Australian Government
Geoscience Australia

Observations of radio sources near the Sun

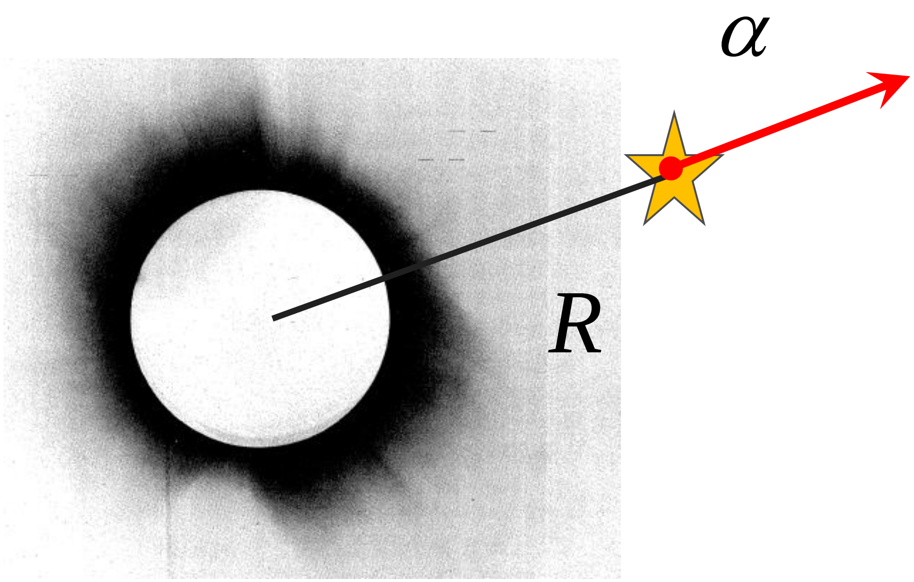
Oleg Titov[1], Sébastien Lambert[2], Benedikt Soja[3], Fenchun Shu[4], Alexei Melnikov[5], Jamie McMallum[6], Lucia McCallum[6], Matthias Schartner[7], Aletha de Witt[8], Dmitri Ivanov[5], Andrei Mikhailov[5], Sang Oh Yi[9], Wen Chen[10], Bo Xia[10], Masafumi Ishigaki[11], Sergei Gulyaev[12], Tim Natusch[12], Stuart Weston[12]

[1]Geoscience Australia; [2]Paris Observatory, CNRS, Sorbonne University; [3]Jet Propulsion Laboratory; [4]Shanghai Astronomical Observatory; [5]Institute of Applied Astronomy; [6]University of Tasmania; [7]Technical University of Wien; [8]Hartebeesthoek Radio Astronomical Observatory; [9]National Geographic Information Institute, Sejong Space Geodetic Observatory; [10]Shanghai Astronomical Observatory; [11]Geospatial Information Authority of Japan; [12]Auckland University of Technology

General Relativity

Einstein predicted the light deflection for the Solar gravitational field on 1”.75 for the Solar radius R ~ 700.000 km (1915).

$$\alpha = \frac{4GM}{c^2 R}$$



General Relativity

1. Eddington detected the deflection in 1919;
   Dyson, Eddington and Davidson (1920)

IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May* 29, 1919.

By Sir F. W. DYSON, *F.R.S., Astronomer Royal, Prof.* A. S. EDDINGTON, *F.R.S., and Mr.* C. DAVIDSON.

(*Communicated by the Joint Permanent Eclipse Committee.*)

The result from declinations is about twice the weight of that from right ascensions, so that the mean result is

$$1''\cdot98$$

with a probable error of about $\pm 0''\cdot12$.

The Principe observations were generally interfered with by cloud. The unfavourable circumstances were perhaps partly compensated by the advantage of the extremely uniform temperature of the island. The deflection obtained was

$$1''\cdot61.$$

The probable error is about $\pm 0''\cdot30$, so that the result has much less weight than the preceding.

Equation for the light deflection at arbitrary elongation (Shapiro, 1967)

$$\alpha = \frac{2GM}{c^2 r} ctg\frac{\theta}{2}$$

Parametrised **P**ost-**N**ewtonian (PPN) approximation (Will, 1973)

γ = 1 in General Relativity; a constant parameter for all elongations θ

$$\alpha = \frac{2GM}{c^2 r} ctg\frac{\theta}{2} = \frac{(1+\gamma)GM}{c^2 r} ctg\frac{\theta}{2}$$

Small angle approximation $\theta \to 0$

$$\frac{1}{r} ctg\frac{\theta}{2} = \frac{2}{R}$$

$$\alpha = \frac{4GM}{c^2 R} = \frac{2(1+\gamma)GM}{c^2 R}$$

α = 1".75 for grazing light,

$R = R_{\odot}$

Time delay vs light deflection

$$\tau_{geom} = \frac{-\frac{(\boldsymbol{b}\cdot\boldsymbol{s})}{c}\left(1-\frac{(1+\gamma)GM}{c^2 r}-\frac{\langle \boldsymbol{V}_\oplus{}^2\rangle}{2c^2}-\frac{(\boldsymbol{V}_\oplus\cdot\boldsymbol{w}_2)}{c^2}\right)-\frac{1}{c^2}(\boldsymbol{b}\cdot\boldsymbol{V}_\oplus)\left(1+\frac{(\boldsymbol{V}_\oplus\cdot\boldsymbol{s})}{2c}\right)}{1+\frac{1}{c}(\boldsymbol{s}\cdot(\boldsymbol{V}_\oplus+\boldsymbol{w}_2))}$$

$$\tau_{grav} = \frac{(1+\gamma)GM}{c^3}\ln\frac{|\boldsymbol{r}_1|+(\boldsymbol{r}_1\cdot\boldsymbol{s})}{|\boldsymbol{r}_2|+(\boldsymbol{r}_2\cdot\boldsymbol{s})},$$

$$\tau_{GR} = \tau_{grav}+\tau_{coord} = \frac{(1+\gamma)GM}{c^3}\ln\frac{|\boldsymbol{r}_1|+(\boldsymbol{r}_1\cdot\boldsymbol{s})}{|\boldsymbol{r}_2|+(\boldsymbol{r}_2\cdot\boldsymbol{s})}+\frac{(1+\gamma)(\boldsymbol{b}\cdot\boldsymbol{s})}{c}\frac{GM}{c^2 r}$$

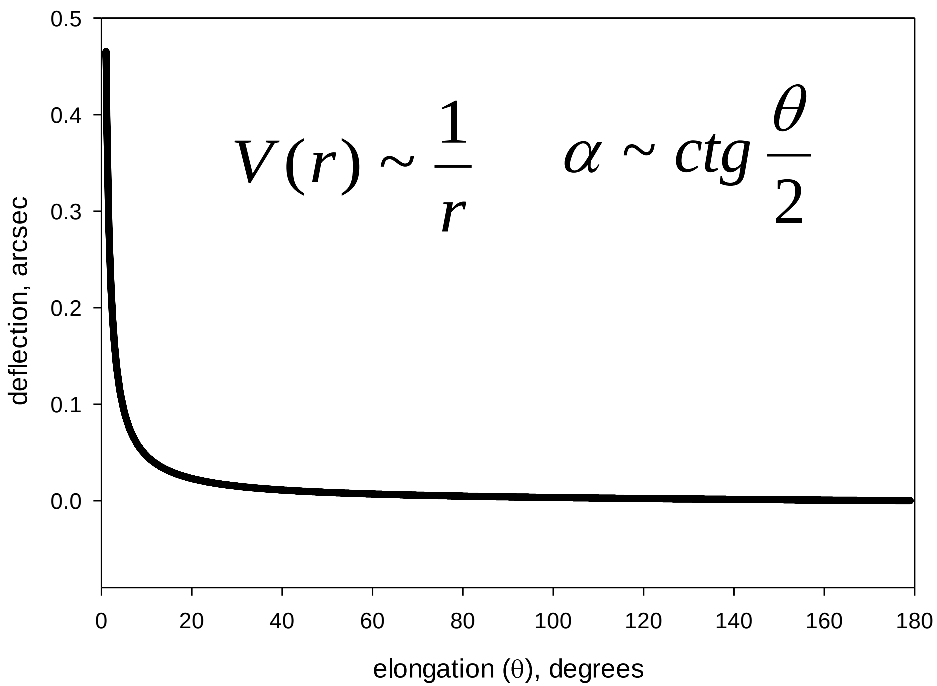
$$\tau_{GR} = \alpha\frac{b}{c}sin\varphi cosA + \cdots \qquad \alpha = \frac{(1+\gamma)GM}{c^2 r}ctg\frac{\theta}{2}$$

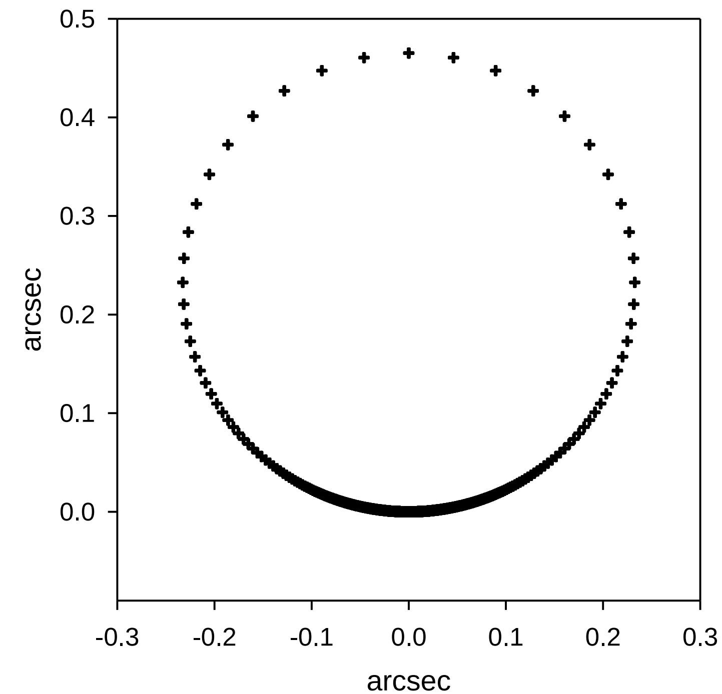
Titov & Girdiuk A&A(2015)

Light deflection in VLBI

$$\alpha = \frac{2GM}{c^2R}\frac{\sin\theta}{1-\cos\theta}$$

Shapiro, Science, (1967); Ward, ApJ, (1970)





For a radio source within 1° from Sun

Test of General Relativity with VLBI

1. The gravitational delay includes the PPN parameter gamma, which is estimated using a large set of geodetic VLBI (since 1980s).
2. The current accuracy of the γ estimate is $\sigma \approx 2 \times 10^{-4}$, whereas numerous modifications of the theory of gravity predict deviation from γ=1 at level of $\Delta\gamma = 10^{-6} \div 10^{-7}$
3. From the “Cassini” experiment $\sigma \approx 2 \times\ 10^{-5}$ (Bertotti et al. 2003)

Test of General Relativity with VLBI

Table 1. Review of γ-determination using geodetic VLBI data.

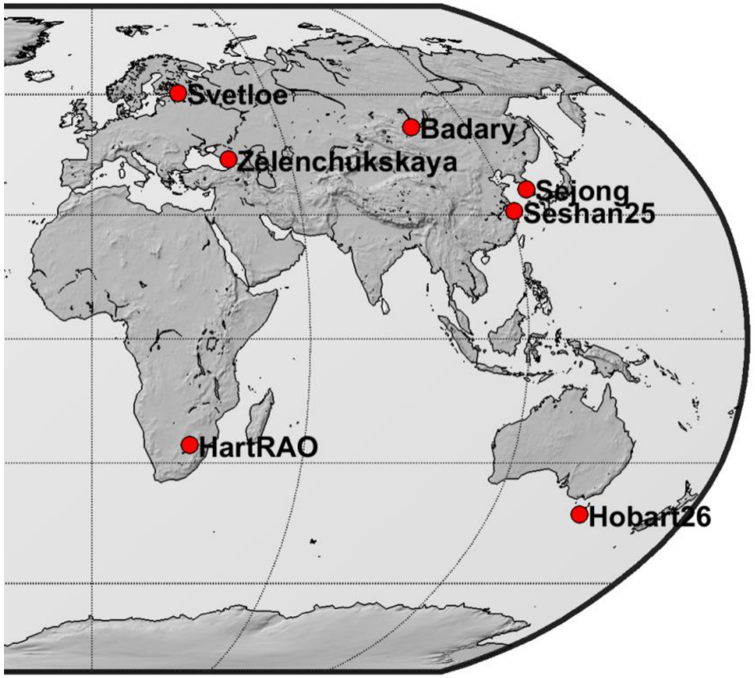
Author(s)	Year	γ	σ	Data
Counselman *et al.*	1974	0.98	±0.06	1972 occultation of 3C279 by the Sun
Fomalont & Sramek	1975	1.0075	±0.022	1974 occultation of 3C279 by the Sun
Fomalont & Sramek	1976	1.0035	±0.018	1974 and 1975 occultation of 3C279 by the Sun
Robertson & Carter	1984	1.008	±0.005	MERIT, POLARIS, IRIS
Carter, Robertson & MacKay	1985	1.000	±0.003	POLARIS, IRIS since 1980
Robertson, Carter & Dillinger	1991	1.000	±0.002	POLARIS, IRIS, CDP since 1980
Lebach *et al.*	1995	0.9996	±0.0017	1987 occultation of 3C279 by the Sun
Eubanks *et al.*	1997	0.99994	±0.00031	Geodetic VLBI sessions from 1979 to 1997
Shapiro *et al.*	2004	0.9998	±0.0002[1]	Geodetic VLBI sessions from 1979 to 1999
Lambert & Le Poncin-Lafitte	2009	0.99984	±0.00015[2]	Geodetic VLBI sessions from 1979 to 2008

From "Cassini" σ ~ $2 \cdot 10^{-5}$ *Bertotti et al (2003)*

Single VLBI experiment to estimate parameter γ

Experiment AUA020 - custom designed and scheduled (IVS OPC did not support the R&D proposal)

AUA020 - 1 May 2017 with 7 radio telescopes (Asia, Australia, South Africa, Europe), data correlated in Shanghai Astronomical Observatory



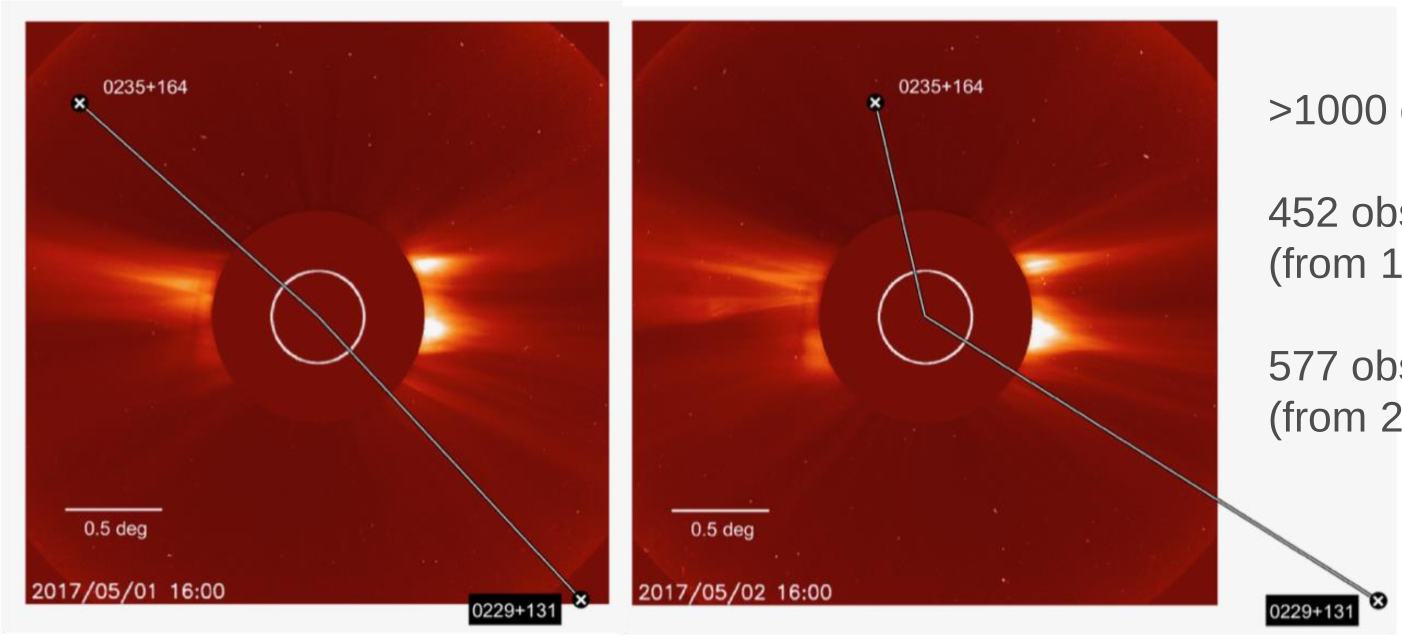
24-hour experiment

first 6 hours and the last hour – standard geodetic schedule

17 hours – focusing on two radio sources near the Sun

Single VLBI experiment to estimate parameter γ

Two radio sources were observed within 1°-3° from the Sun during 17 hours



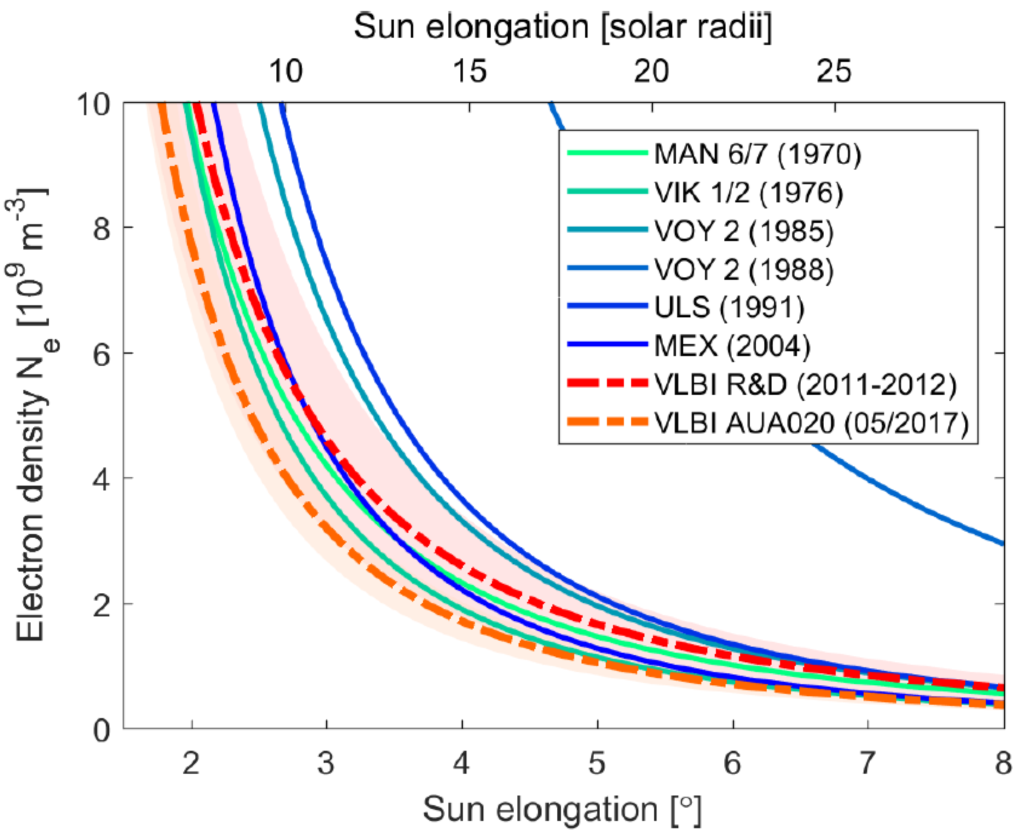
>1000 observations

452 obs of 0235+164 (from 1º.5 to 1º.15)

577 obs of 0229+131 (from 2º.2 to 2º.6)

Solar corona electon density

Comparison to spacecraft tracking II



$$N_e(r) = N_0\, r^{-\beta}$$

- Estimating N_0 & β:

  $N_0 = (0.61 \pm 0.05)\ 10^{12}\ \mathrm{m}^{-3}$

  $\beta = 2.18 \pm 0.06$

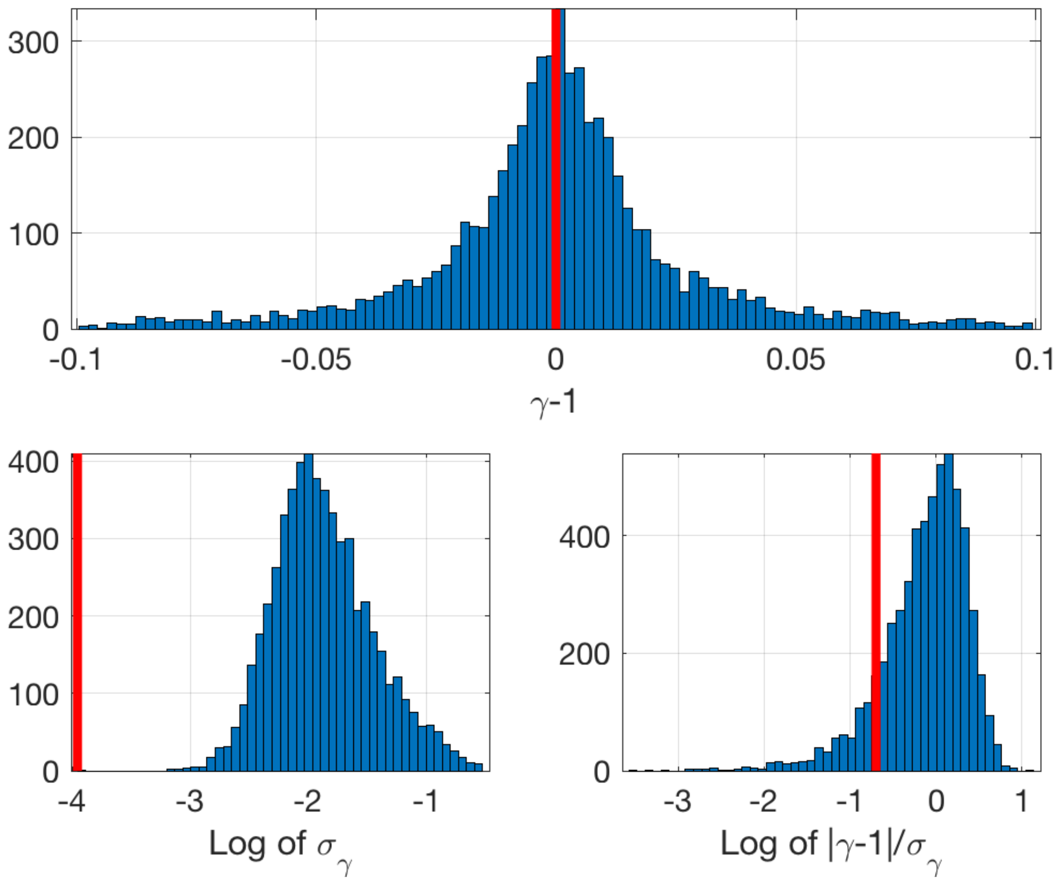
First determination of **both power-law parameters** N_0 & β

•2+ radio sources close to the Sun needed

(Soja et al. EGU 2018)

Estimation of PPN parameter γ (ICRF2)

In general relativity γ = 1



To find correction Δγ

AUA020 vs all other IVS sessions

Estimation of $\Delta\gamma \cdot 10^{-4}$

0235+164	1.16	+/-	1.29
0229+131	0.32	+/-	2.83

Both sources
$\Delta\gamma = 0.89\ (+/-\ 0.94) \cdot 10^{-4}$, i. e.
better than from a global solution

Testing general relativity with geodetic VLBI

Astronomy & Astrophysics manuscript no. 33459
July 19, 2018

Testing general relativity with geodetic VLBI

What a single, specially designed experiment can teach us

O. Titov[1], A. Girdiuk[2], S. B. Lambert[3], J. Lovell[4], J. McCallum[4], S. Shabala[4], L. McCallum[4], D. Mayer[2], M. Schartner[2], A. de Witt[5], F. Shu[6], A. Melnikov[7], D. Ivanov[7], A. Mikhailov[7], S. Yi[8], B. Soja[9], B. Xia[6], and T. Jiang[6]

[1] Geoscience Australia, Canberra, PO Box 378, ACT, 2601, Australia, e-mail: oleg.titov@ga.gov.au
[2] Department of Geodesy and Geoinformation, Research Group Advanced Geodesy, TU Wien, Gusshausstraße 27-29/E120.4, Wien-1040, Austria
[3] SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, Paris, France
[4] University of Tasmania, Private Bag 37, Hobart, Tasmania, 7001, Australia
[5] Hartebeesthoek Radio Astronomy Observatory, PO Box 443, Krugersdorp, 1740, South Africa
[6] Shanghai Astronomical Observatory, 80 Nandan Road, Shanghai, 200030, China
[7] Institute of Applied Astronomy, Kutuzov Embankment, 10, Saint-Petersburg, 191187, Russia
[8] National Geographic Information Institute, Space Geodetic Observatory, Sejong, PO Box 30060, South Korea
[9] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

Estimation of PPN parameter γ (OCCAM vs SOLVE)

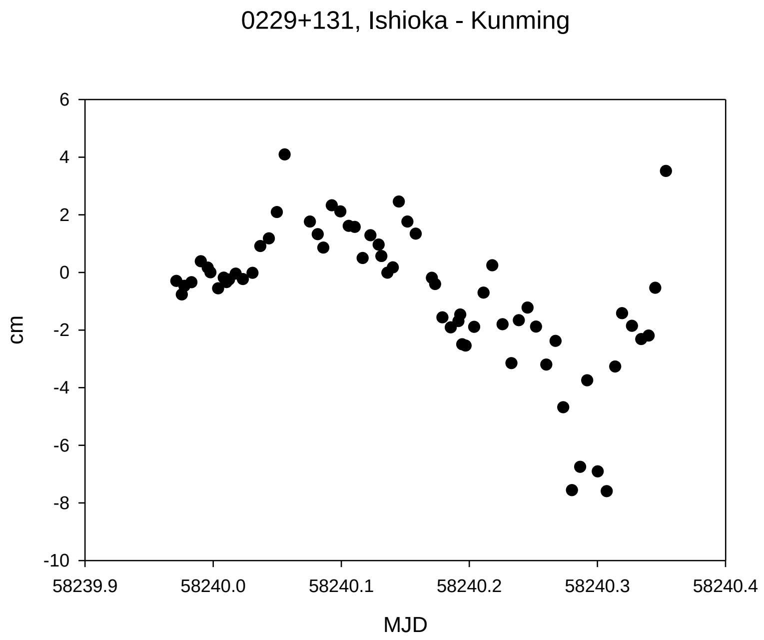
Estimation of $\Delta\gamma \cdot 10^{-4}$

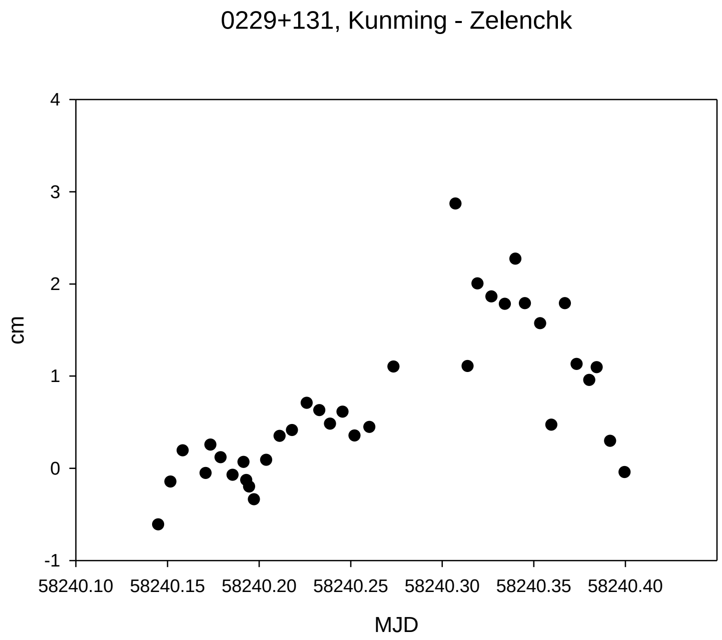
	OCCAM	SOLVE
0235+164	1.64 +/- 1.29	1.85 +/- 1.48
0229+131	0.32 +/- 2.83	-6.84 +/- 2.53
Both sources	0.89 +/- 0.94	-0.26 +/- 1.09

New global solution done by Sebastien Lambert using VLBI data since 1979 (6301 sessions, 12.6 millions delays) provides $\sigma = 0.92 \cdot 10^{-4}$ **with AUA020 and** $\sigma = 0.97 \cdot 10^{-4}$ **without AUA020**

Single VLBI experiment AOV022

1 May 2018 with 9 radio telescopes (Asia, Australia, South Africa, Europe, NZ), data correlated in Shanghai Astronomical Observatory





Post-fit residuals show a strong systematic depending on baseline.
Strong source structure effect – needs to be cleaned

Conclusion

1. VLBI observations at small elongation angles are important
2. Solar corona could be estimated if two radio sources are measured at different elongation angles
3. AUA020 - formal accuracy of the PPN parameter γ is better than 10^{-4}
4. Estimate of γ is sensitive to the coordinates of the reference radio sources

Australian Government
Geoscience Australia

Any Questions?

Thank you for your attention

Phone: +61 2 6249 9111
Web: www.ga.gov.au
Email: oleg.titov@ga.gov.au
Address: Cnr Jerrabomberra Avenue and Hindmarsh Drive, Symonston ACT 2609
Postal Address: GPO Box 378, Canberra ACT 2601