimate velocity of irregularities

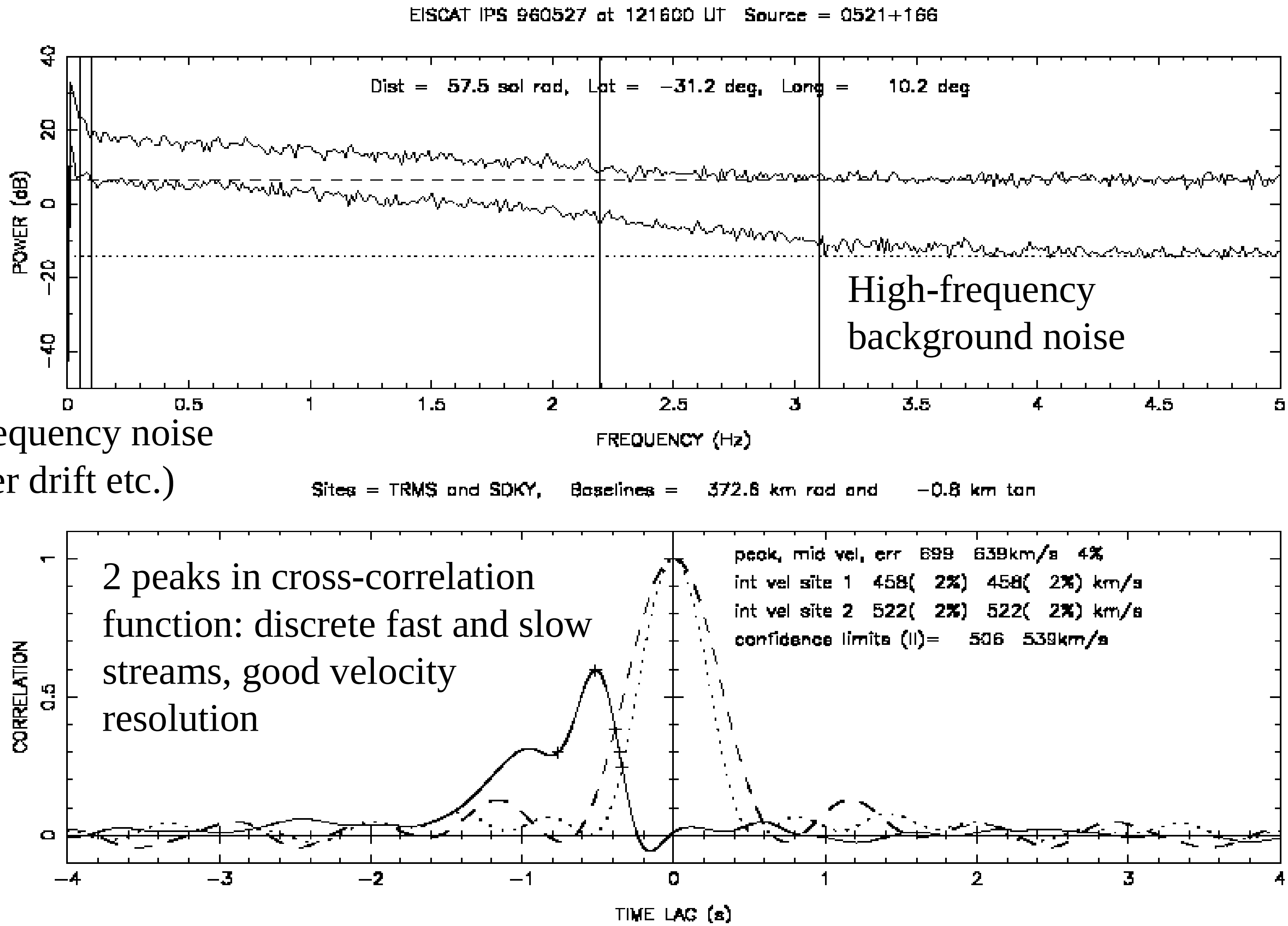
1st STEREO workshop

2-site IPS

- Diffraction pattern sampled with two suitably spaced radio telescopes
- Comparison of scintillation pattern observed at the two sites gives 2 auto-spectra, one cross-spectra
- Time-lag for maximum cross-correlation between scintillation patterns gives direct (first-approximation) estimate of outflow speed







High-frequency background noise

Low-frequency noise (receiver drift etc.)

2 peaks in cross-correlation function: discrete fast and slow streams, good velocity resolution

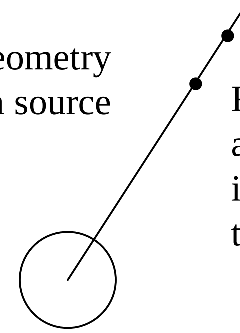
IPS measurements - single site vs. multi-site

Single-site

- Can make measurements whenever a suitable source lies close to the Sun in the sky and in the field-of-view of the antenna
- No restrictions on observing times from system geometry
- Measurements provide single auto-spectrum
- Many more measurements possible
- Less information from each measurement

Multi-site

- Can only make measurements when the geometry of the source, the Sun and the antennas is favourable
  - Require ray-paths from source to antennas to lie in same radial plane which passes through centre of Sun

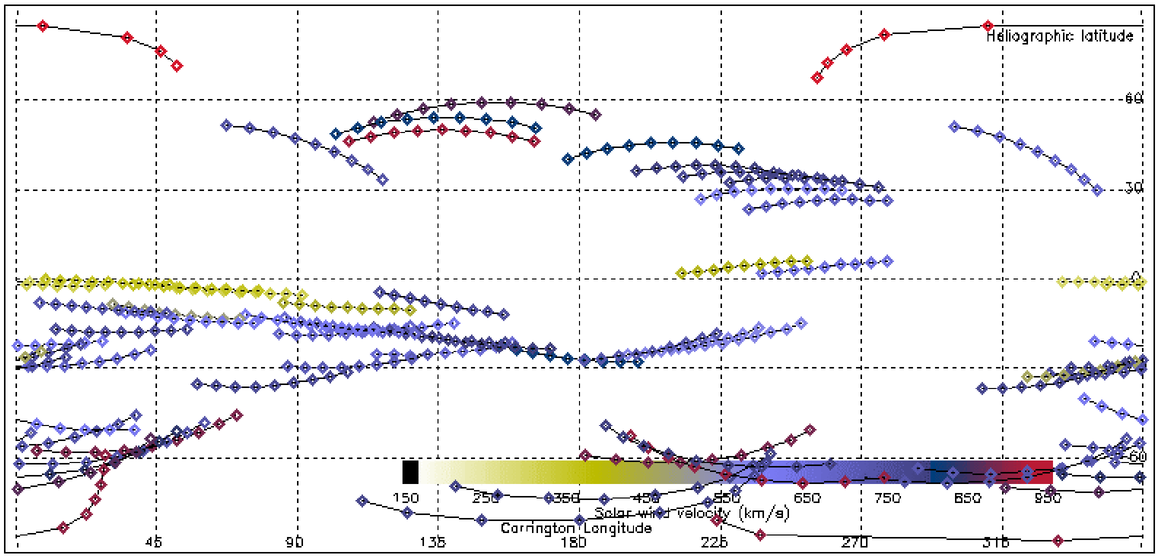


- Measurements provide 2 auto-spectra, one cross-spectra
- Fewer measurements possible, but more information from each observation

Interpretation of IPS results

- IPS measurements are made up of contributions from the whole of the ray-path through the solar wind from the source to the receiver
- As there is usually more than one speed of solar wind across the ray-path the first estimate of velocity will be "blurred" - *"Classical" IPS (from 1962 to ~1993) suffered from this limitation*
- Since 1993 two techniques have been developed to remove this limitation and get a much "sharper" view of the solar wind:

    - Long-baseline IPS (UCSD and Aberystwyth, data from EISCAT, VLBA)
        - Velocity resolution improves when antenna separation larger (> 200 km)
        - Known association between dark (low-density corona) and fast wind
        - Map IPS ray-paths down to coronal heights, identify regions likely to be immersed in fast flow
        - Fit data using 2-velocity model
    - Tomographic reconstruction of the solar wind from multiple overlapping IPS measurements (Nagoya STELab and UCSD, data from Toyokawa)



1996

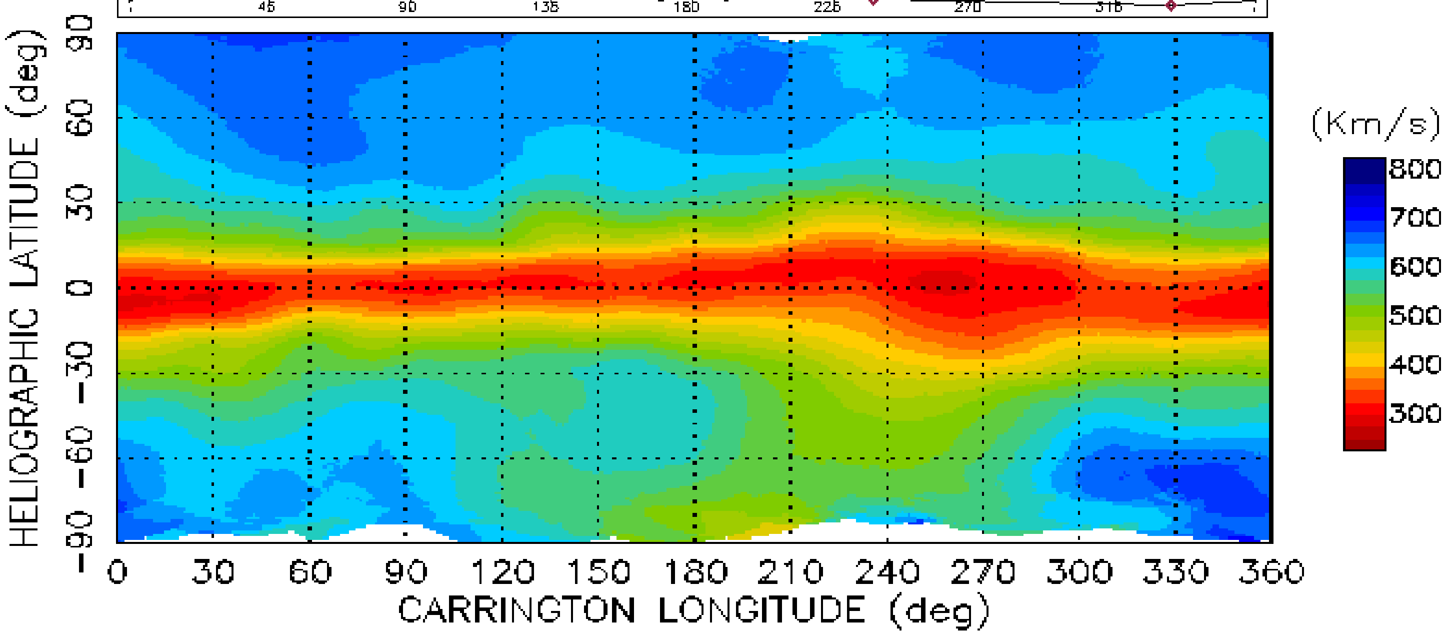
EISCAT: 933.5 MHz

Heliocentric distances of 15-85 R

May-October

Mapped ballistically to 215 R

Large polar fast streams, narrow and slightly twisted belt of slow wind above equator

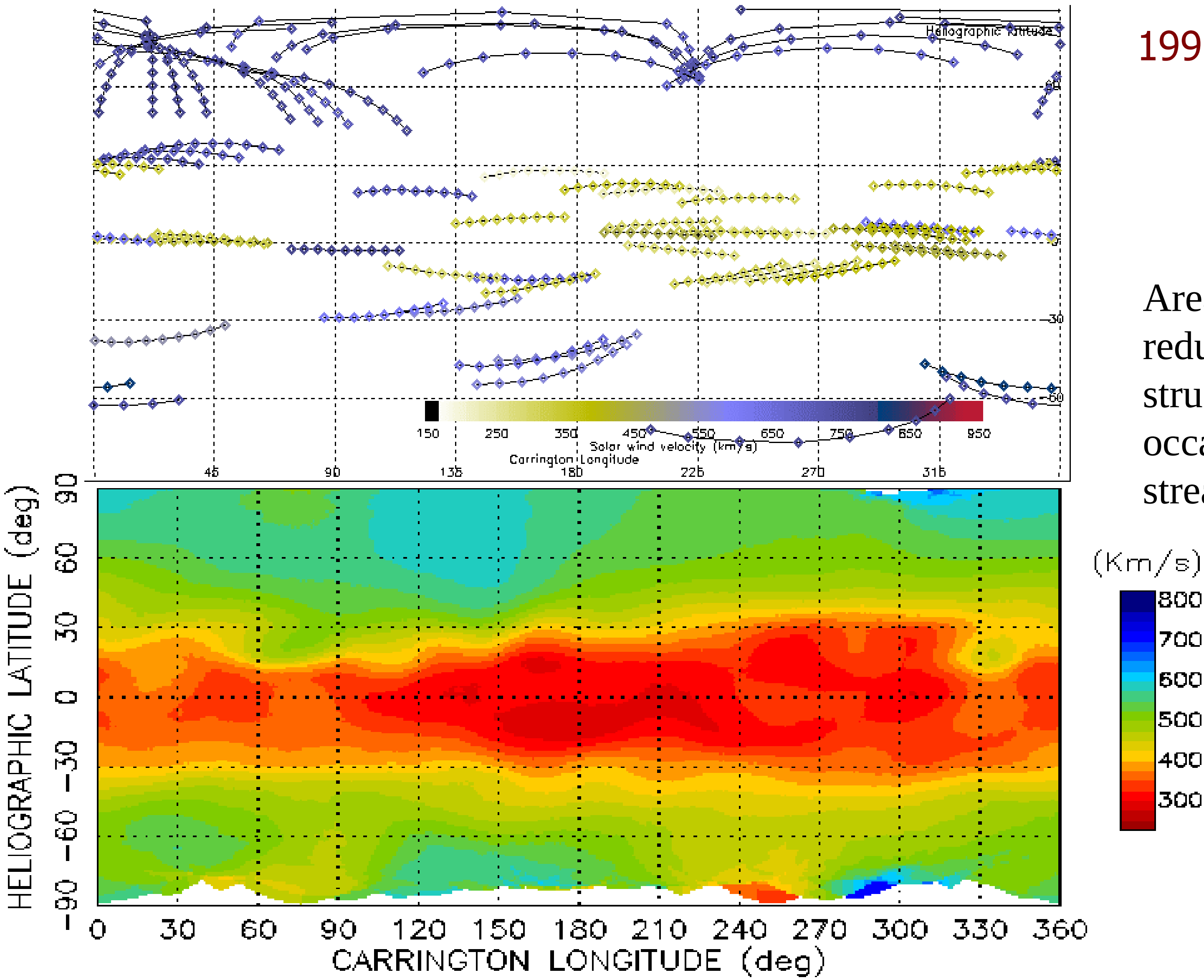


Toyokawa: 327 MHz

Heliocentric distances of ~45 -150 R

May-October

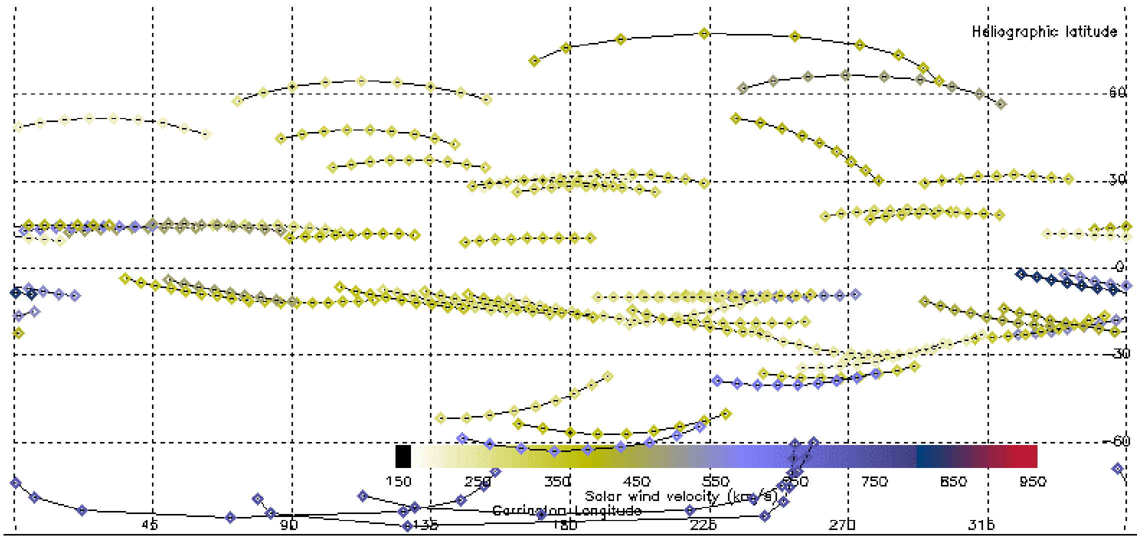
Mapped ballistically to 2.5 R

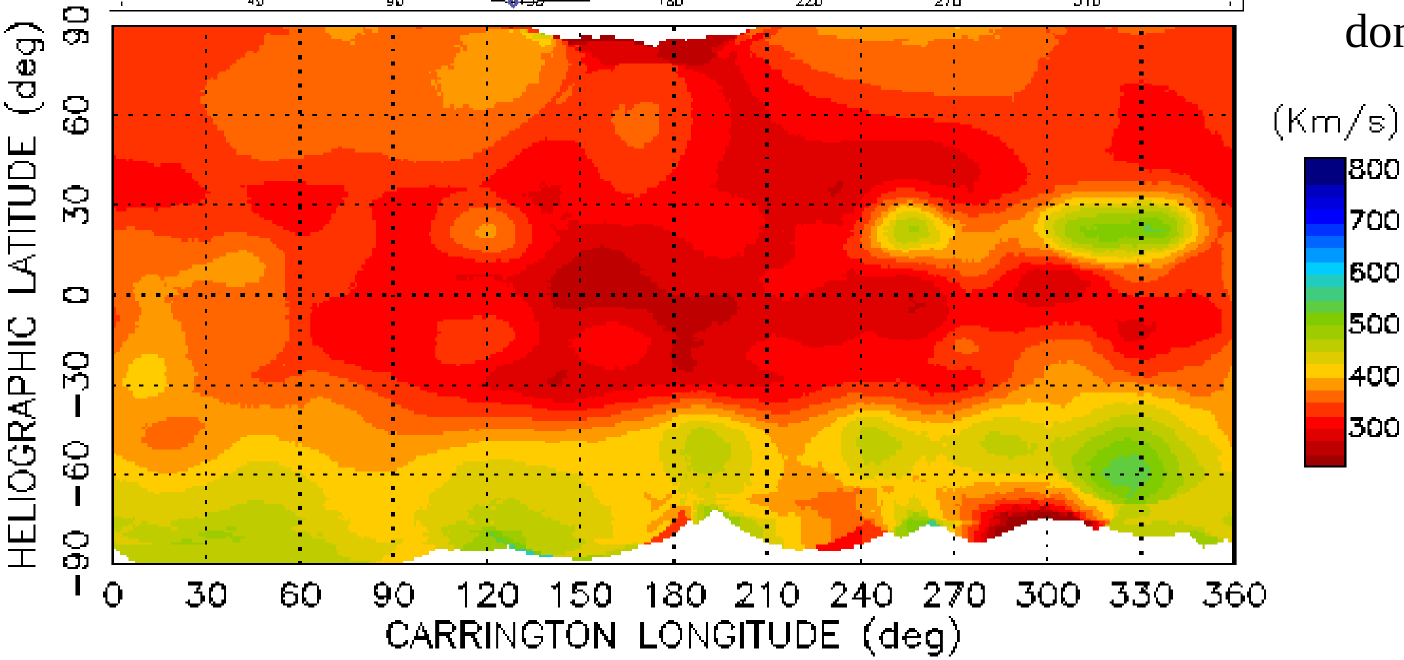


1998

Area of polar fast streams reduced, broader and more structured belt of slow wind, occasional equatorial fast streams

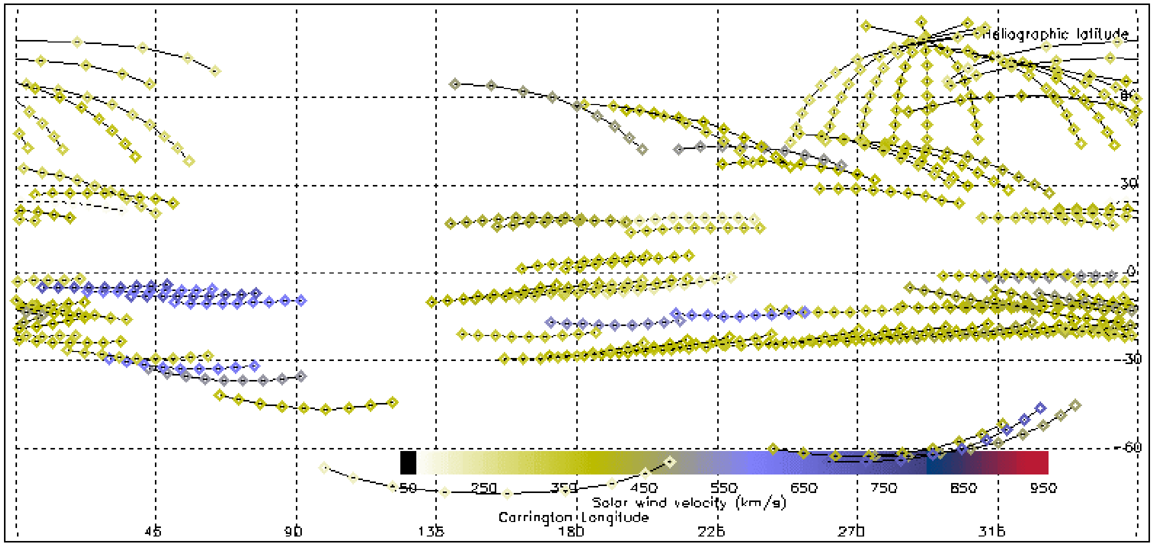
Interplanetary Aberystwyth Scintillation

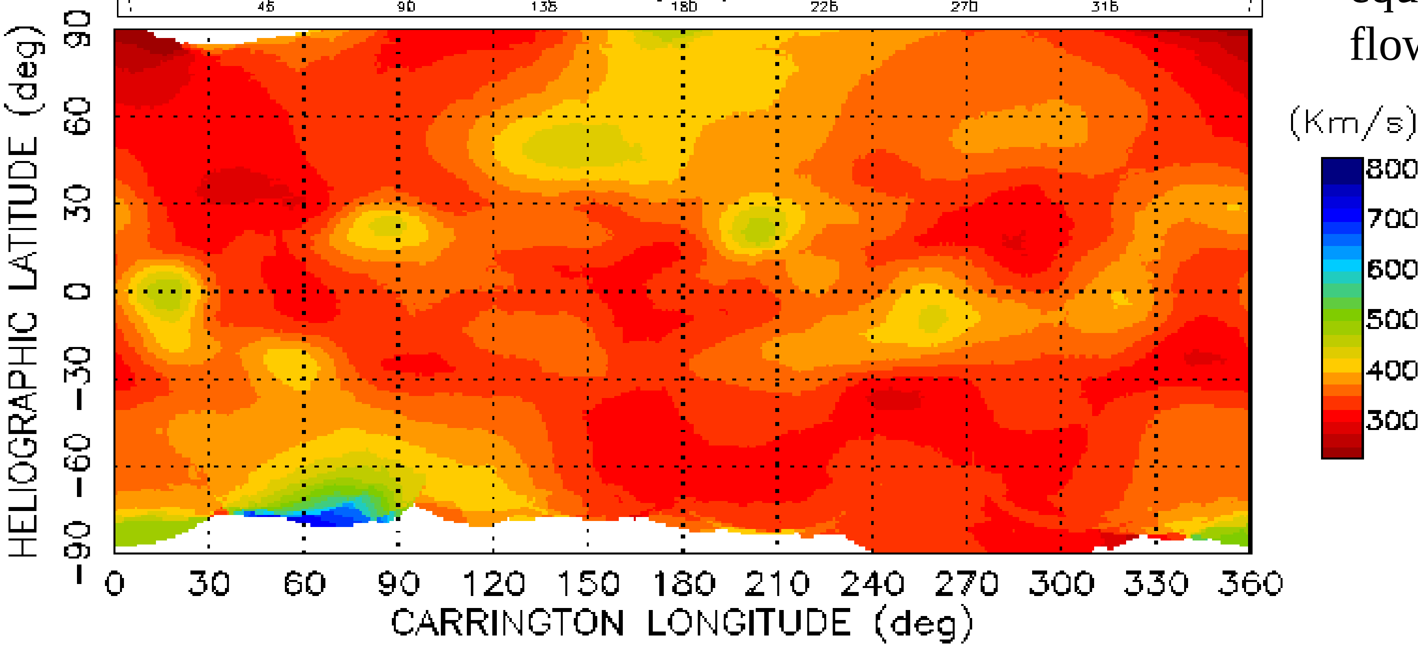




1999

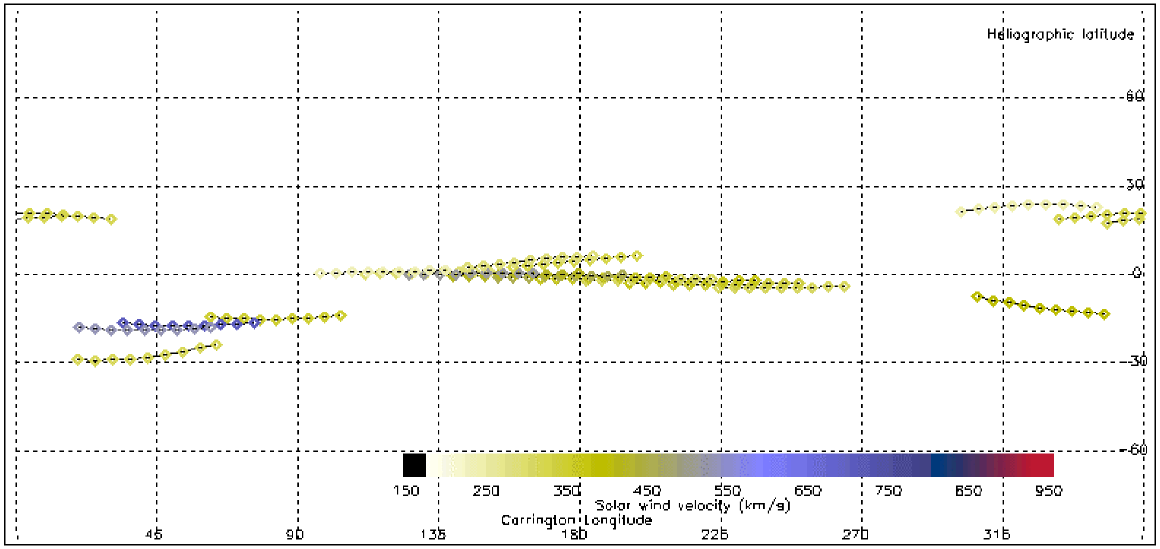
Northern polar fast stream absent, still significant fast flow at high southern latitudes, patches of fast flow near equator, otherwise slow-dominated



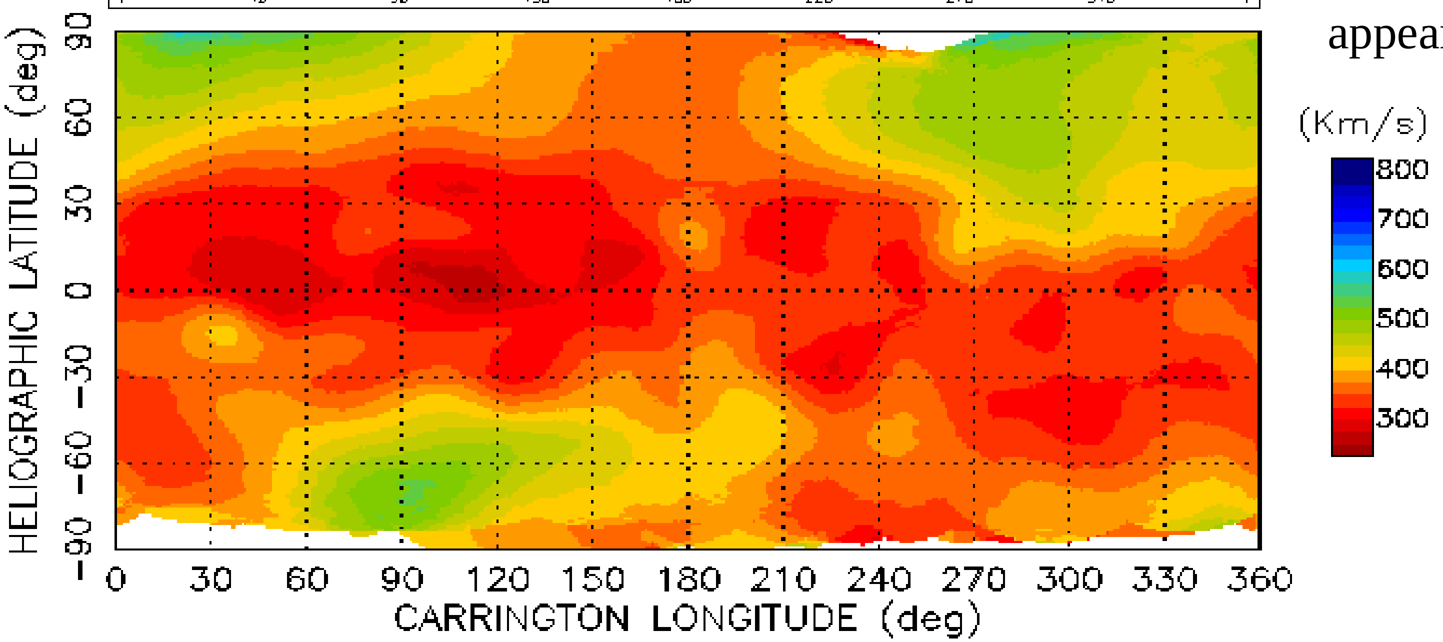


2000

Large mid-latitude coronal hole extending to high northern latitudes, much fast flow above equator, some high-latitude fast flow remaining in south



2001

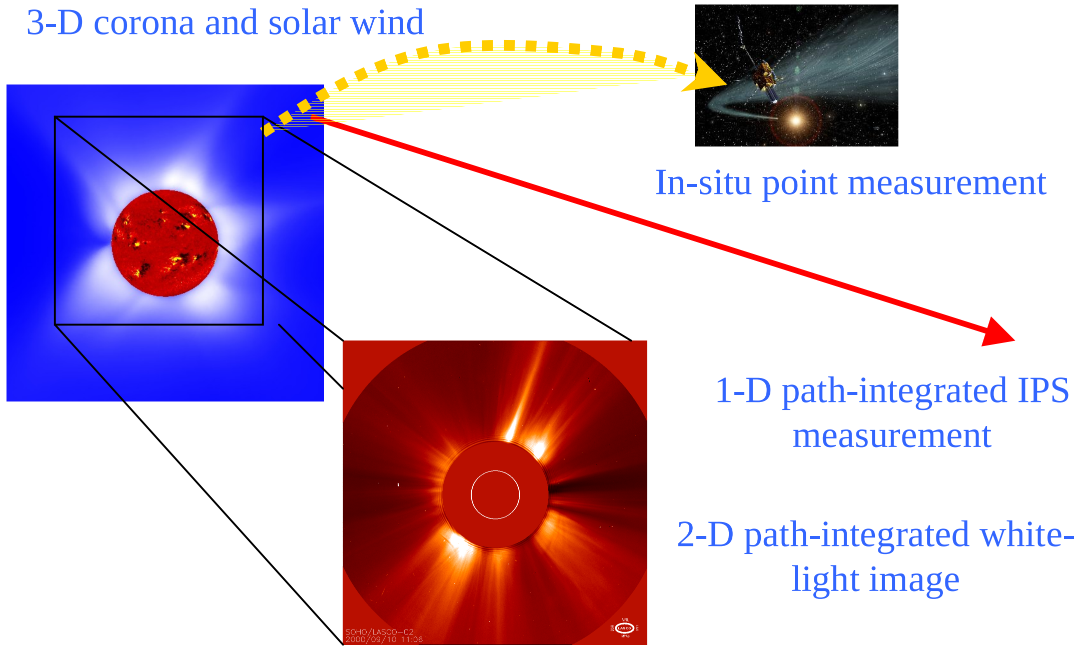


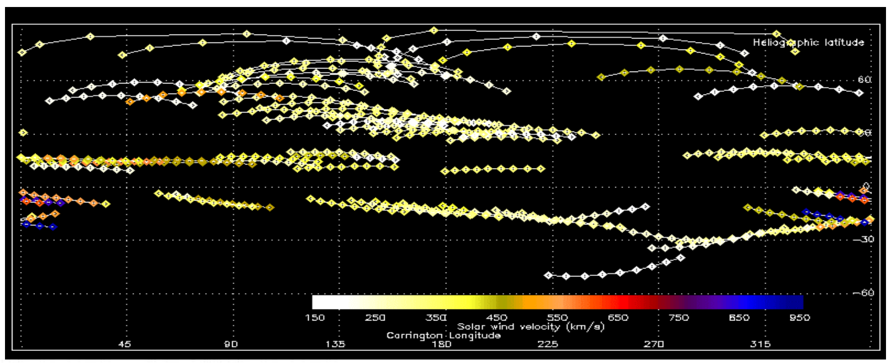
Large fast streams re-emerging in northern hemisphere. Fast flow re-emerging in south. Coherent belt of slow wind re-appearing

Comparing coronal, IPS and in-situ measurements

- **Coronal images**: 2-D path-integrated images of structures in plane of sky
- **IPS observations**: 1-D path-integrated observations at 90° to plane of sky
- **In-situ observations**: O-D observations of parameters in single position at single time

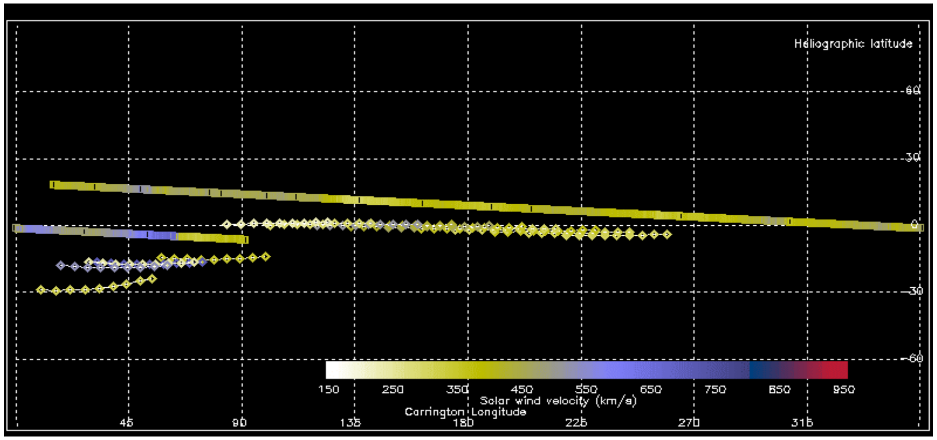
- Sun rotates: can get 2-D and 3-D information by comparing observations over a solar rotation
- Solar wind is a time-variant structure *particularly at solar maximum*

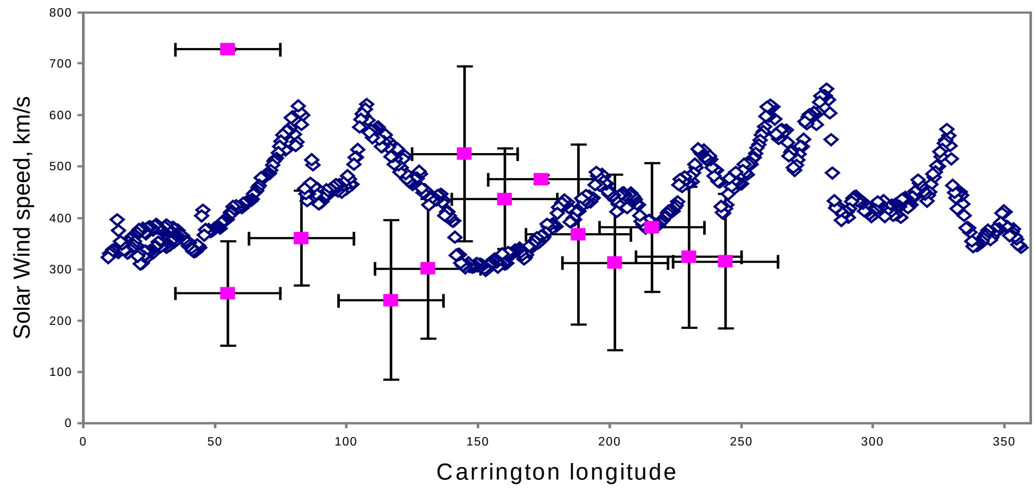




2-D map of solar wind built up from IPS

Evolution of solar wind macrostructure with heliocentric distance



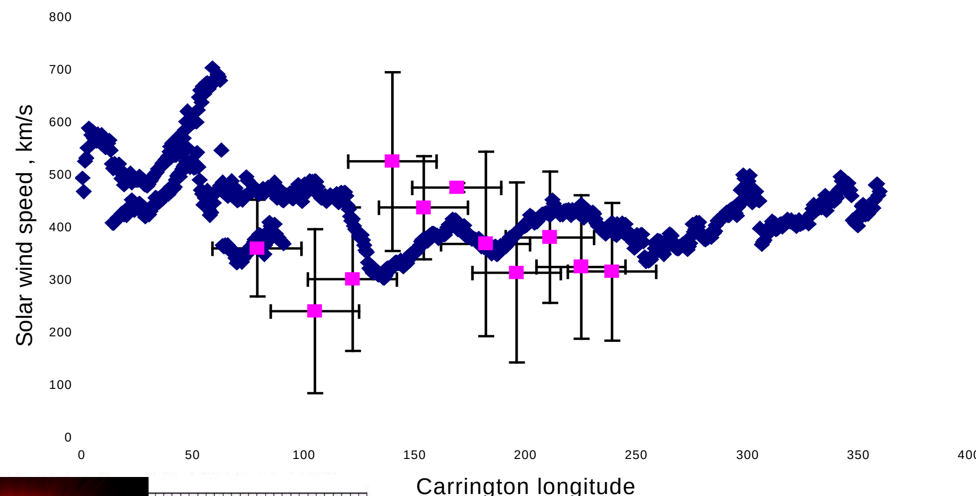


Ulysses second fast latitude scan (May 2001 Ecliptic pass): IPS/in-situ comparison study

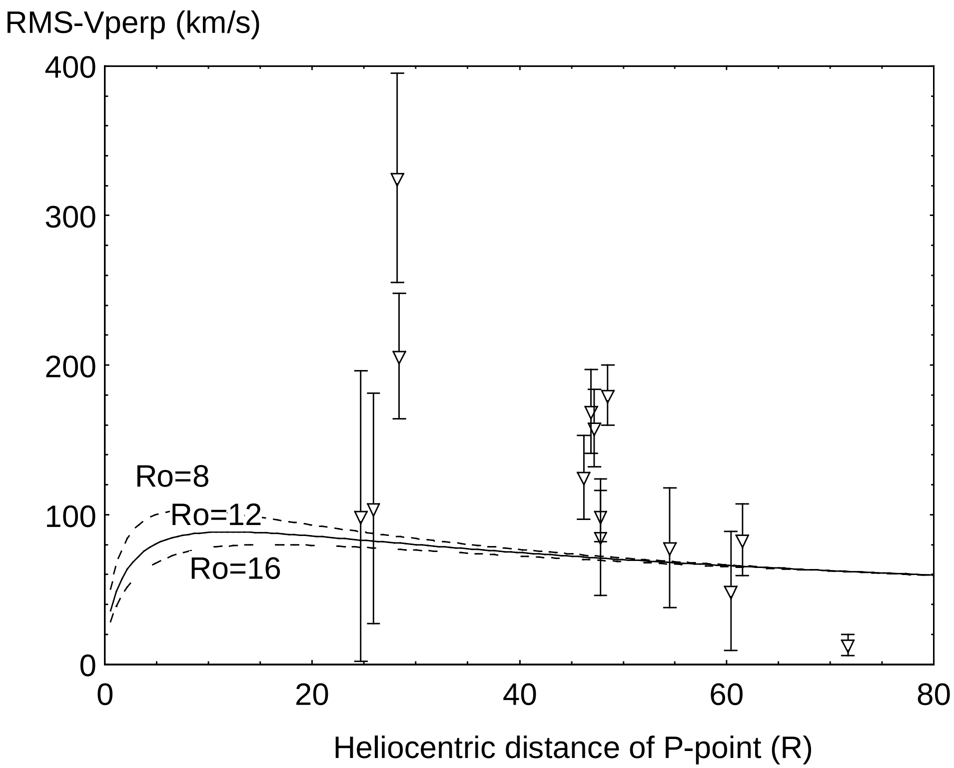
- IPS data mapped ballistically to in-situ distances
- Compared with in-situ measurements from Wind and Ulysses

Generally good agreement

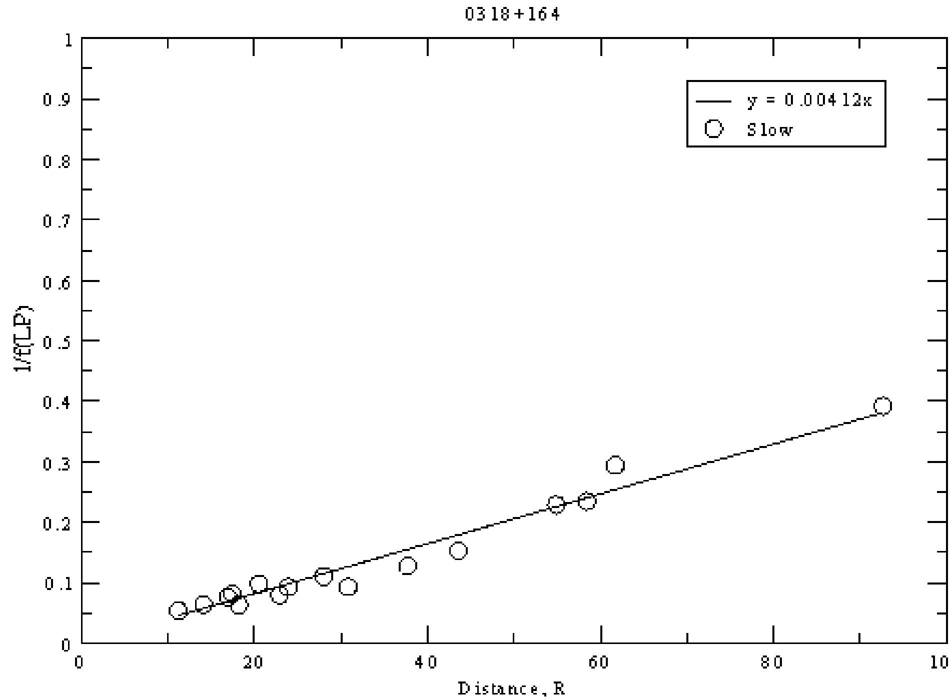
- Perhaps greater variability in IPS velocities?
- Longitudes of fast/slow streams don't always match - evolution in stream velocities and azimuthal flow?



Evolution of solar wind microstructure with heliocentric distance



Random velocity perpendicular to the flow direction *(upper limit on Alfvén wave transverse velocity)* vs. heliocentric distance from IPS measurements



Maximum frequency at which significant scintillation was detected vs. heliocentric distance for slow-wind dominated observations of the strong compact source CTA-21.

Uncertainties in IPS velocity measurements

1. IPS observations include contributions from whole of ray-path through solar wind

- ★ Scintillation contributed by each region depends on gradients in electron concentration
- ★ Profile of electron concentration along ray-paths not known

At present we treat the solar wind as consisting of two components (fast, low density and slow, high density) which expand radially so that $N \propto R^{-2}$ and scintillation contributed $\propto R^{-4}$

Not an accurate model of scattering process (particularly at solar maximum) ⇒ uncertainty in velocity estimates

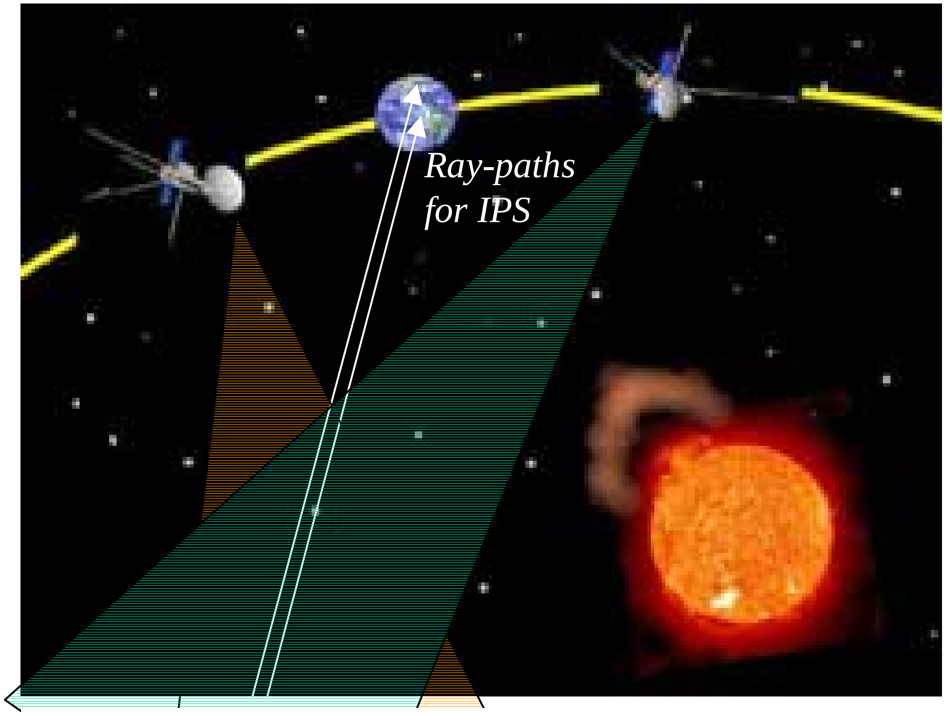
2. Effects of source structure

Current IPS analysis methods consider the scintillation pattern as originating in the interference of waves from a point source. Real astronomical sources often have structure on scales resolved by the baselines for multi-site IPS (~0.1” of arc for EISCAT).

3. Ambiguities in fitting

IPS analysis is a badly under-determined problem: random variation perpendicular to the flow vector can be confused with variation in flow speed over the ray-path. Bias in bulk flow speed

IPS and STEREO
1. What STEREO will do to improve IPS



Heliospheric imagers

★ The Heliospheric imagers on STEREO measure white-light intensity from 12 R out to 318 R

★ Each imager "sees" a 2-D plane-of-sky projection of density structures in the corona and solar wind

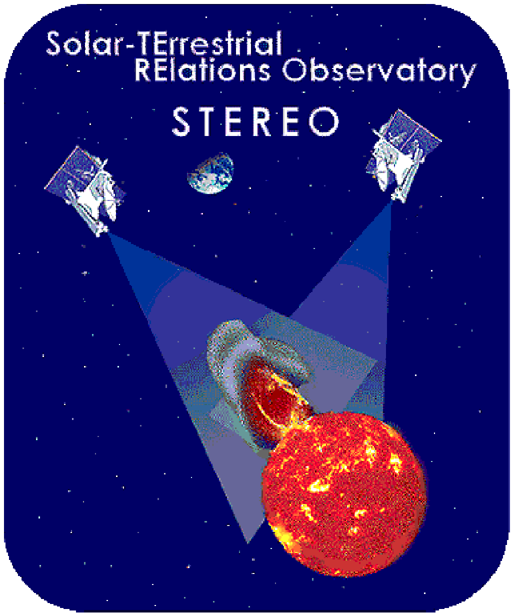
★ Combining measurements from both instruments gives a 3-D image of solar wind density structure

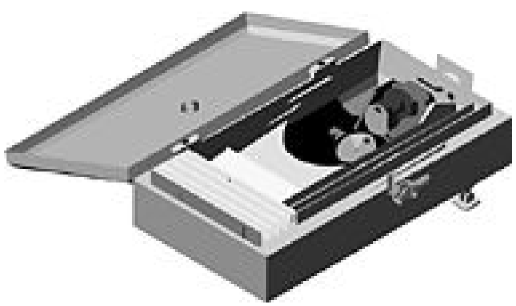
⇒ Can calculate electron density profile along IPS ray-paths

SECCHI|STEREO measurements of white-light intensity will make it possible to unambiguously determine where contributions to overall scintillation pattern originate

Will lead to great improvements in reliability and accuracy of IPS velocity measurements

IPS and STEREO
2. What IPS can provide to support STEREO observations





The heliospheric imagers will provide extremely good information on large-scale density structures, but not normally on the velocity of streams of solar wind

IPS measurements can provide accurate measurements of solar wind speed from ~20 - 200 R (depending on observing frequency):

★ Measurements of solar wind speed over a range of distances, tracking the evolution of velocity structures
★ Measurements of ambient solar wind ahead of CMEs, assisting studies of CME/Solar Wind interaction
★ Studies of the development of stream-stream interaction regions
★ Evolution of solar wind microstructure (turbulence)

IPS is also more sensitive to small variations in electron density than white-light measurements and so can pick out faint density structures in CMEs

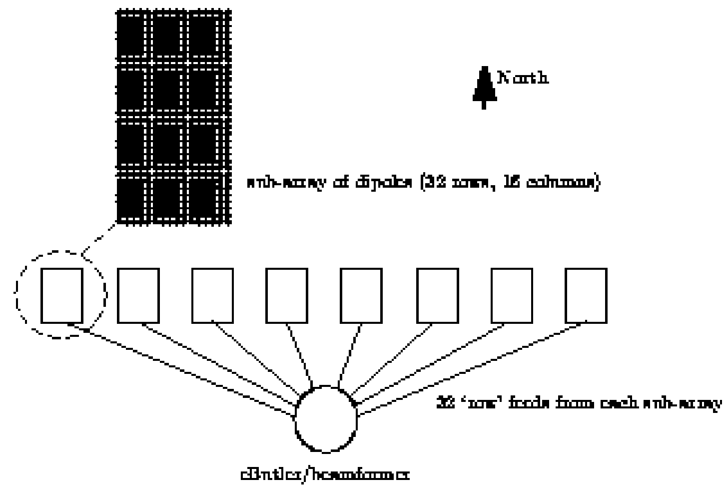
IPS and STEREO
3. A new-generation IPS system to support STEREO

Scientific requirements

• Provide information on the large-scale structure of the solar wind

- •Interaction regions between fast and slow wind
- •Interaction regions between CMEs and solar wind.

• Provide information for 3D tomographic reconstruction of the solar wind



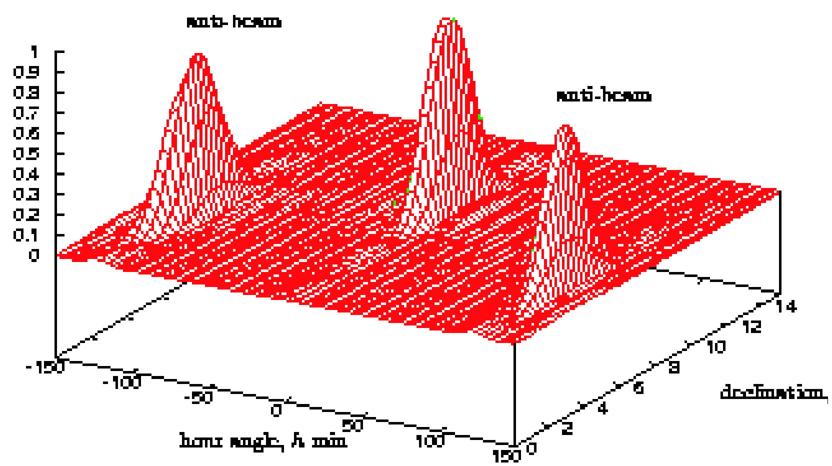
Observational requirements

• Observe enough sources to:

• create daily maps of ‘G-value’ and velocity

• detect transient events on a daily basis

★ Make more than 100 15-minute source-observations 3 times a day - 300 daily observations



• Observe a significant sub-set of observations with 2 sites

★ Make ~20-30 15-minute source-observations/day with two sites