3D curvature determination for the Bastille Interplanetary Shock: Multi-Satellite Triangulation

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The shock normal direction

……..important basic information describing the shock properties

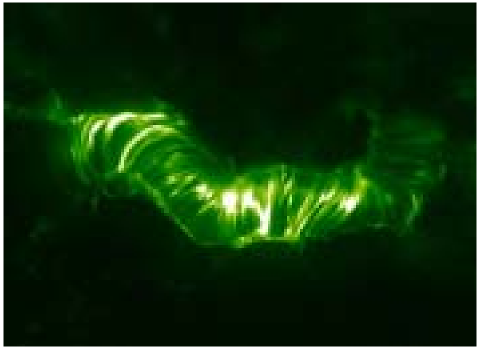
For example,
it is believed that the acceleration process of electrons emitting type II radio bursts depends critically on the shock angle.

Determination of the shock normal:
conceptually simple, but not straightforward in reality

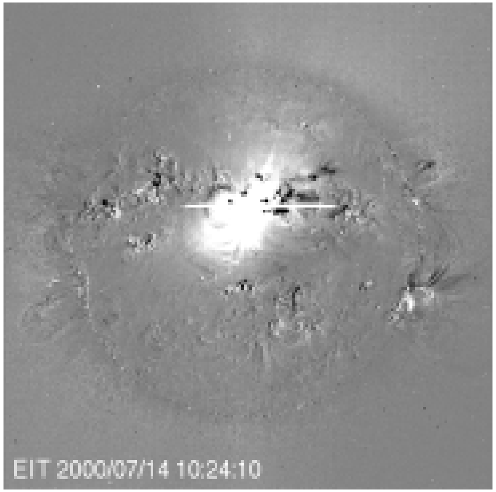
→ e.g., Russell et al.(2000) JGR *105*, 25143-

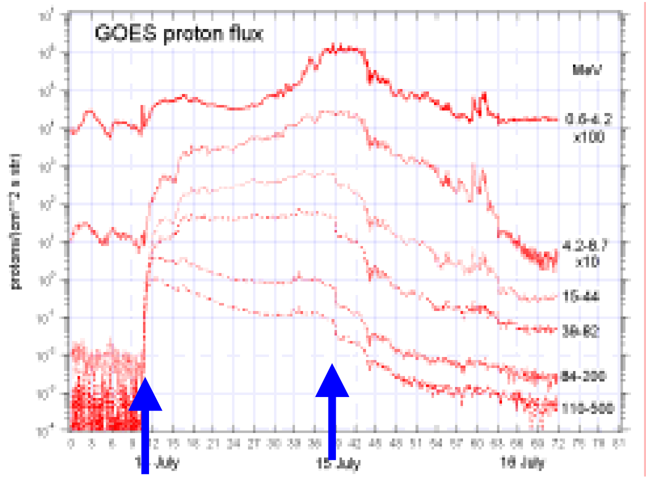
Determination of the shock normal direction

The Bastille day flare in 2000 …. IPS arrived on the next day
(average speed … 1AU/28hours ~ 1500 km/s)



Trace image

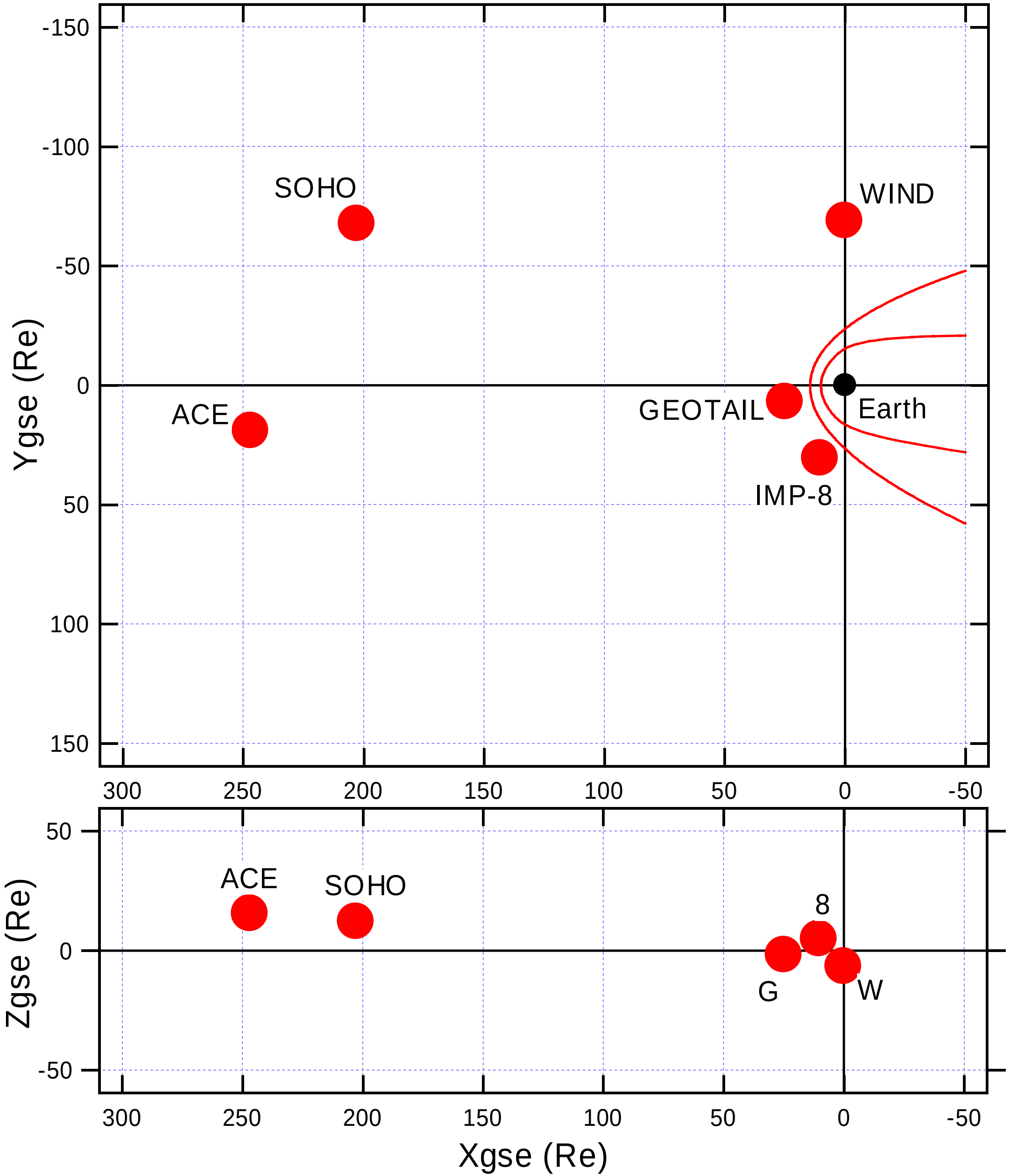




flare/CME shock arrival

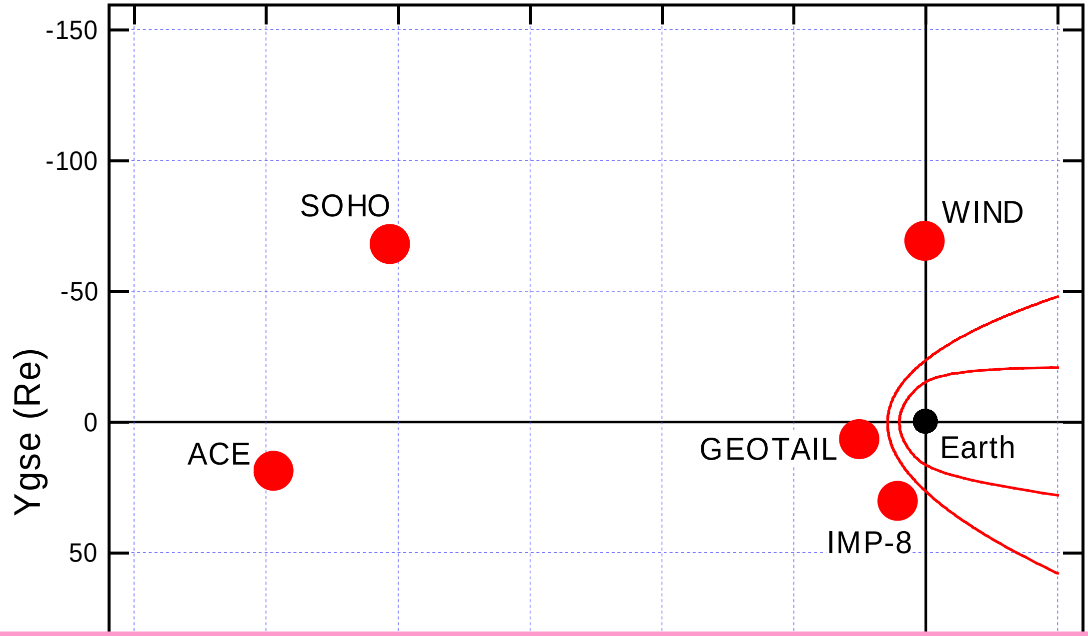
Lessons from the study of the Bastille IP shock
… ACE, SOHO,WIND,GEOTAIL and IMP-8
were all in the upstream solar wind!

satellite constellation on 15 July 2000



satellite
constellation
on 15 July 2000

solar wind



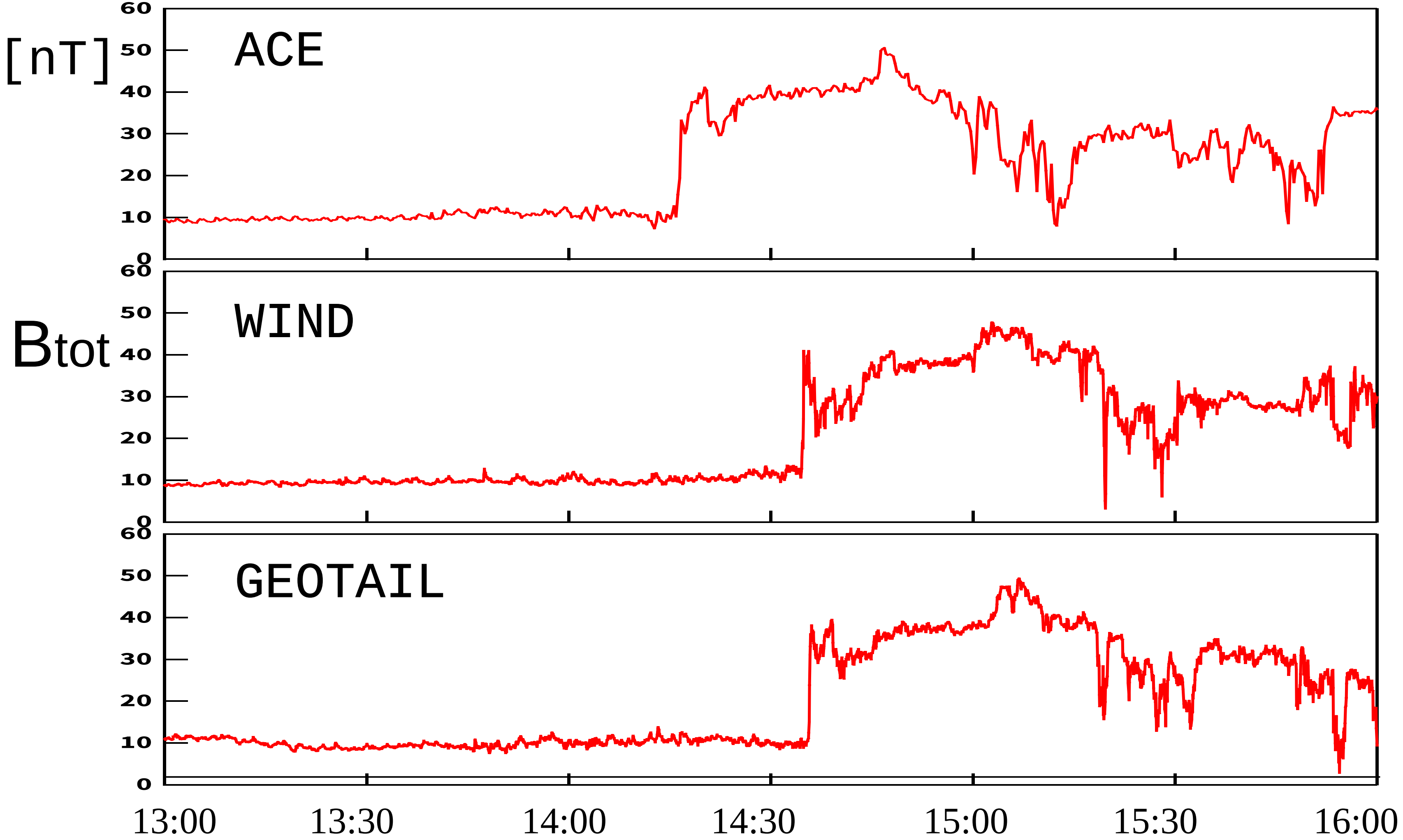
We are going to show the results of

1. The conventional methods based on the single satellite observation (minimum variance, etc.)
2. 4-satellite method for the plane surface model
3. 5-satellite method for the spherical surface model
4. 5-satellite method for the plane surface model with constant dV_{shock}/dt (time derivative of the shock speed)

Xgse (Re)

the Bastielle interplanetary shock on 15 July 2000

3 of 5 satellites gave the magnetic field data



local determination of the shock normal direction

The conventional methods give consistent answers:

- WIND best fit (Lepping et al., 2001, *Solar Phys.* **204**, 287):

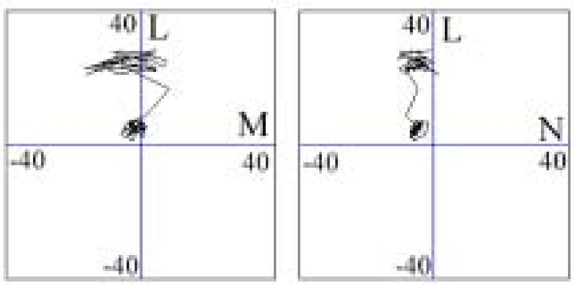
n_W = (-0.93, +0.26,+0.26)

phi~164°, theta~15°

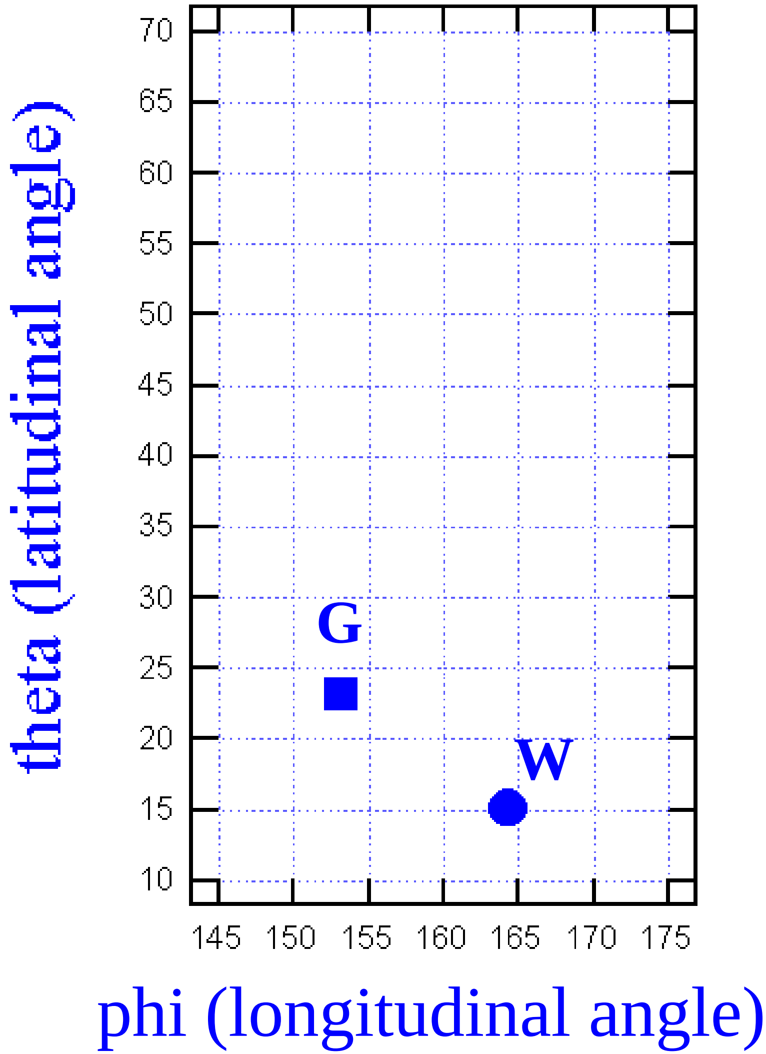
- magnetic minimum variance/Geotail:

n_G = (-0.82, +0.42,+0.39)

phi~153°, theta~23°

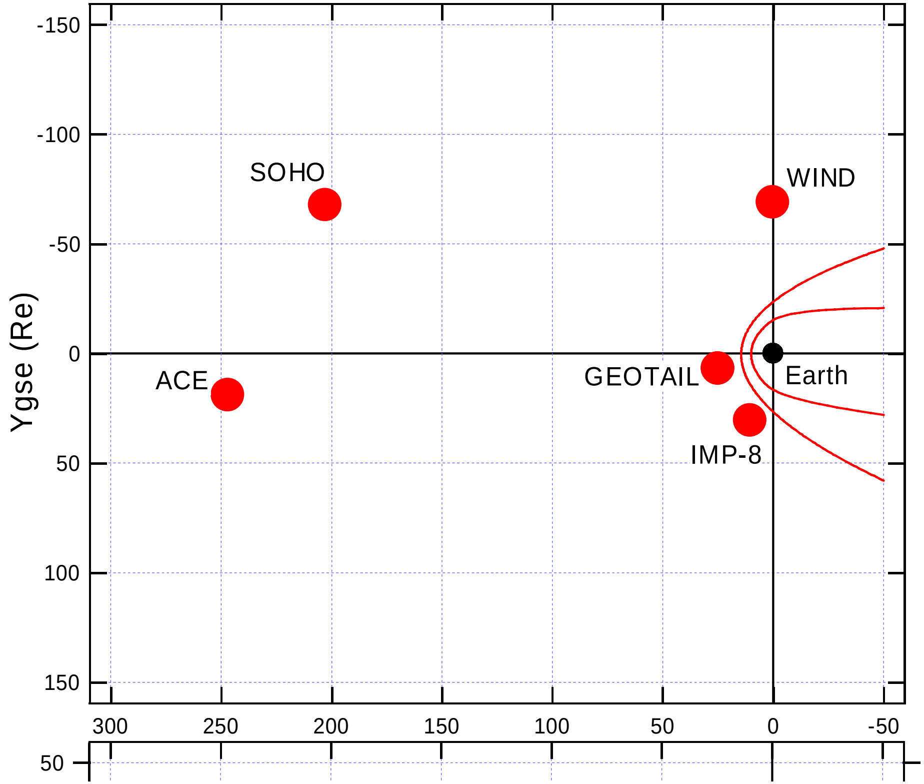


n_W and n_G agree
(they make an angle ~ 13°
which is within a typical error range.)



satellite constellation on 15 July 2000 and shock arrival times

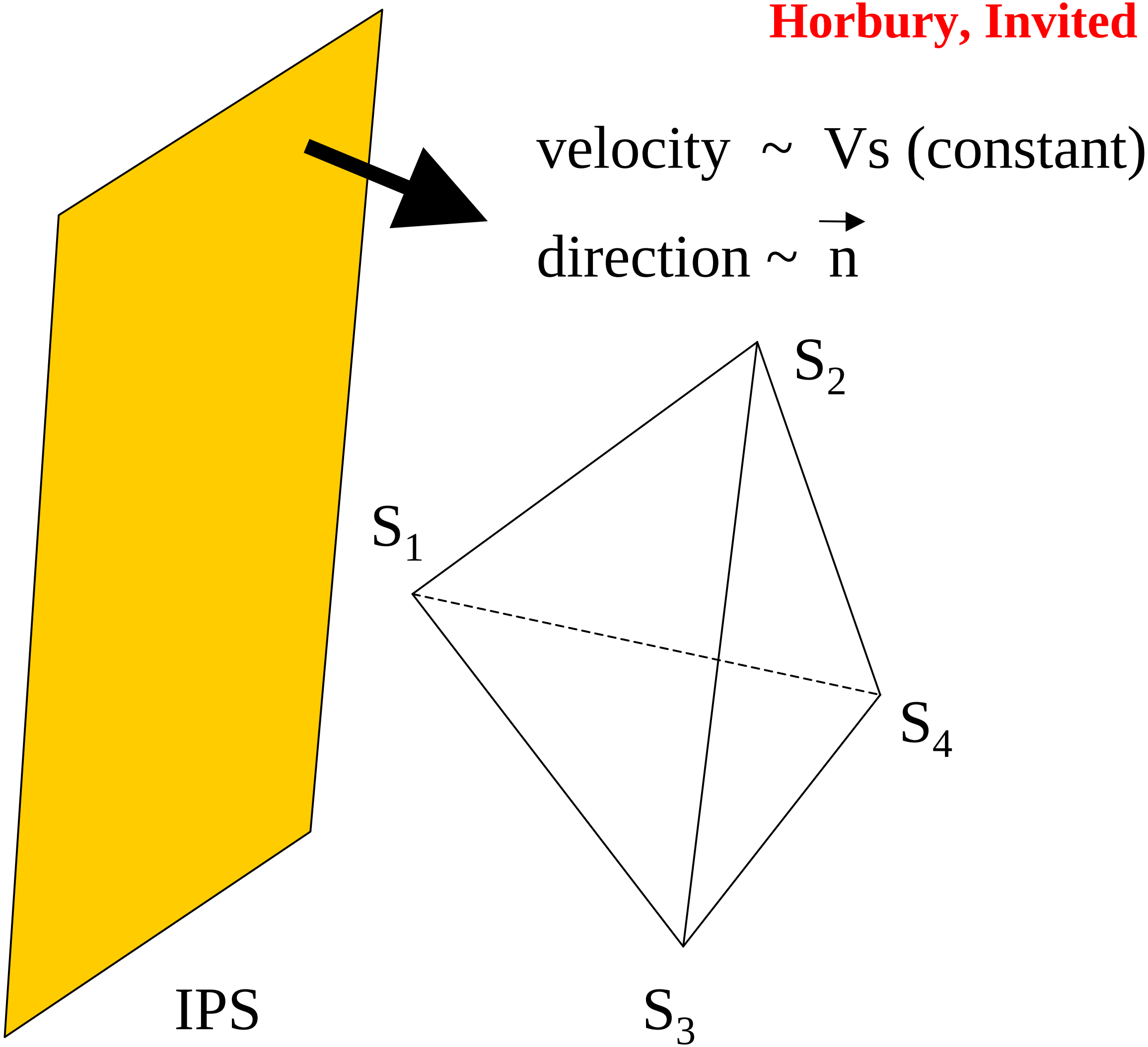
SOHO and IMP8 gave the plasma data. (IMP8 magnetometer was not working during this event, unfortunately.)

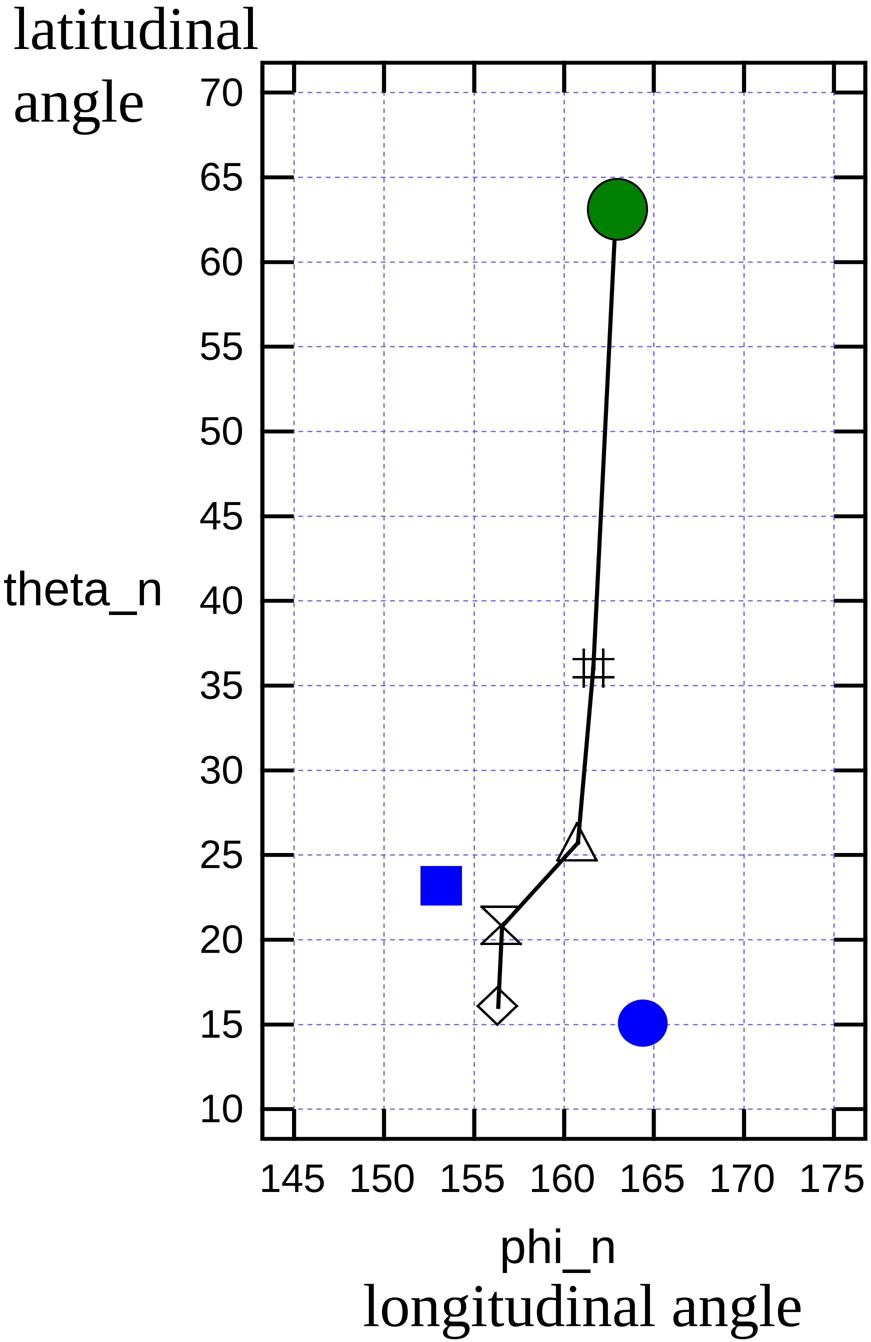


Satellite	X [Re]	Y [Re]	Z [Re]	Time [UT]	Time error [sec]	Data source
ACE	247.03	18.88	15.58	14:16:24	±1	B
SOHO	202.9	−67.8	12.29	14:17:31	±3	plasma
GEOTAIL	25.03	6.8	−1.64	14:35:45	±3	B
WIND	0.23	−69	−6.5	14:34:50	±3	B
IMP8	10.5	30.5	5	14:38:34	±22	plasma

4 satellites determine shock parameters if the shock has a plane surface.

Russell et al., 1983;
Horbury, Invited talk on the first day





plane surface model
--- results

shock normal direction
(phi, theta)

Best fit normals by conventional methods

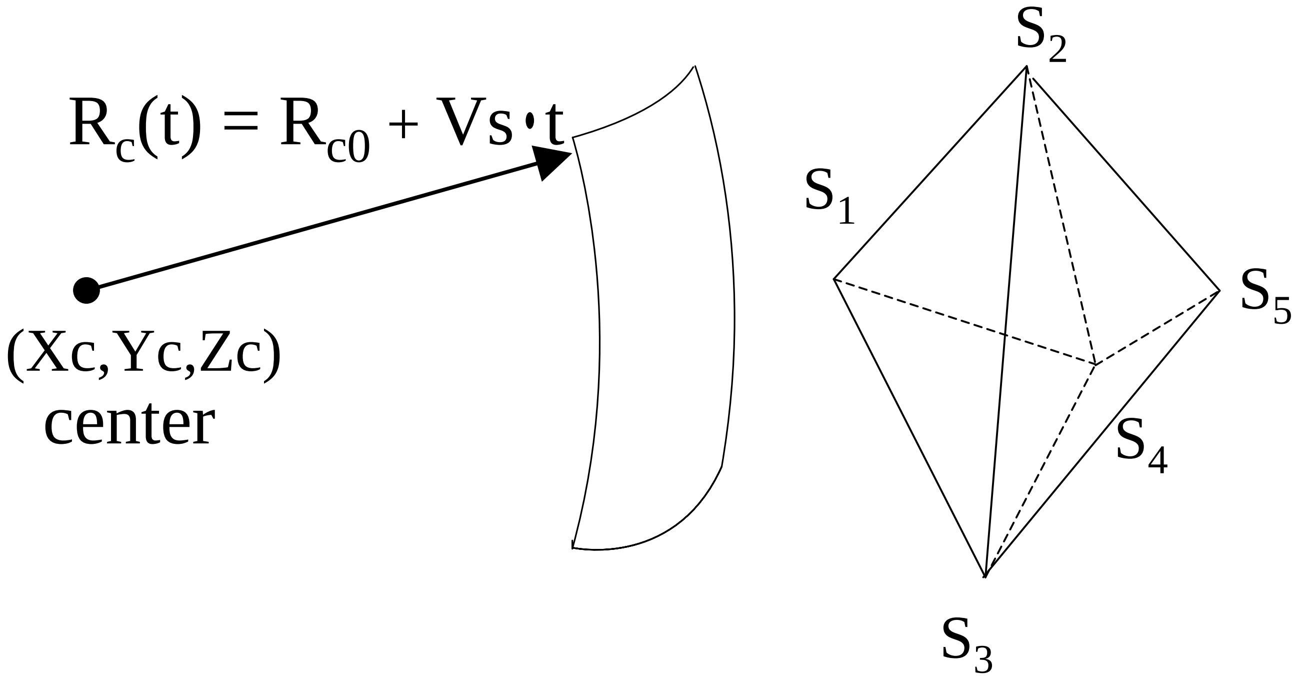
- GTL MVM
- WIND

4-satellite method for plane shocks

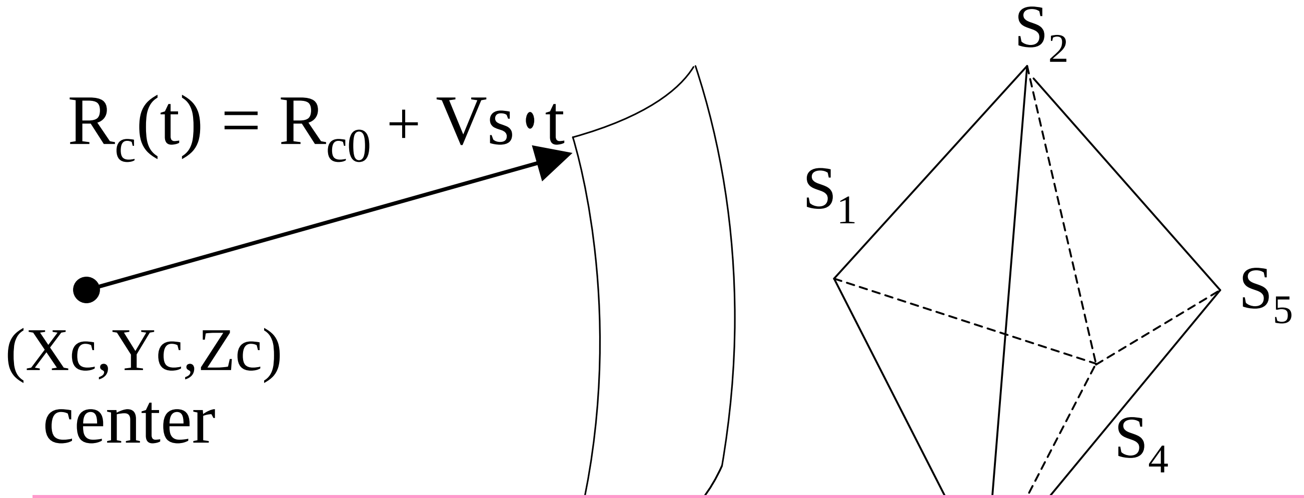
- A-S-G-W
- A-S-8-W
- A-S-G-8
- S-G-8-W
- A-G-8-W

The result with the largest departure from the conventional methods does not depend on the IMP8 timing uncertainly.

5-satellite method for spherical shocks



5-satellite method for spherical shocks



$$R_{c0} + Vs\, t_1 = [\, (X_1 - Xc)^2 + (Y_1 - Yc)^2 + (Z_1 - Zc)^2]^{1/2}$$
$$R_{c0} + Vs\, t_2 = [\, (X_2 - Xc)^2 + (Y_2 - Yc)^2 + (Z_2 - Zc)^2]^{1/2}$$
$$R_{c0} + Vs\, t_3 = [\, (X_3 - Xc)^2 + (Y_3 - Yc)^2 + (Z_3 - Zc)^2]^{1/2}$$
$$R_{c0} + Vs\, t_4 = [\, (X_4 - Xc)^2 + (Y_4 - Yc)^2 + (Z_4 - Zc)^2]^{1/2}$$
$$R_{c0} + Vs\, t_5 = [\, (X_5 - Xc)^2 + (Y_5 - Yc)^2 + (Z_5 - Zc)^2]^{1/2}$$

five unknowns (R_{c0}, Vs, Xc, Yc, Zc) and five equations

→ solvable (We need iterations to treat nonlinearity of Vs)

formulation (2)

Let us take the S_1 position as the origin of the new coordinate.
Then we have,

$$R_{c0} = [\, Xc^2 + Yc^2 + Zc^2]^{1/2} \qquad (1)$$
$$R_{c0} + Vs\,(t_2 - t_1) = [\, (X_2-Xc)^2 + (Y_2-Yc)^2 + (Z_2-Zc)^2]^{1/2} \qquad (2)$$
$$R_{c0} + Vs\,(t_3 - t_1) = [\, (X_3-Xc)^2 + (Y_3-Yc)^2 + (Z_3-Zc)^2]^{1/2} \qquad (3)$$
$$R_{c0} + Vs\,(t_4 - t_1) = [\, (X_4-Xc)^2 + (Y_4-Yc)^2 + (Z_4-Zc)^2]^{1/2} \qquad (4)$$
$$R_{c0} + Vs\,(t_5 - t_1) = [\, (X_5-Xc)^2 + (Y_5-Yc)^2 + (Z_5-Zc)^2]^{1/2} \qquad (5)$$

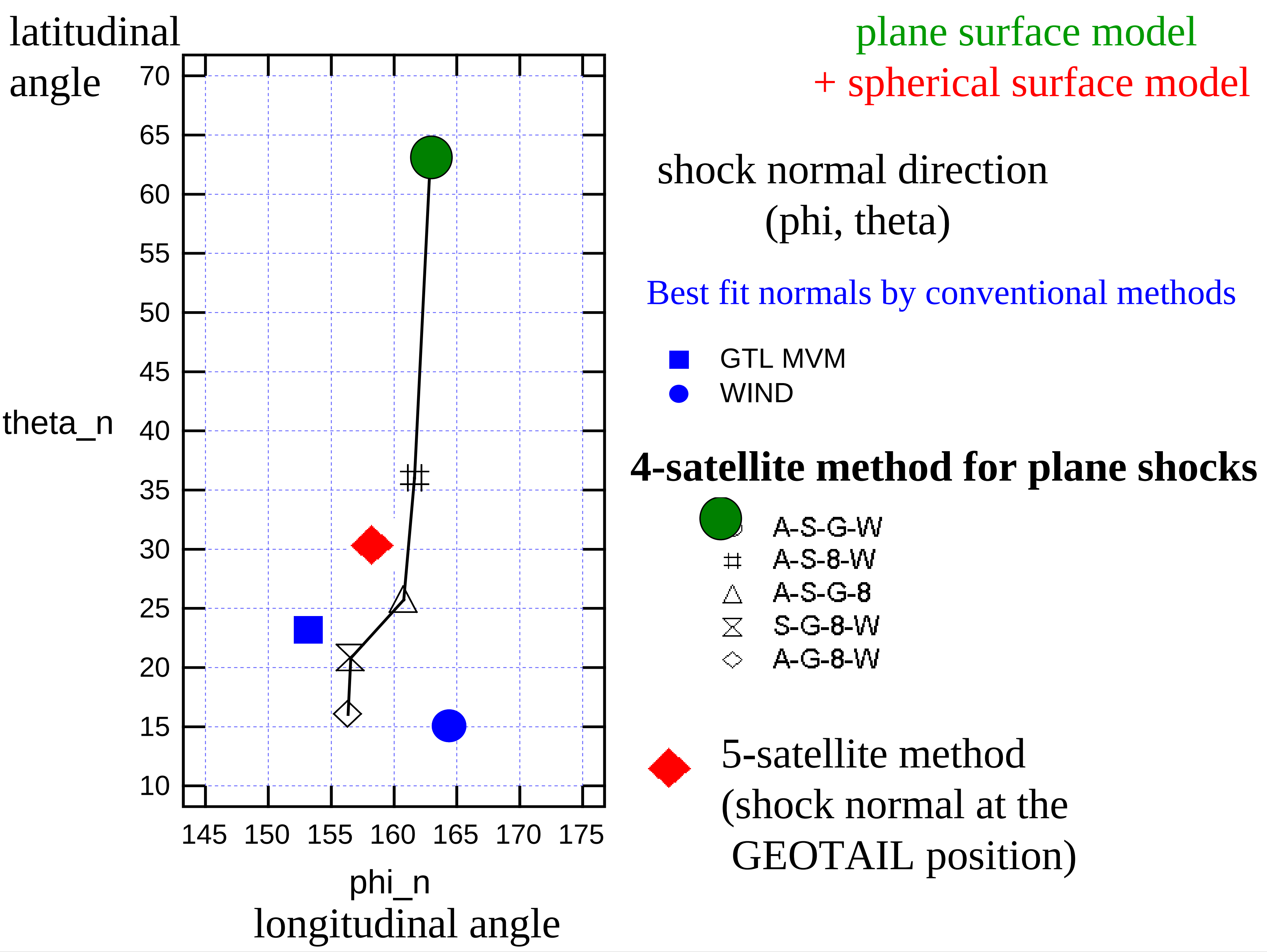
From (2)~(5), we have a set of nonlinear equations,

$$X_2Xc+Y_2Yc+Z_2Zc+Vs\,(t_2 - t_1)\,R_{c0} = [\, X_2^2+Y_2^2+Z_2^2 - Vs^2\,(t_2 - t_1)^2\,]/2 \qquad (2')$$
$$X_3Xc+Y_3Yc+Z_3Zc+Vs\,(t_3 - t_1)\,R_{c0} = [\, X_3^2+Y_3^2+Z_3^2 - Vs^2\,(t_3 - t_1)^2\,]/2 \qquad (3')$$
$$X_4Xc+Y_4Yc+Z_4Zc+Vs\,(t_4 - t_1)\,R_{c0} = [\, X_4^2+Y_4^2+Z_4^2 - Vs^2\,(t_4 - t_1)^2\,]/2 \qquad (4')$$
$$X_5Xc+Y_5Yc+Z_5Zc+Vs\,(t_5 - t_1)\,R_{c0} = [\, X_5^2+Y_5^2+Z_5^2 - Vs^2\,(t_5 - t_1)^2\,]/2 \qquad (5')$$

Note that if we fix Vs (2')~(5') are linear with respect to (Xc,Yc,Zc,R_{c0}).
Our procedure is, therefore,

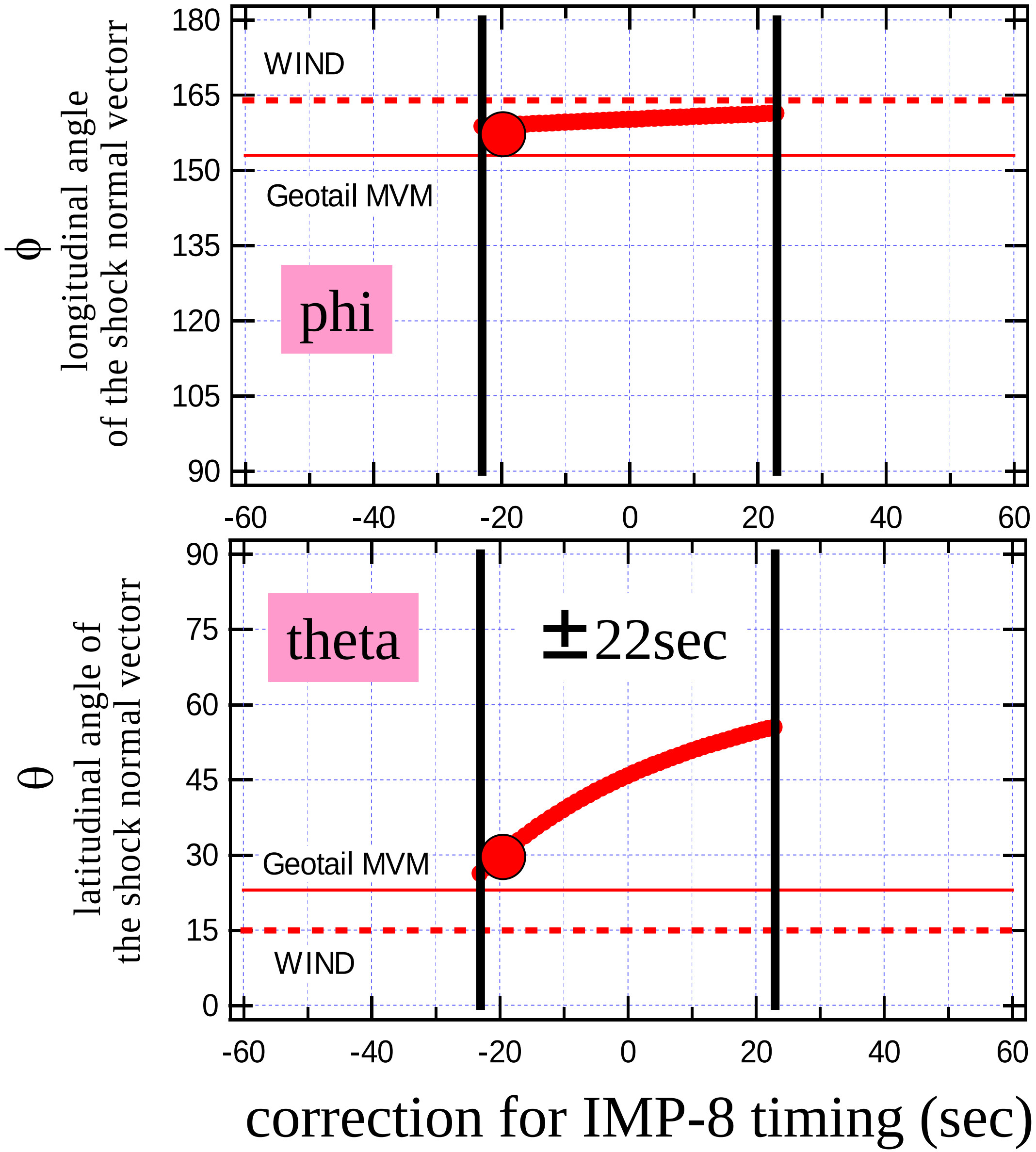
(a) Solve (2')~(5') for a trial value of Vs, and obtain (Xc,Yc,Zc,R_{c0}).

(b) Search Vs so that $[Xc^2 + Yc^2 + Zc^2]^{1/2} - R_{c0} = 0$ is satisfied.



latitudinal angle
theta_n
70
65
60
55
50
45
40
35
30
25
20
15
10
145 150 155 160 165 170 175
phi_n
longitudinal angle
plane surface model
+ spherical surface model
shock normal direction
(phi, theta)
Best fit normals by conventional methods
GTL MVM
WIND
4-satellite method for plane shocks
A-S-G-W
A-S-8-W
A-S-G-8
S-G-8-W
A-G-8-W
5-satellite method
(shock normal at the
GEOTAIL position)

spherical surface model
shock normal direction



Shock normal direction depends on the choice of the timing corrections for the IMP-8 data.

We have set the IMP8 timing correction at -20 sec so as to make the shock normal direction consistent with those by the conventional methods.

spherical surface model --- Rc and Vs

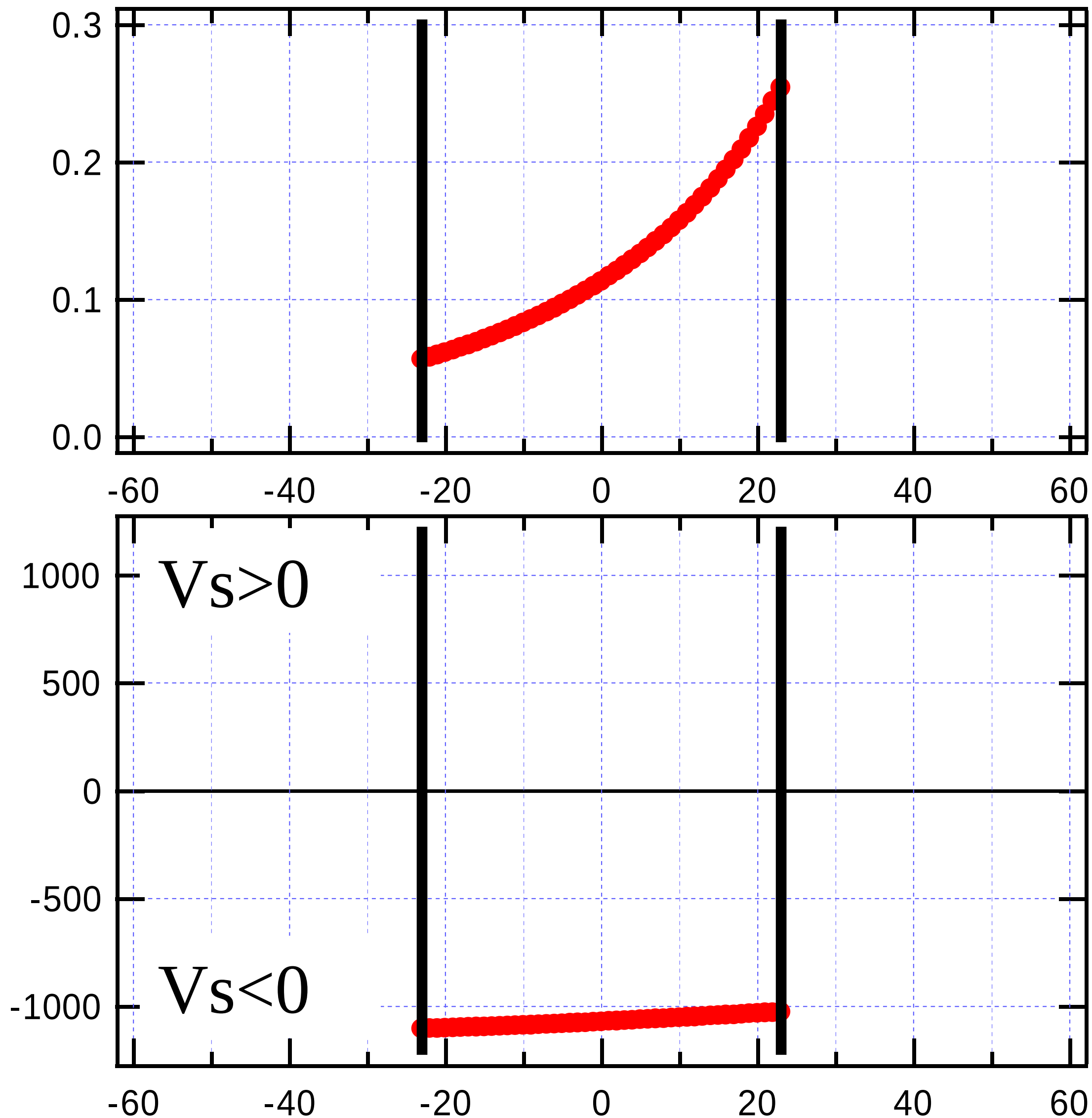
Curvature radius of the shock surface

Rc

AU

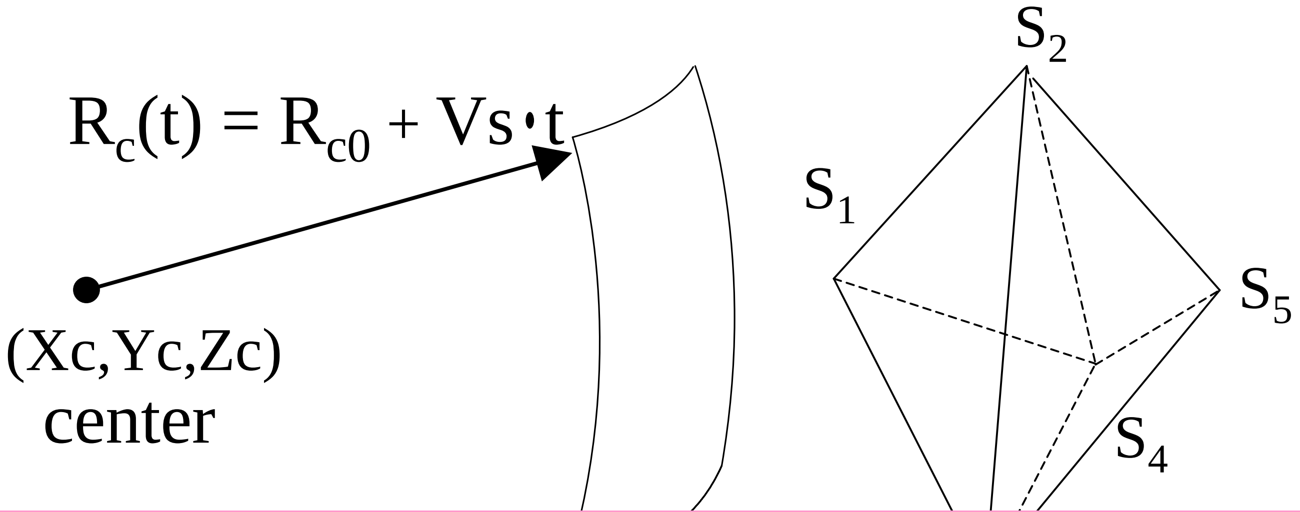
shock speed

Vs (projected to the ecliptic plane)



correction for IMP-8 timing (sec)

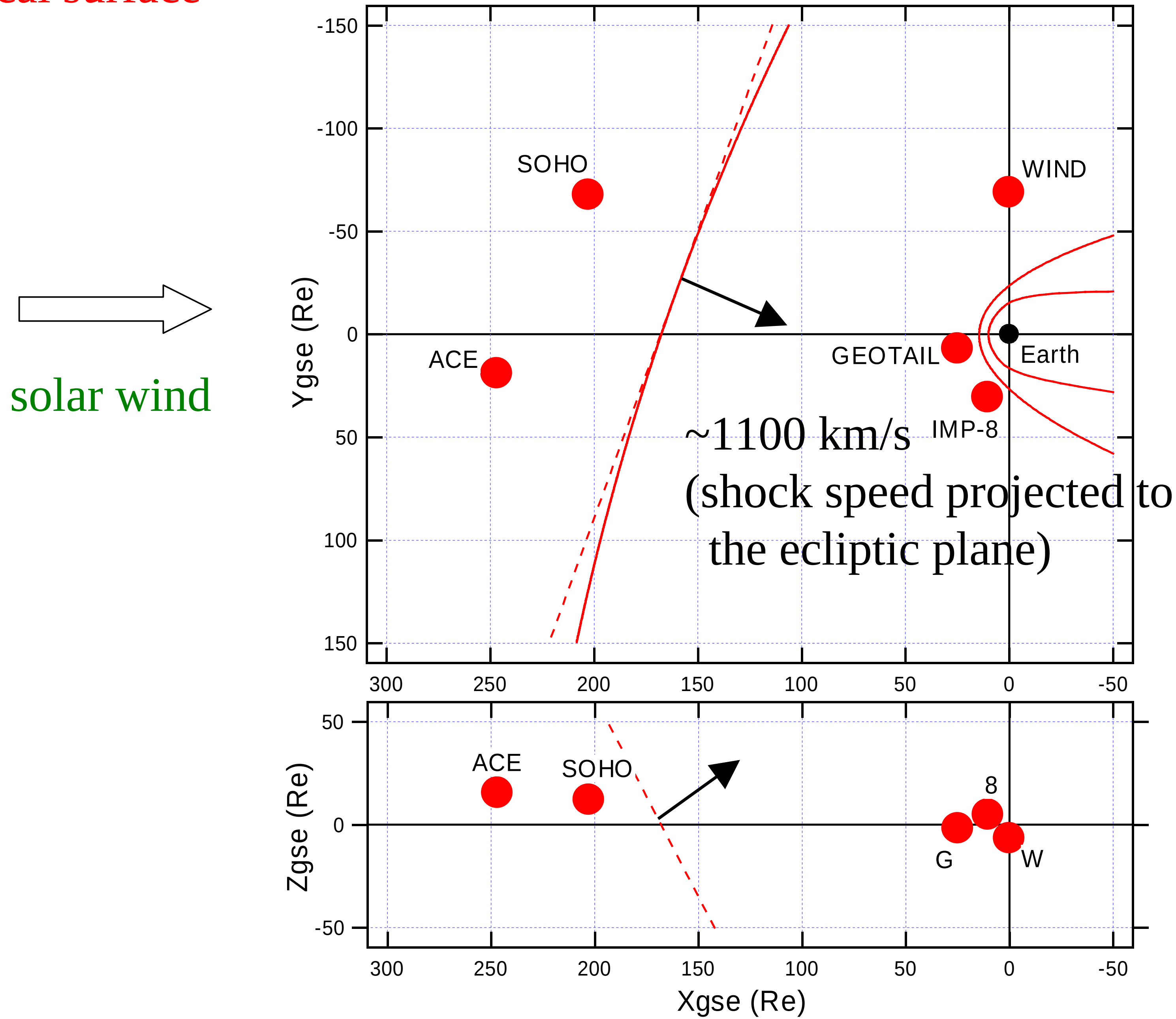
If the shock surface is spherical …. 5 satellites needed



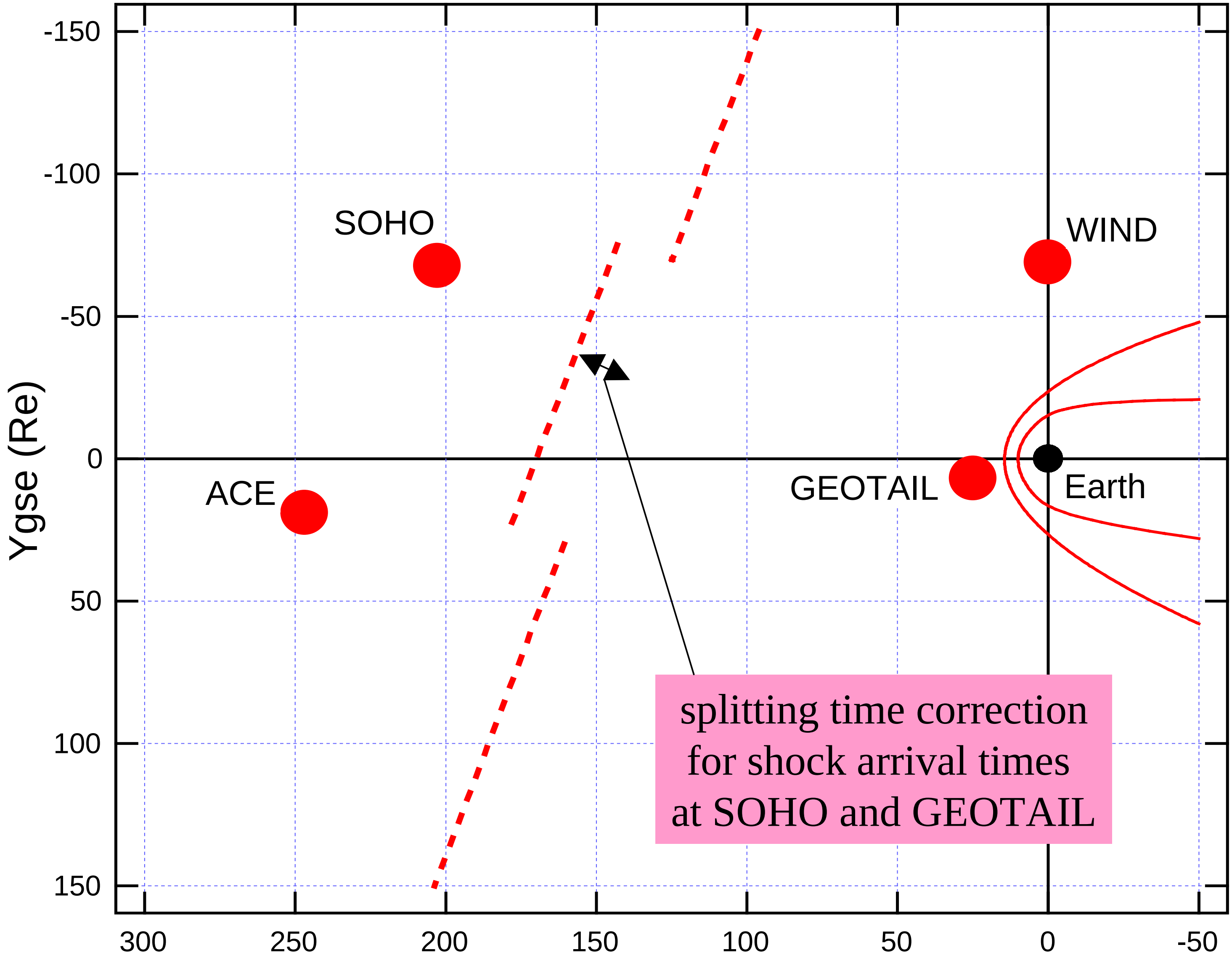
Initially we expect that the center is inside of 1AU and Vs>0, namely the shock has a ***convex*** shape expanding in time.

However, we should also take into account of the case where the center is outside of 1AU and Vs<0, namely the shock has a ***concave*** shape shrinking in time.

spherical surface model

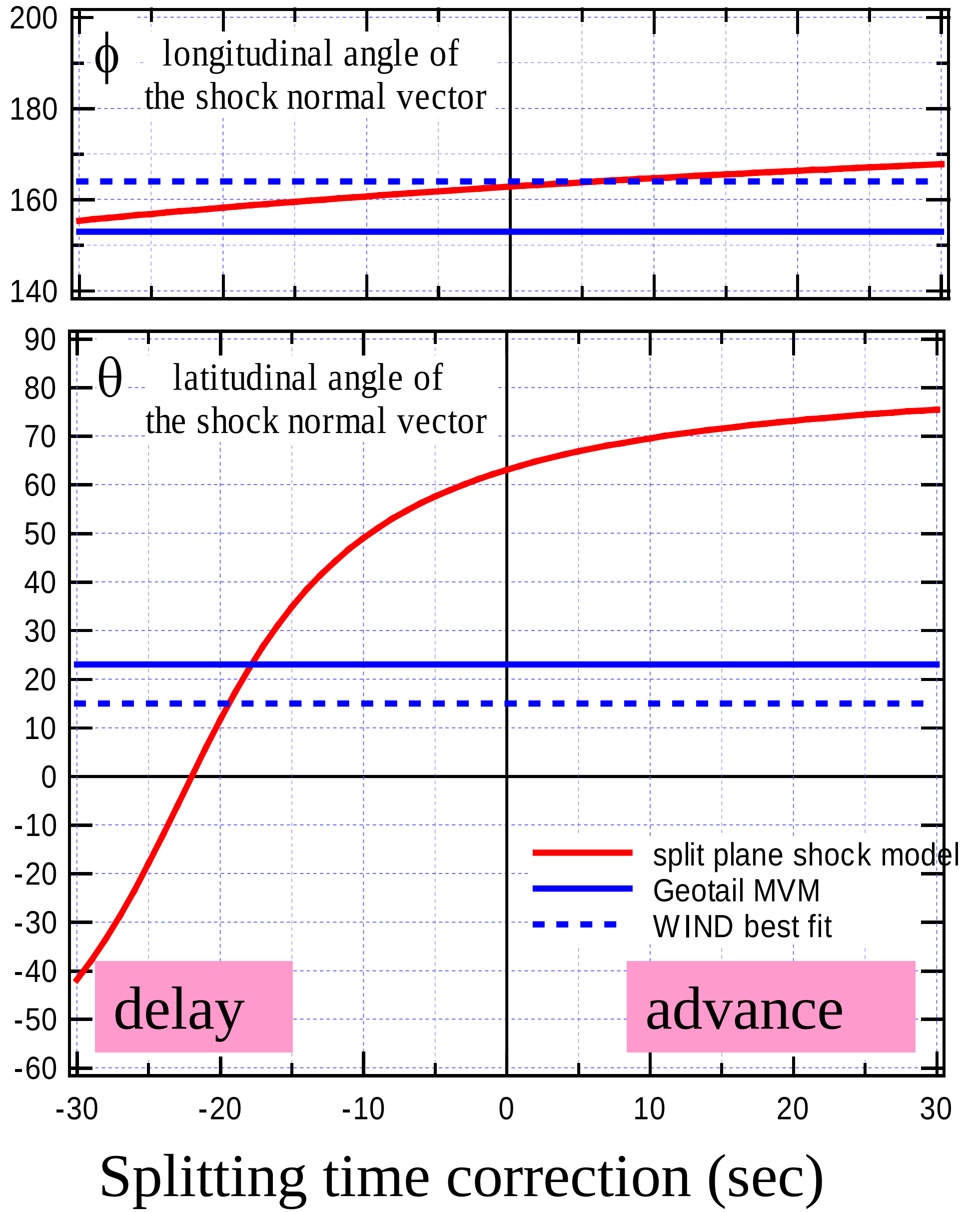


An artificial model: split plane surface model



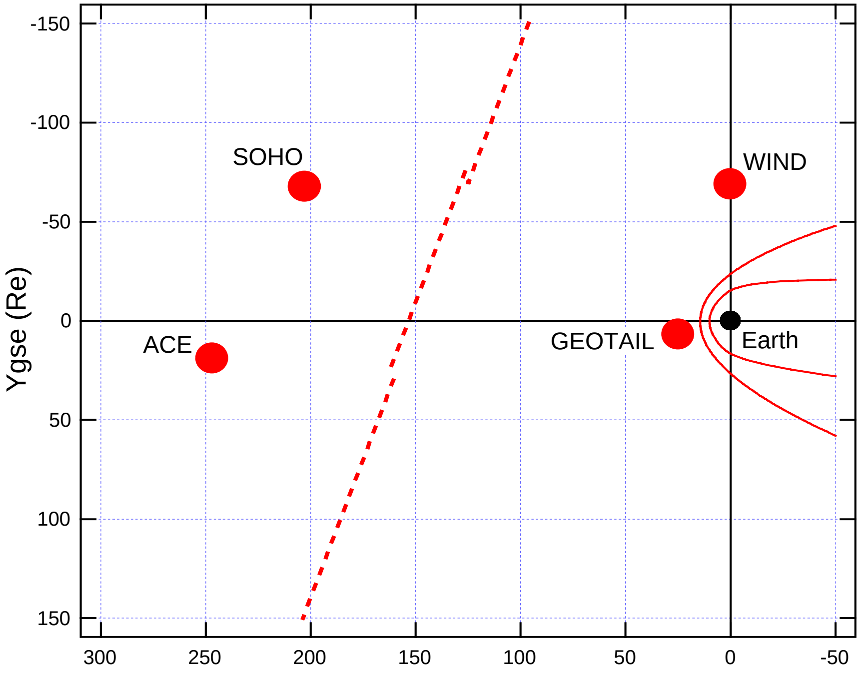
split plane surface model --- solution

Choose the best splitting time:
… agree with results from the conventional methods (WIND best fit, Geotail MVM)

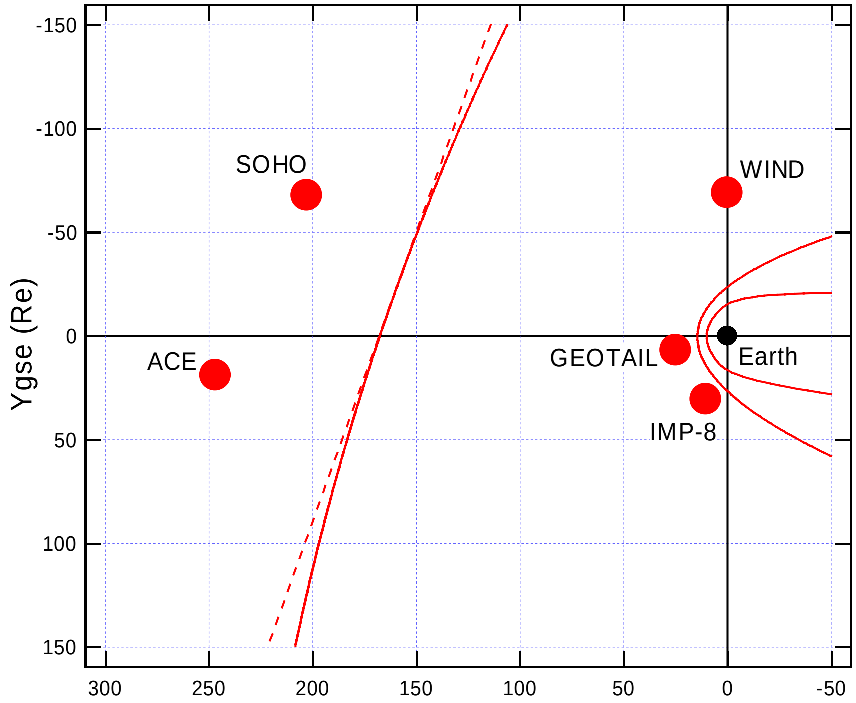


split plane surface model vs. spherical surface model

4-satellite method
Split plane surface model



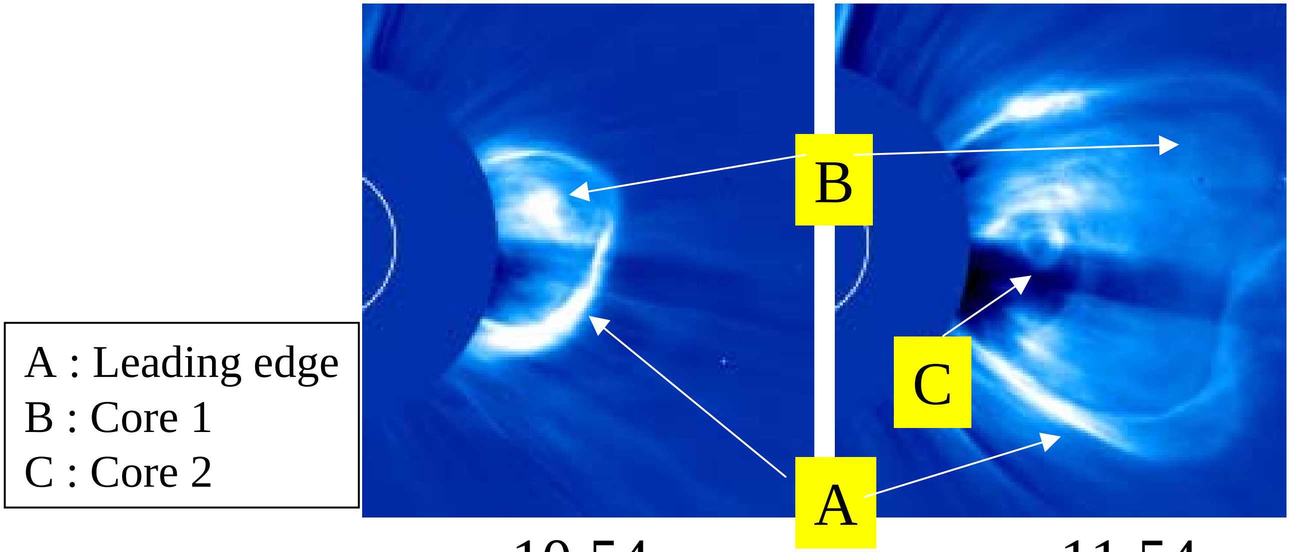
5-satellite method
spherical surface model



These two results seem to be not inconsistent.

It may not be so crazy to think of a concaved-shape IPS:

18 Jan 2000 CME SOHO/LASCO



10:54 11:54

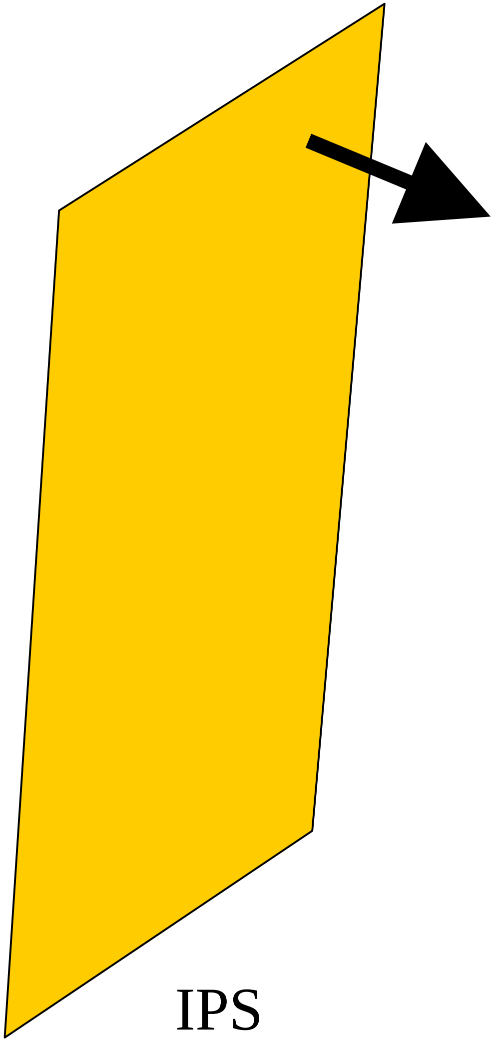
Ahead of such a concaved-shape CME, the shock may also have a concave shape ***locally***.

Question to solar radio astronomers:

Are there any peculiar type-II bursts relating to concaved shocks?

plane surface model with constant dVs/dt

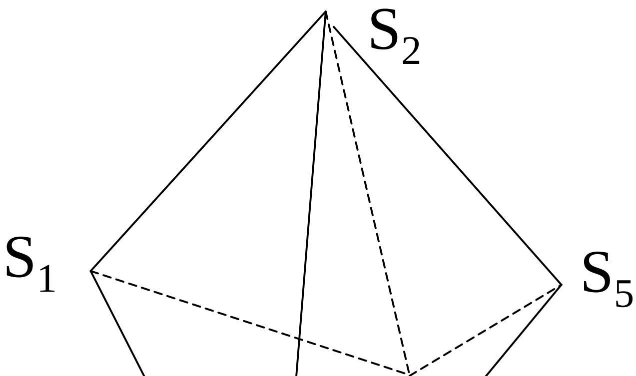
5 satellites determine shock parameters if the shock has a plane surface.



velocity ~ $Vs = Vs_0 + a\,'\,t$

(a: constant)

direction ~ $\vec{n}$



Physically unacceptable result:
IPS was accelerated from
660 km/s (at ACE) to
1330 km/s (at WIND)

Summary and comments

- We have formulated a 5-satellite method in which the shock curvature is derived from shock arrival times at these satellites.
- The method is applied to obtain the curvature radius of the Bastille interplanetary shock in 2000.
- This Bastille IPS seems to have had a concave shape locally when it arrived at the near-earth environment.

Application of the 5-satellite method:
STEREO + 3 other spacecraft

possible Japan's contribution to STEREO
(in addition to the Solar-B collaboration)
around Earth … GEOTAIL(1992-?), SELENE (2005-)
around Mars … NOZOMI (orbit insertion in Jan 2004)