SERC SPACE ENVIRONMENT RESEARCH CENTRE

A method for sampling debris laser ranging data to generate range rates for orbit determination

James Bennett

Australian Government
Department of Industry and Science
Business Cooperative Research Centres Programme

Context

- SERC (RP3) are building a conjunction & threat warning service:
  - All-on-all conjunction assessments;
  - Optus (GEO):
    - Reliable conjunction assessments for mission longevity (less manoeuvres), safety;
    - Performed first active manoeuvre this year, another has also occurred;
  - Laser debris manoeuvre in LEO (debris-on-debris conjunctions):
    - 10+ kW CW laser for photon pressure manoeuvre (Dr Ben Greene presentation);

Optus B3

Catalogue & conjunction assessment service

- Precision tracking data;
  - Passive (with AO corrections)
    - Dr Francis Bennet presentation;
  - Active
    - Prof Yue Gao presentation;
- Spin analyses (MoU Graz):
  - Spin & orientation using CCD, photon counters, kHz SLR
    - Dr Daniel Kucharski presentation;
- Object characterisation;
- Signature matching;
- Station monitoring;
- Reliable OD & OP;
- Information-gain driven sensor network scheduling;
- Efficient CPU & GPU computation;
- Nonlinear error propagation (conj. assessments & sensor acquisition);
- Information-theory based catalogue construction (MoU Uni of Arizona)…

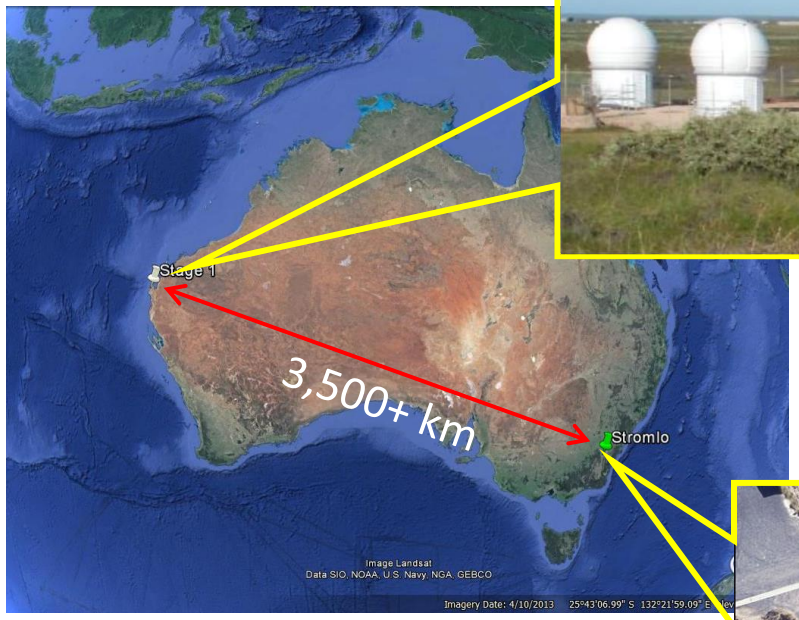
This work: maximise information derived from sensor.

Context

- Laser ranging to uncooperative debris objects;
  - New sensors, different mission – SSA;
  - Multiple acquisition systems;
  - Precision 3-dimensional observation data;
    - Very important in orbit determination in data sparse scenarios;
    - Stable, precise, rapid slew mounts allow for fast acquisition and precision angular observations.
    - Accurate & reliable mount modelling
      - Good distribution of stars observations for fitting;
      - Singular system;
      - Correlation of physical terms, avoid over-parameterisation, minimise intra-node error;
      - Well aligned system;
      - Automated.

New WA tracking site

- Partnership between EOS Space Systems & Lockheed Martin with support from AUS DoD;
- WA construction sees optical + laser tracking systems located in Western Australia (3,500+ km from Mt Stromlo);



Mount Stromlo

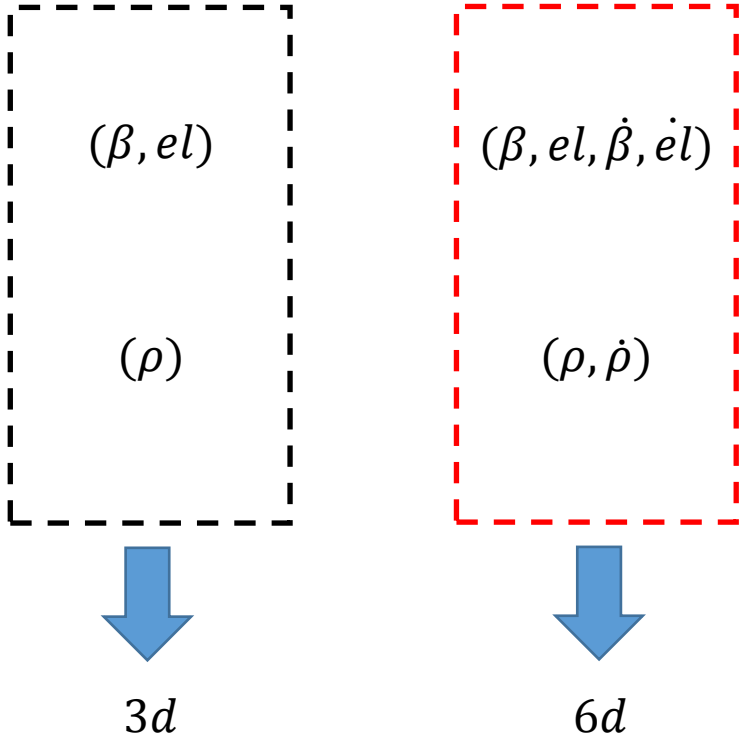
- Q4 2016 commissioning
- Passive, active precision tracking of uncooperative debris;
- Very little light pollution;
- Fully automated.

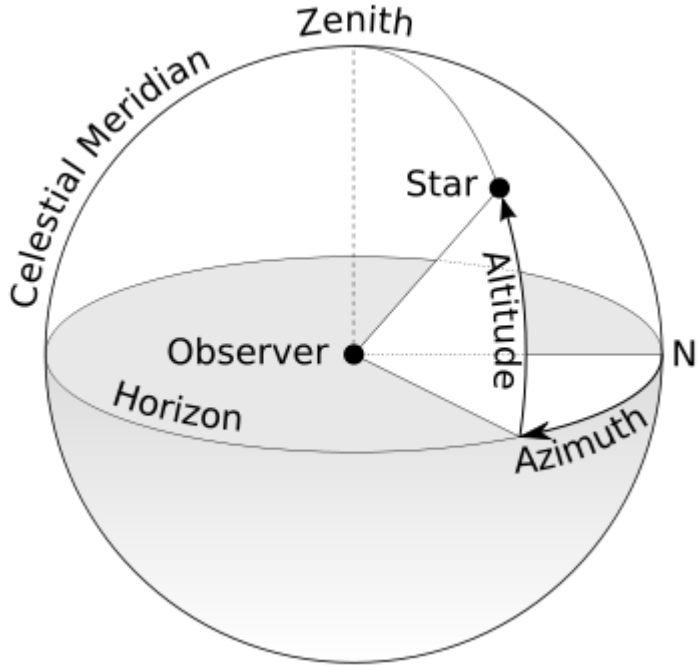
Motivation – 6 dimensional tracking information

- High-rate localised data not as useful as fewer observations distributed along the orbit path (orbit determination).
- However, high-rate data is important for object characterisation, e.g., characterising spin & orientation.

Motivation – 6 dimensional tracking information

- Passive optical:
- Active laser ranging:





- Useful for:
  - IOD & track associations;
  - Object identification;
  - Multiple object tracking in the FoV (passive);

Motivation – 6 dimensional tracking information

Earth-centred inertial:

$$\boxed{\boldsymbol{r}_{ECI}, \boldsymbol{v}_{ECI}} \rightarrow 6d$$

$$\boldsymbol{r}_{ECI} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \boldsymbol{v}_{ECI} = \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}$$

Earth-centred Earth-Fixed:

$$\boldsymbol{r}_{ECEF} = \boldsymbol{r}_{site,ECEF} + \boldsymbol{\rho}_{ECEF}$$
$$\boldsymbol{v}_{ECEF} = \dot{\boldsymbol{\rho}}_{ECEF}$$

Topcentric SEZ:

$$\boldsymbol{\rho}_{SEZ} = ROT2\left(\frac{\pi}{2} - \phi_{gd}\right) ROT3(\lambda) \boldsymbol{\rho}_{ECEF}$$
$$\dot{\boldsymbol{\rho}}_{SEZ} = ROT2\left(\frac{\pi}{2} - \phi_{gd}\right) ROT3(\lambda) \dot{\boldsymbol{\rho}}_{ECEF}$$

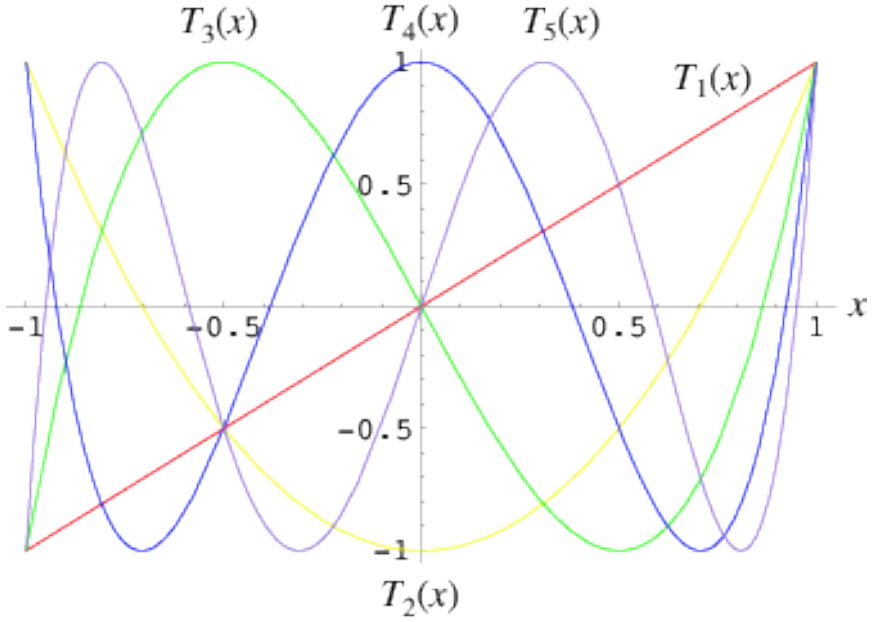
$$\boldsymbol{\rho}_{SEZ} = \begin{bmatrix} -\rho \cos(el) \cos(\beta) \\ \rho \cos(el) \sin(\beta) \\ \rho \sin(el) \end{bmatrix}, \dot{\boldsymbol{\rho}}_{SEZ} = \frac{d}{dt} \boldsymbol{\rho}_{SEZ}$$

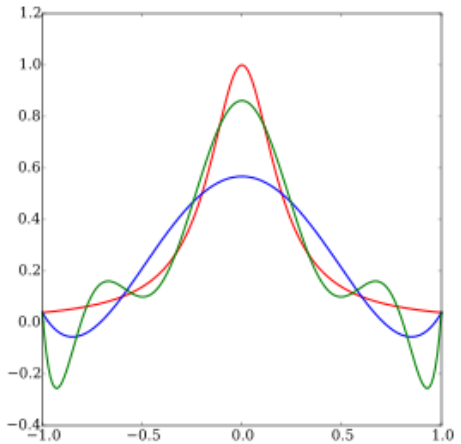
Observations:

$$\boxed{(\beta, \dot{\beta}, el, \dot{el}, \rho, \dot{\rho})} \rightarrow 6d$$

Chebyshev Polynomial Fitting

- Chebyshev polynomials are orthogonal. Recursive;
- Minimise Runge's phenomena for interpolation.
- Piecewise LS fitting used here, avoid ill-conditioned system;
- If function form fits data well then residuals should be normally distributed. Outliers!





Chebyshev Poynomials

- Recursive definition of Cheby polynomials of 1st kind:

$$T_0(x) = 1, \qquad T_1(x) = x, \qquad T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x).$$

- Approximating function:

$$f(x) = \sum_{n=0}^{2} a_n T_n(x), \;\; x \in [-1,1].$$

- Recursive definition of Cheby polynomials of 2nd kind:

$$U_0(x) = 1, \qquad U_1(x) = 2x, \qquad U_{n+1}(x) = 2xU_n(x) - U_{n-1}(x).$$

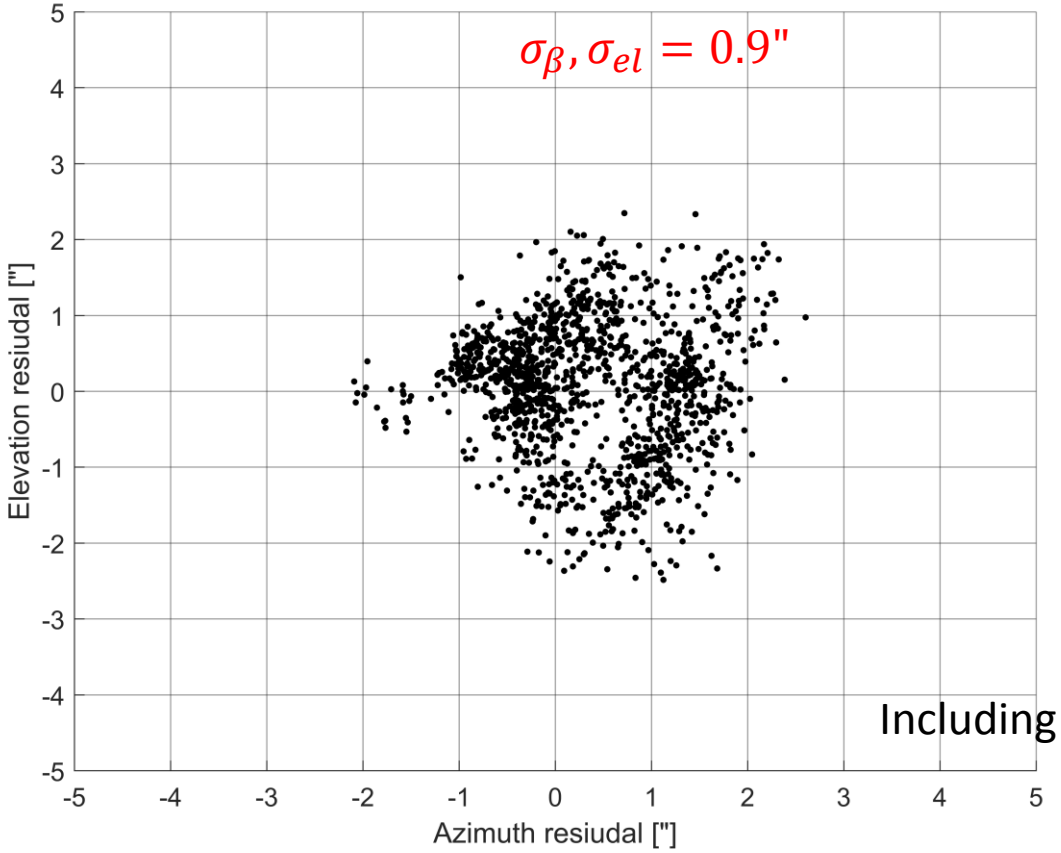
- Approximating function derivative:

$$f'(x) = \sum_{n=1}^{2} a_n \, n \, U_{n-1}(x), \;\; x \in [-1,1].$$

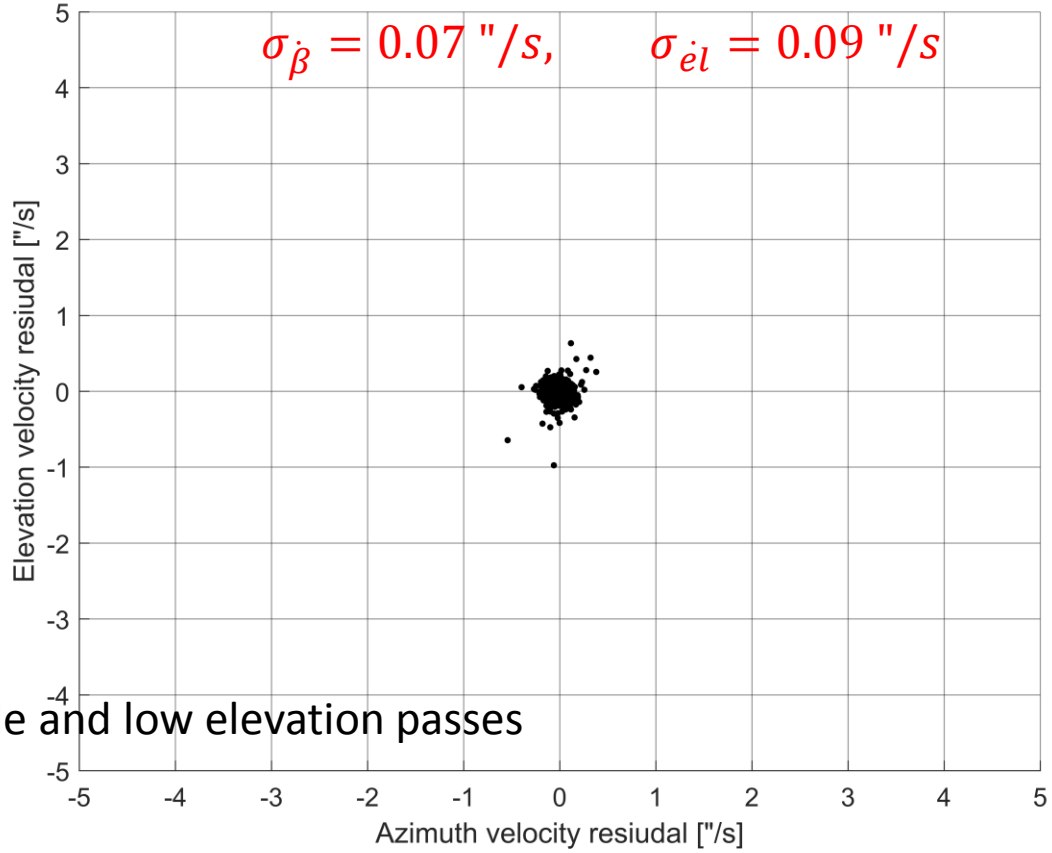
- Normalisation:

$$x = \frac{2t - (t_a + t_b)}{t_b - t_a}, t \in [t_a, t_b].$$

Angles and angles rate residuals for Lageos 1 & Lageos 2



β, el residuals in arc-seconds



$\dot\beta, \dot el$ residuals in arc-sec/s

Including keyhole and low elevation passes

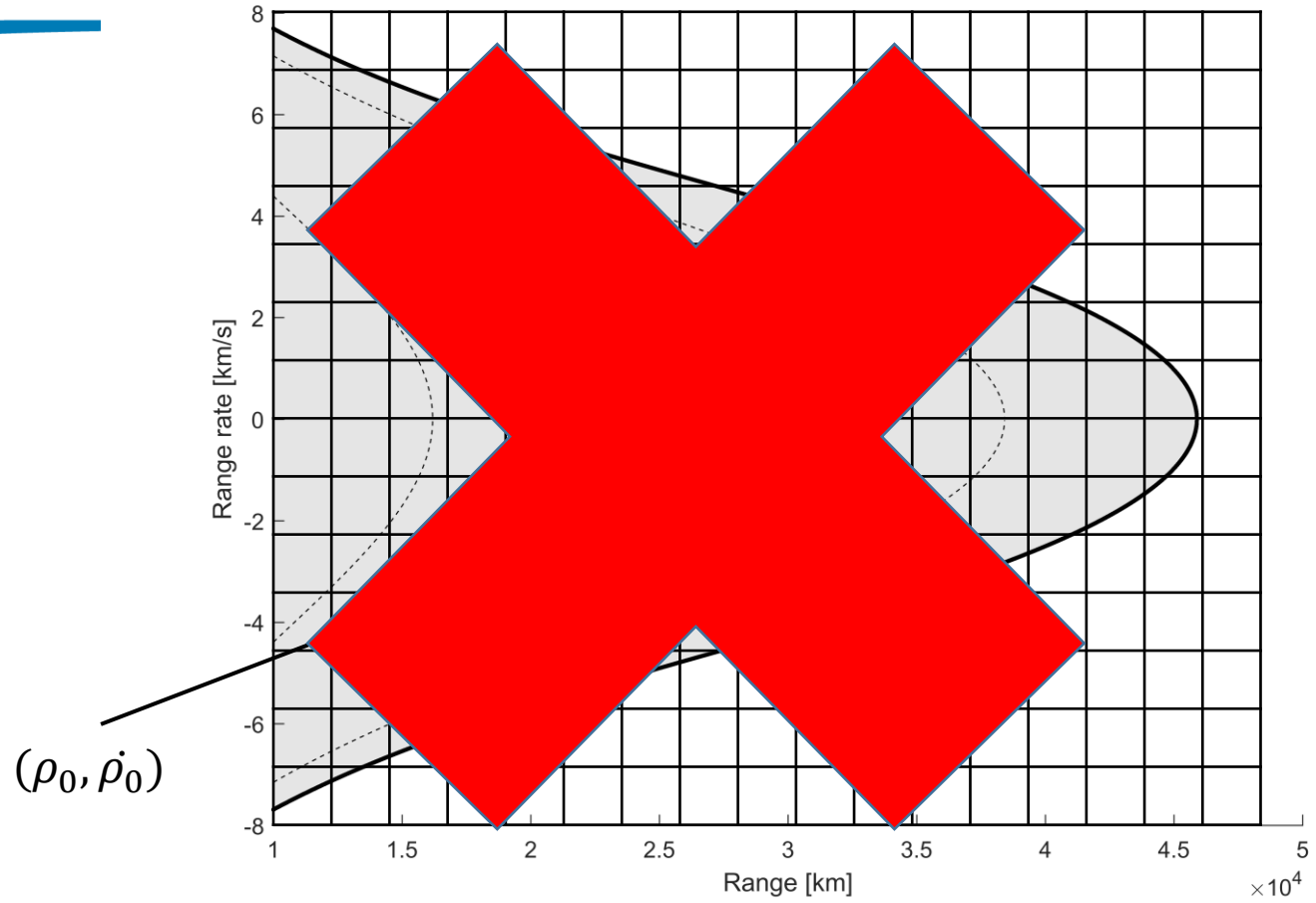
$(\beta, \dot\beta, el, \dot el)$ $(\rho, \dot\rho)$

Admissible regions

- Passive optical:
  - Underdetermined system
    - Two-body energy:

$$\xi = \frac{\|\boldsymbol{v}\|^2}{2} - \frac{\mu}{\|\boldsymbol{r}\|},$$

$$\xi = 0 \rightarrow (\rho, \dot{\rho})$$



Chebyshev Poynomials

- Approximating function:

$$f(x) = \sum_{n=0}^{2} a_n T_n(x), \quad x \in [-1,1].$$

- Approximating function derivative:

$$f'(x) = \sum_{n=1}^{2} a_n \, n \, U_{n-1}(x), \quad x \in [-1,1].$$

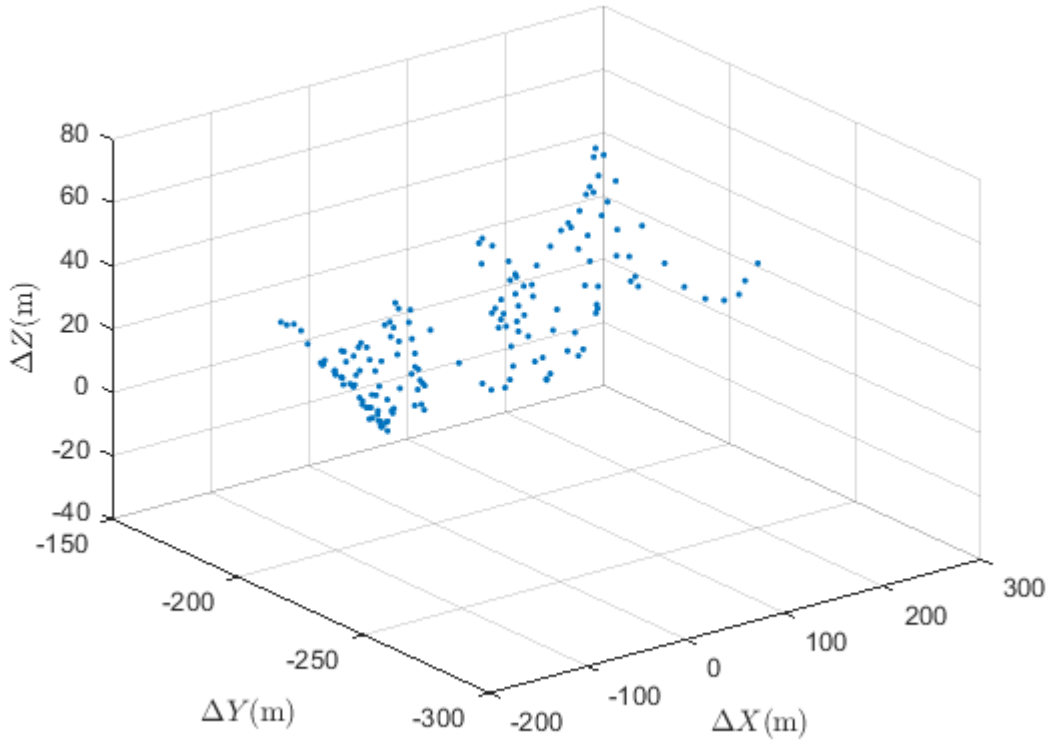
- Normalisation:

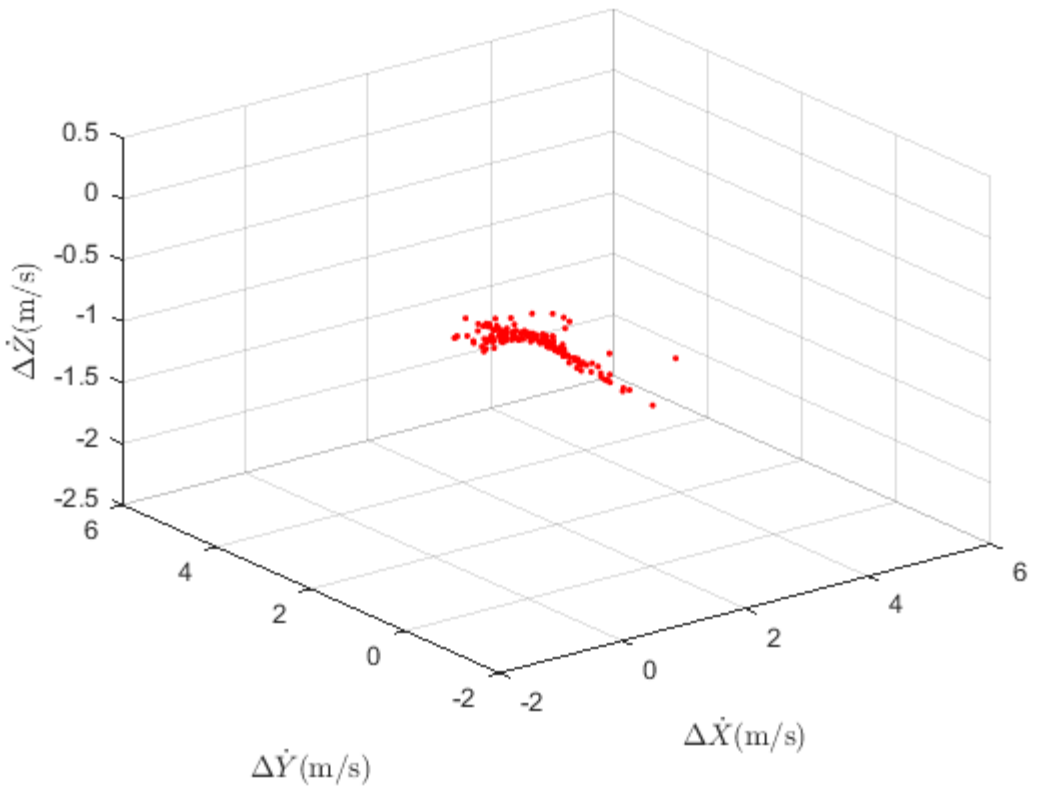
$$x = \frac{2t - (t_a + t_b)}{t_b - t_a}, t \in [t_a, t_b].$$

$$(\rho, \dot{\rho})$$

Result - Full state information

- Including the rates of change allow for calculation of a state vector directly;
- Constrain physical object parameters?





Conclusions

- Method gives full 6d tracking information;
  - Better OD constraint, improves orbit determination convergence;
- Multi-object detection, tracking, correlation.
- Improvements would be achieved for higher rate observation collection
  - Photon counter, kHz laser;
- Improved in the case of existing state information, transform to residual space;
- Space debris tracking - mission support?

Conjunction assessment

- 75 close approaches with ILRS objects over 3 day prediction;

Primary	Secondary	TCA Date	TCA Time	Distance	Velocity	AGE Primary	Age Secondary	Name	Name
NORAD	NORAD			[km]	[km/s]	[days]	[days]		
22824	735	15/10/2016	16:00:48	1.126	14.286	2.477	3.353	0 STELLA	0 OPS 3367 B
36605	16495	16/10/2016	22:32:20	1.163	3.138	3.629	5.282	0 TANDEM X	0 COSMOS 1726
27944	33854	17/10/2016	12:07:12	1.169	13.223	4.223	4.944	0 LARETS	0 IRIDIUM 33 DEB
31698	16495	16/10/2016	22:32:20	1.24	3.138	3.561	5.282	0 TERRA SAR X	0 COSMOS 1726
27944	33854	17/10/2016	12:07:12	1.263	13.223	4.223	5.649	0 LARETS	0 IRIDIUM 33 DEB
36605	16495	16/10/2016	22:32:20	1.275	3.138	3.629	4.296	0 TANDEM X	0 COSMOS 1726
22824	35330	17/10/2016	20:12:04	1.454	0.097	4.652	6.025	0 STELLA	0 CZ-4 DEB
27391	41475	14/10/2016	14:45:01	1.481	14.488	1.421	2.354	0 GRACE 1	0 CADRE
39086	30499	15/10/2016	15:13:19	1.574	0.837	2.742	4.131	0 SARAL	0 FENGYUN 1C DEB
27392	41475	14/10/2016	10:09:53	1.583	14.489	1.24	1.591	0 GRACE 2	0 CADRE
27944	26980	17/10/2016	06:39:16	1.728	14.965	3.995	5.343	0 LARETS	0 SL-16 DEB
41335	22824	14/10/2016	16:33:03	1.834	12.447	1.388	2.769	0 SENTINEL 3A	0 STELLA
36605	33504	16/10/2016	07:28:22	1.842	15.196	3.001	4.669	0 TANDEM X	0 KORONAS-FOTON
36605	33504	16/10/2016	07:28:22	1.845	15.196	3.001	3.678	0 TANDEM X	0 KORONAS-FOTON
22824	41335	14/10/2016	16:33:03	1.869	12.447	1.5	1.388	0 STELLA	0 SENTINEL 3A
22824	41335	14/10/2016	16:33:03	1.904	12.447	1.5	1.879	0 STELLA	0 SENTINEL 3A
22824	41335	14/10/2016	16:33:03	1.92	12.447	1.5	2.229	0 STELLA	0 SENTINEL 3A
31698	33504	16/10/2016	07:28:22	1.936	15.196	2.933	3.678	0 TERRA SAR X	0 KORONAS-FOTON
22824	41335	14/10/2016	16:33:03	1.963	12.447	1.5	2.72	0 STELLA	0 SENTINEL 3A
39086	5397	14/10/2016	00:53:37	2.093	14.911	1.145	1.42	0 SARAL	0 OV1-21 R/B
31698	16495	16/10/2016	22:32:20	2.196	3.138	3.561	4.296	0 TERRA SAR X	0 COSMOS 1726
41464	22447	16/10/2016	06:23:46	2.236	9.875	2.884	4.942	0 MVL 300	0 DELTA 2 R/B(1)
7646	31005	16/10/2016	05:25:26	2.257	7.202	3.029	4.619	0 STARLETTE	0 FENGYUN 1C DEB
22824	2141	17/10/2016	16:03:53	2.292	5.071	4.479	4.94	0 STELLA	0 SCOUT A DEB
27392	41475	14/10/2016	10:09:53	2.317	14.489	1.24	2.29	0 GRACE 2	0 CADRE
41335	30366	17/10/2016	00:50:54	2.563	6.933	3.733	5.246	0 SENTINEL 3A	0 FENGYUN 1C DEB
41335	30366	17/10/2016	00:50:54	2.619	6.933	3.733	4.131	0 SENTINEL 3A	0 FENGYUN 1C DEB
40903	39186	17/10/2016	02:35:03	2.687	5.634	3.824	4.603	0 XW-2A	0 RESURS P1
40903	39186	17/10/2016	02:35:03	2.7	5.634	3.824	4.871	0 XW-2A	0 RESURS P1
40903	39186	17/10/2016	02:35:03	2.715	5.634	3.824	4.215	0 XW-2A	0 RESURS P1
41464	22447	16/10/2016	06:23:46	2.766	9.875	2.884	4.09	0 MVL 300	0 DELTA 2 R/B(1)
27391	41475	14/10/2016	15:30:50	2.802	14.497	1.453	2.768	0 GRACE 1	0 CADRE
27391	41475	14/10/2016	15:30:50	2.803	14.497	1.453	2.768	0 GRACE 1	0 CADRE
39068	34270	14/10/2016	17:54:47	2.807	11.285	1.587	2.599	0 STSAT 2C	0 COSMOS 2251 DEB
39068	34270	14/10/2016	17:54:47	2.891	11.285	1.587	3.082	0 STSAT 2C	0 COSMOS 2251 DEB

Conjunction assessment – cont.

- Accurate debris object tracking can provide extra mission support to customers;
- Laser manoeuvre could potentially help protect non-manoeuvrable objects.

22824	735	15/10/2016	17:41:44	2.908	14.286	2.547	3.983	0 STELLA	0 OPS 3367 B
22824	735	15/10/2016	17:41:44	2.921	14.286	2.547	3.423	0 STELLA	0 OPS 3367 B
22824	31563	14/10/2016	04:51:57	2.947	8.222	1.013	2.05	0 STELLA	0 FENGYUN 1C DEB
27392	41475	14/10/2016	10:55:43	2.98	14.499	1.272	2.195	0 GRACE 2	0 CADRE
27944	33854	17/10/2016	06:22:27	3.115	13.207	3.984	4.705	0 LARETS	0 IRIDIUM 33 DEB
27944	32474	14/10/2016	20:02:27	3.13	12.895	1.553	2.908	0 LARETS	0 CZ-4 DEB
27392	41475	14/10/2016	10:55:42	3.153	14.499	1.272	1.622	0 GRACE 2	0 CADRE
22824	41074	17/10/2016	05:56:33	3.165	13.116	4.058	5.046	0 STELLA	0 NOAA 16 DEB
27944	32474	14/10/2016	20:02:27	3.181	12.895	1.553	2.618	0 LARETS	0 CZ-4 DEB
22824	41074	17/10/2016	05:56:33	3.236	13.116	4.058	5.605	0 STELLA	0 NOAA 16 DEB
27944	33854	17/10/2016	06:22:27	3.341	13.207	3.984	5.41	0 LARETS	0 IRIDIUM 33 DEB
7646	18426	17/10/2016	02:39:51	3.343	13.091	3.914	4.816	0 STARLETTE	0 SCOUT G-1 DEB
27944	33854	17/10/2016	08:00:57	3.36	13.213	4.052	5.478	0 LARETS	0 IRIDIUM 33 DEB
7646	18426	17/10/2016	02:39:51	3.372	13.091	3.914	5.83	0 STARLETTE	0 SCOUT G-1 DEB
27391	41475	14/10/2016	15:30:49	3.46	14.497	1.453	2.386	0 GRACE 1	0 CADRE
39086	22829	17/10/2016	04:53:07	3.477	13.519	4.311	4.31	0 SARAL	0 EYESAT A
39086	33782	16/10/2016	05:08:29	3.531	14.88	3.322	4.028	0 SARAL	0 COSMOS 2251 DEB
39086	33782	16/10/2016	05:08:29	3.58	14.88	3.322	4.708	0 SARAL	0 COSMOS 2251 DEB
27944	33854	17/10/2016	08:00:57	3.587	13.213	4.052	4.773	0 LARETS	0 IRIDIUM 33 DEB
31698	41458	17/10/2016	07:50:08	3.588	1.636	3.948	4.479	0 TERRA SAR X	0 OUFTI-1
38077	21978	16/10/2016	05:12:15	3.702	1.79	2.925	4.27	0 LARES	0 COSMOS 2189
22824	735	15/10/2016	14:19:53	3.749	14.286	2.407	3.283	0 STELLA	0 OPS 3367 B
22824	735	15/10/2016	14:19:53	3.755	14.286	2.407	3.843	0 STELLA	0 OPS 3367 B
39086	34046	16/10/2016	17:10:21	3.786	12.624	3.823	5.061	0 SARAL	0 COSMOS 2251 DEB
39086	30499	15/10/2016	15:13:19	3.936	0.837	2.742	3.164	0 SARAL	0 FENGYUN 1C DEB
39086	15482	17/10/2016	00:04:30	4.064	6.524	4.11	4.708	0 SARAL	0 COSMOS 1624
39086	15482	17/10/2016	00:04:30	4.064	6.524	4.11	4.708	0 SARAL	0 COSMOS 1624
39086	15482	17/10/2016	00:04:30	4.084	6.524	4.11	5.216	0 SARAL	0 COSMOS 1624
39086	15482	17/10/2016	00:04:30	4.085	6.524	4.11	5.216	0 SARAL	0 COSMOS 1624
36508	39588	15/10/2016	03:14:21	4.372	14.592	1.941	2.583	0 CRYOSAT 2	0 COSMOS 2251 DEB
22824	29101	17/10/2016	10:33:14	4.398	14.83	4.25	5.708	0 STELLA	0 SL-16 DEB
31698	41612	14/10/2016	10:16:53	4.467	6.777	1.05	2.254	0 TERRA SAR X	0 FLOCK 2P-10
36605	41612	14/10/2016	10:16:53	4.471	6.777	1.118	2.254	0 TANDEM X	0 FLOCK 2P-10
36508	39588	15/10/2016	03:14:21	4.482	14.592	1.941	3.555	0 CRYOSAT 2	0 COSMOS 2251 DEB
27944	33854	17/10/2016	13:45:41	4.56	13.229	4.291	5.718	0 LARETS	0 IRIDIUM 33 DEB
27944	33854	17/10/2016	13:45:41	4.701	13.229	4.291	5.013	0 LARETS	0 IRIDIUM 33 DEB
31698	41612	14/10/2016	10:16:53	4.878	6.777	1.05	1.794	0 TERRA SAR X	0 FLOCK 2P-10
36605	41612	14/10/2016	10:16:53	4.883	6.777	1.118	1.794	0 TANDEM X	0 FLOCK 2P-10
39086	37612	15/10/2016	09:38:25	4.889	14.66	2.509	2.52	0 SARAL	0 CZ-4 DEB
39086	37612	15/10/2016	09:38:25	4.891	14.66	2.509	4.13	0 SARAL	0 CZ-4 DEB

SERC SPACE ENVIRONMENT RESEARCH CENTRE

Thank you

jamesbennett@serc.org.au
jbennett@eosspacesystems.com

info@serc.org.au

facebook.com/serc.aus

@serc_aus

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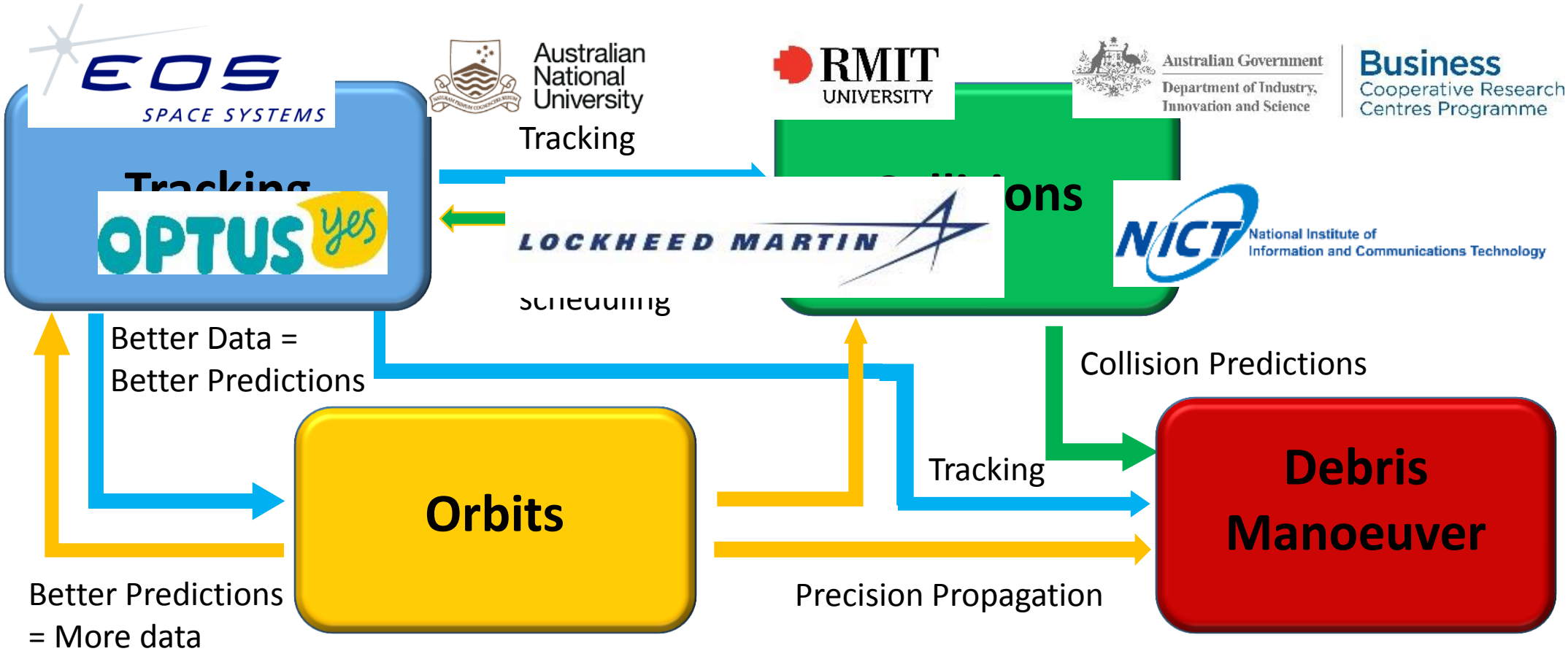

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