COMPUTATIONAL PROCEDURE TO INCREASE THE SHOOTING ACCURACY OF SWARMS OF SPACE-BASED LASER TRACKERS TO DEFLECT NEOs BY MEANS OF ABLATION

J. M. Gambi[1], **M. L. Garcia del Pino**[2], **J. Mosser**[3] and **E. B. Weinmueller**[3]

[1]Univ. Carlos III de Madrid, [2]IES Alpajes Aranjuez, [3]Technische Universitaet Wien

7th IAA PLANETARY DEFENSE CONFERENCE 2021
Vienna, April 26-30, 2021

Aim and Scope

- Following a current trend (*), we introduce a computational procedure to increase the shooting accuracy for laser spacecrafts deflecting threatening NEOs by means of ablation.
- The equations in the procedure are post-Newtonian (p-N) and take into account the gravitational gradients from the spacecrafts to the NEOs.
- The spacecrafts are meant to be lightweight, grouped and coordinated in swarms.
- At operative distances proposed in (**), the corrections to the current locations can be decisive to precisely reach spinning and tumbling NEOs at designated spots (***).

(*) A. Gibbings, M. Vasile, J.M. Hopkins, D. Burns and I. Watson (2012). Potential of laser-induced ablation for future space applications, Space Policy, 28: pp. 149-153.
(**) A. Gibbings, J.M. Hopkins, D. Burns, M. Vasile and I. Watson (2011). Exploring and exploiting asteroids with laser ablation. In: UK Space Conference, Coventry, UK, 4-5 July 2011.
(***) N. Thiry and M. Vasile (2015). Deflection of Uncooperative Targets Using Laser Ablation, Proc. of SPIE-The International Society for Optical Engineering. SPIE. http://dx.doi.org/10.1117/12.2197261

Heliocentric equations

(Notation as in extended abstract)

- To improve the trajectory of the target, D, with the spacecrafts S_i next to D, we use [(†)]

$$\bar{R}_i = \frac{s_i^3 - s_i^1}{2}\left[1 - \frac{\mu}{2}\int_0^1 (1-u)^2 \left(\frac{3\left(\mathbf{R}_i \cdot \mathbf{r}_i(u)\right)^2}{r_i(u)^5} - \frac{R_i^2}{r_i(u)^3}\right) du\right].$$

- To isolate the p-N effects from other perturbations, the equations of motion of D and of the spacecrafts from the final orbital elements are [(‡)]

$$\frac{d^2\bar{\mathbf{r}}}{dt^2} = \frac{-\mu\bar{\mathbf{r}}}{\bar{r}^3}\left[1 - \frac{2\mu\bar{\mathbf{r}}}{\bar{r}} + 2\left(\frac{d\bar{\mathbf{r}}}{d2}\right)^2 - \left(\frac{3}{\bar{r}^2} + \frac{2\mu}{\bar{r}^3}\right)\left(\bar{\mathbf{r}} \cdot \frac{d\bar{\mathbf{r}}}{dt}\right)^2\right]$$

$$+\frac{2\mu}{\bar{r}^3}\left(1 + \frac{2\mu}{\bar{r}}\right)\left(\bar{\mathbf{r}} \cdot \frac{d\bar{\mathbf{r}}}{dt}\right)\frac{d\bar{\mathbf{r}}}{dt}.$$

(†) J.M. Gambi and M.L. Garcia del Pino (2021). Post-Newtonian Tracking Formulae to Increase the Shooting Accuracy of Autonomous LEO Laser Trackers, Adv. Space Research, 67: pp. 2282-2303. https://doi.org/10.1016/j.asr.2021.01.028

(‡) J.M. Gambi, M.L. Garcia del Pino, J. Mosser, and E.B. Weinmüller (2021). Computational Modeling and Simulation to Increase Laser Shooting Accuracy of Autonomous LEO Trackers, Photonics, 8(2), 55: https://doi.org/10.3390/photonics8020055

Relative equations

(Notation as in extended abstract)

- The equations for the relative motion of D with respect to the spacecraft S_i are $^{(\star)}$

$$\frac{d^2\bar{\mathbf{R}}_i}{ds^2} = \mu \int_0^1 \left(\frac{3\left(\bar{\mathbf{R}}_i \cdot \bar{\mathbf{r}}_i(u)\right)\bar{\mathbf{r}}_i(u)}{\bar{r}_i(u)^5} - \frac{\bar{\mathbf{R}}_i}{\bar{r}_i(u)^3} \right)(1 - 2u + 3u^2)du$$

$$-\mu \int_0^1 \nabla\alpha \left(\frac{3\left(\bar{\mathbf{R}}_i \cdot \bar{\mathbf{r}}_i(u)\right)^2}{\bar{r}_i(u)^5} - \frac{\bar{R}_i^2}{\bar{r}_i(u)^3} \right)(1 - u)u^2 du$$

($\star$) J.M. Gambi, M.L. Garcia del Pino, J. Gschwindl, and E.B. Weinmüller (2017). Post-Newtonian Equations of Motion for LEO Debris Objects and Space-based Acquisition, Pointing and Tracking Laser Systems. Acta Astronautica, 141: pp. 132–142.

Control and time coordination (∗∗)

(Notation as in extended abstract)

$$\bar{R}_i = \frac{s_i^3 - s_i^1}{2}\left[1 - \frac{\mu}{2}\int_0^1 (1-u)^2 \left(\frac{3\left(\mathbf{R}_i \cdot \mathbf{r}_i(u)\right)^2}{r_i(u)^5} - \frac{R_i^2}{r_i(u)^3}\right) du\right]$$

$$t_{1_i} = t_2 - \bar{R}_{i_2}\left[1 + \frac{1}{6}\frac{\mu}{\bar{r}_{D_2}^3}\left(\frac{3\left(\bar{\mathbf{R}}_{i_2} \cdot \bar{\mathbf{r}}_{D_2}\right)^2}{\bar{r}_{D_2}^2} - \bar{R}_{i_2}^2\right) + \frac{\mu}{\bar{r}_{D_2}} + \frac{1}{2}\bar{v}_{D_2}^2\right]$$

(∗∗) J.M. Gambi and M.L. Garcia del Pino (2021). Post-Newtonian Tracking Formulae to Increase the Shooting Accuracy of Autonomous LEO Laser Trackers, Adv. Space Research, 67: pp. 2282-2303. https://doi.org/10.1016/j.asr.2021.01.028

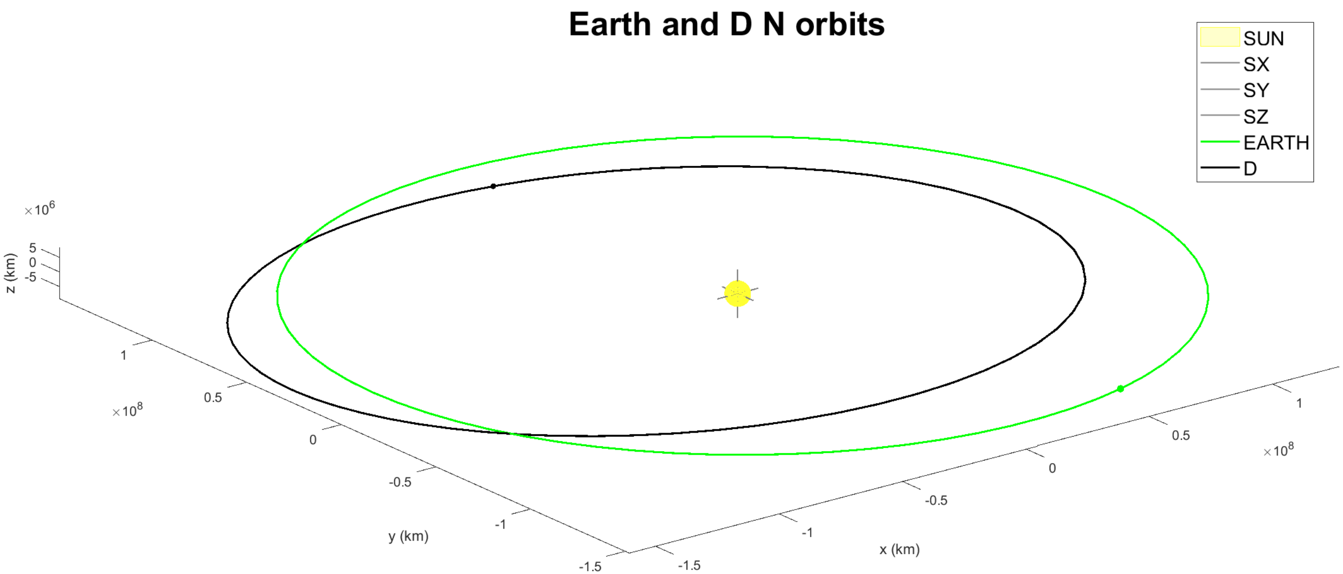
Simulations

- To avoid results contaminated by non p-N orbital corrections, we assume in the simulations below that the orbital elements of D derived by JPL are final.

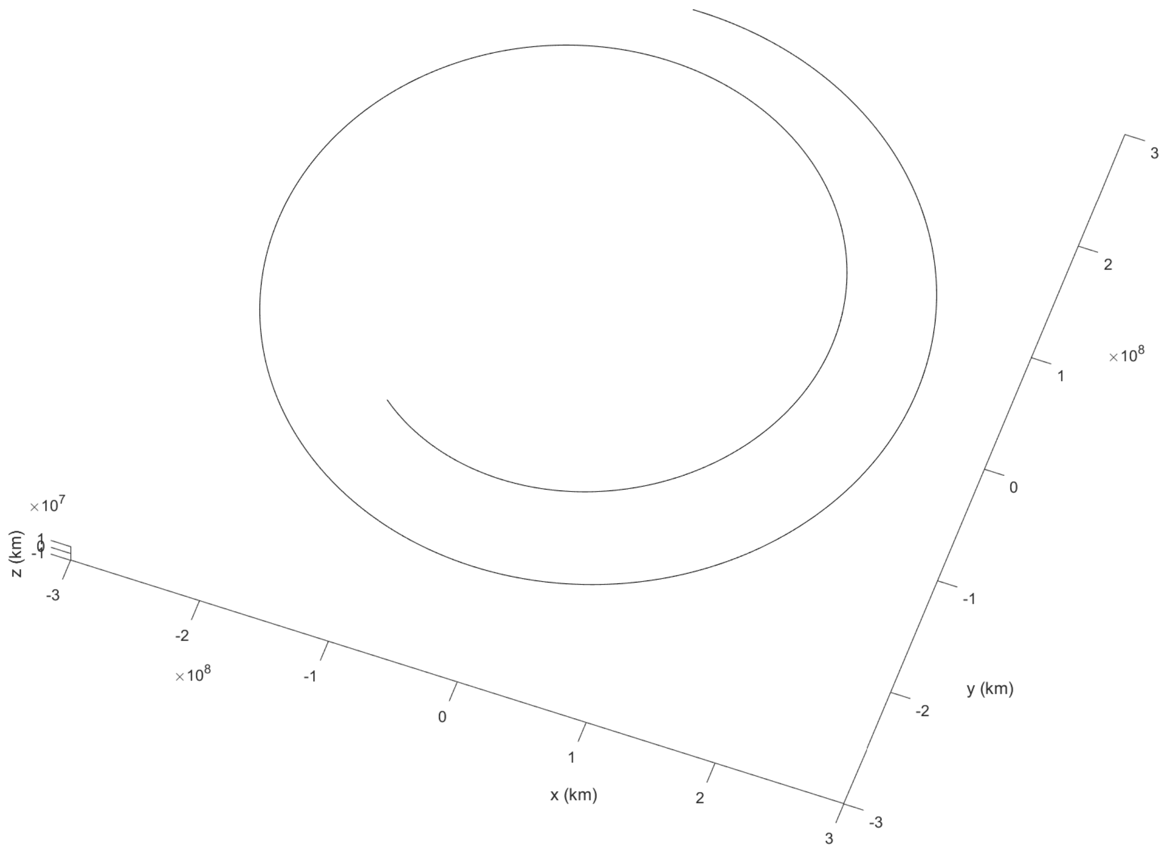
- To analyse which type of swarms are stable and therefore more appropriate to deflect D, the spacecrafts are grouped in two types of swarms:
  - non-coordinated (S_1, S_2 and S_3),
  - coordinated, where the spacecrafts are flying in trailing formation with D (S_1c, S_2c and S_3c).

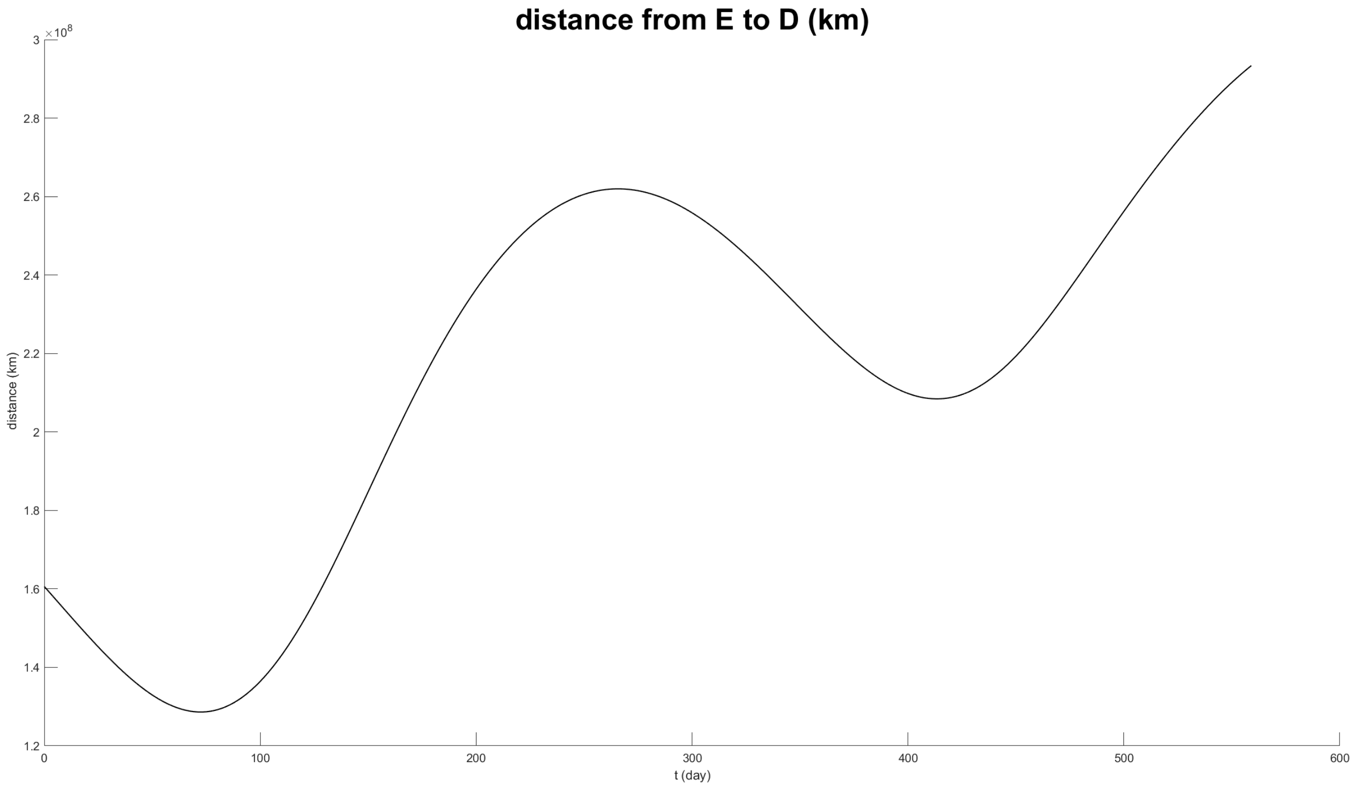
Results for Apophis

- The p-N results for Apophis with orbital elements as of 6/3/2021 are shown below.
- To clearly distinguish and compare the behavior of the two types of swarms of spacecrafts, we consider a time span of 1.73 times the period of Apophis.

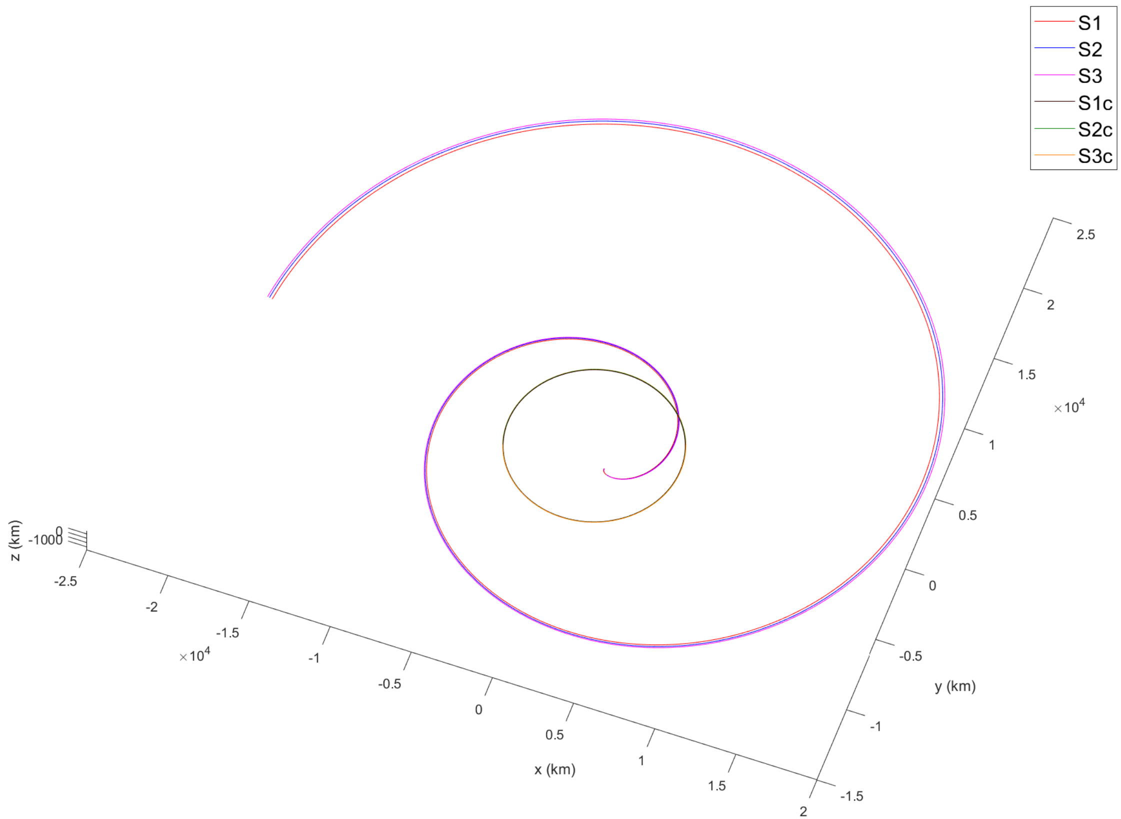

Earth and D N orbits
SUN
SX
SY
SZ
EARTH
D
×10^6
5
0
-5
z (km)
1
0.5
×10^8
0
-0.5
-1
y (km)
-1.5
-1.5
-1
x (km)
-0.5
0
0.5
1
×10^8

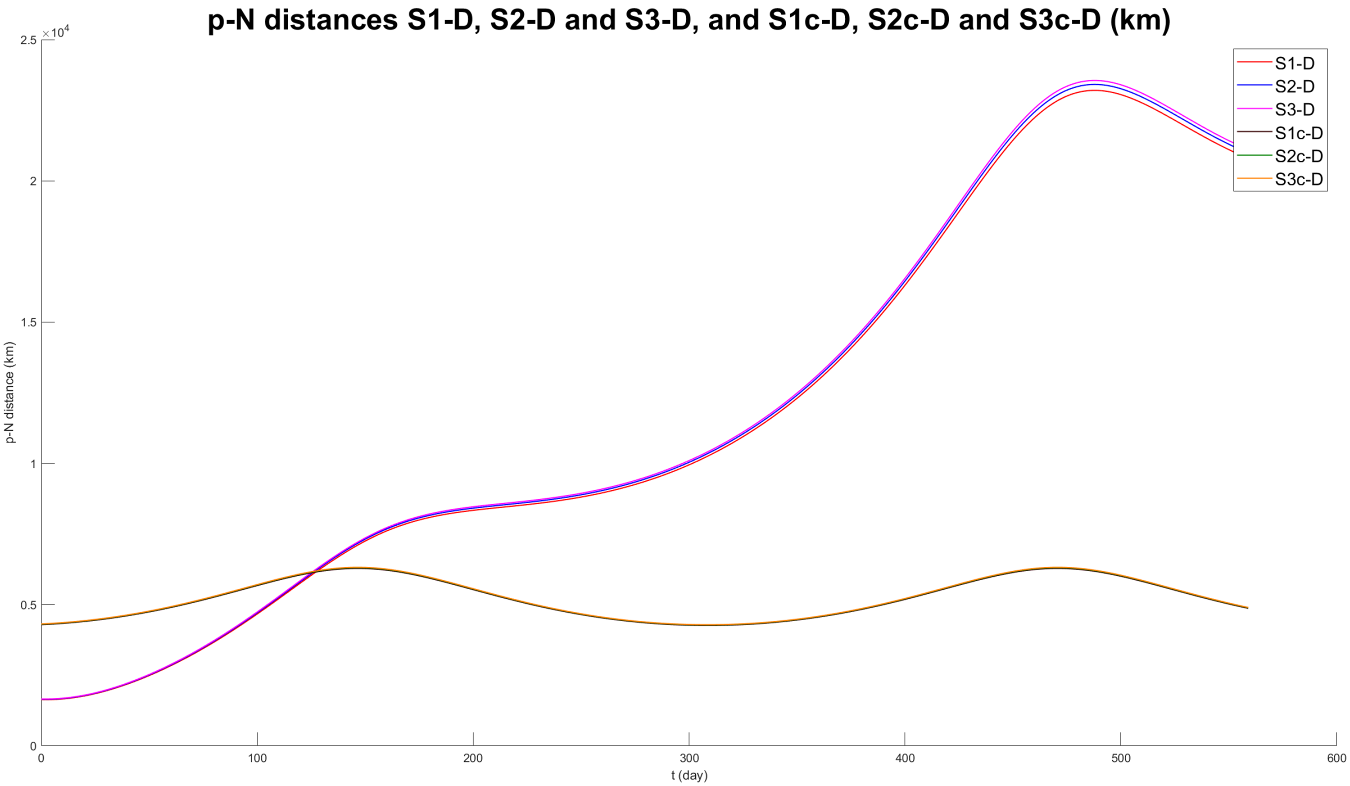
relative orbits of D w.r.t. E

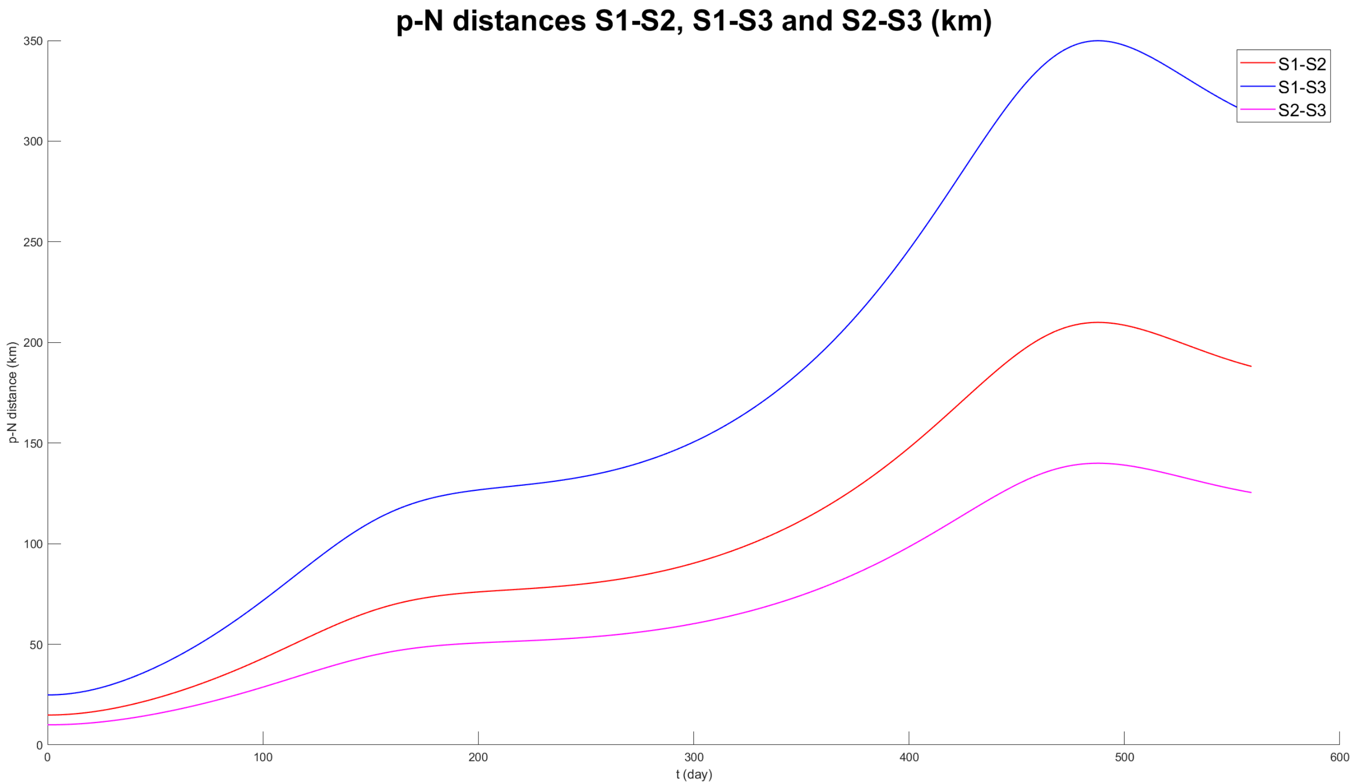


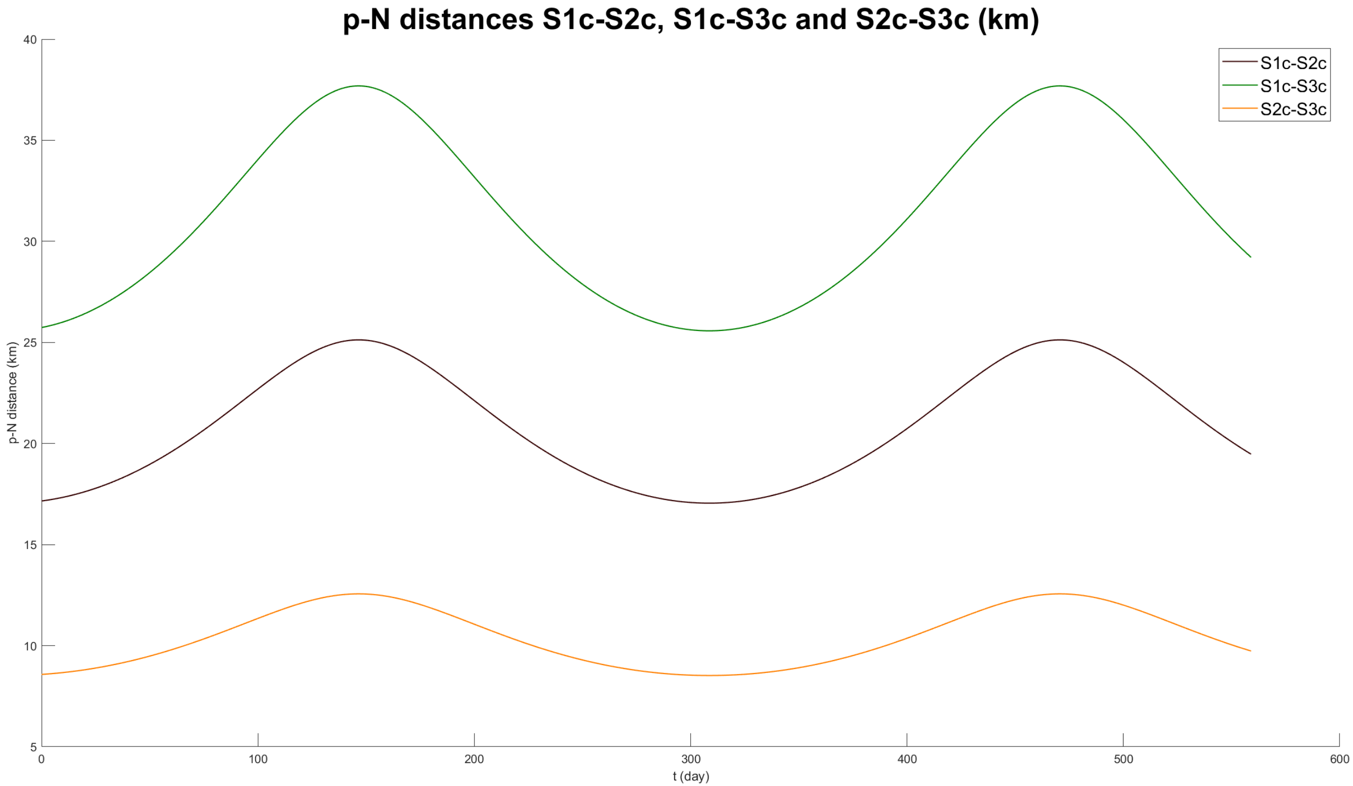

distance from E to D (km)
×10^8
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
distance (km)
0
100
200
300
400
500
600
t (day)

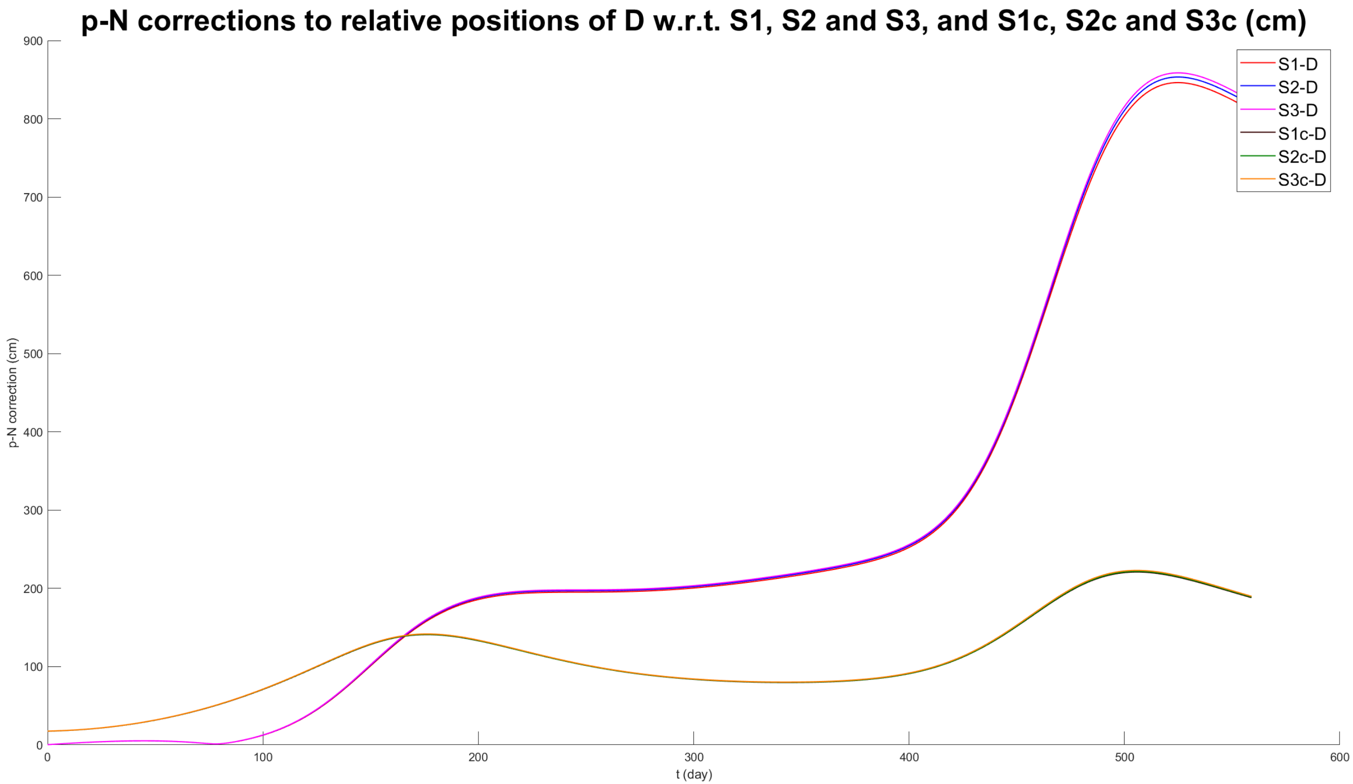
p-N relative orbits of D w.r.t. S1, S2 and S3, and S1c, S2c and S3c



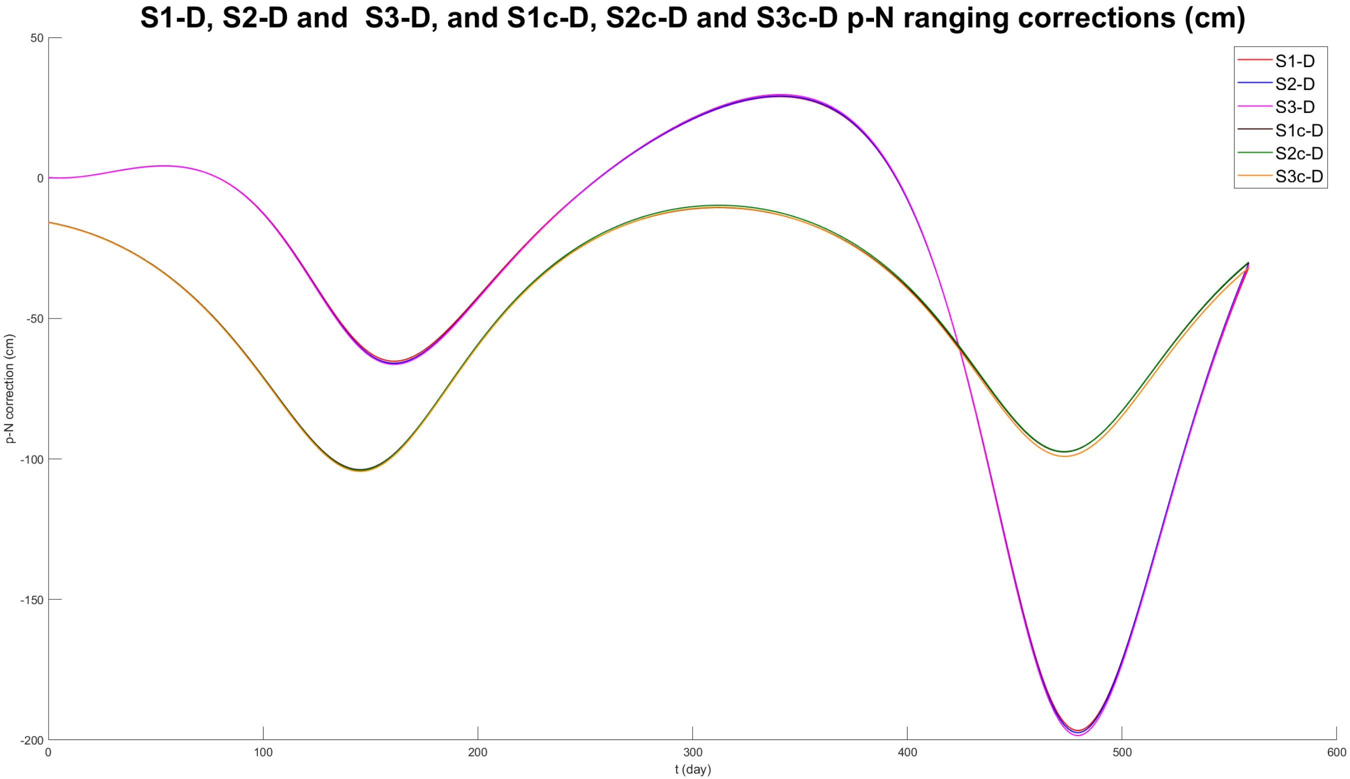

p-N distances S1-D, S2-D and S3-D, and S1c-D, S2c-D and S3c-D (km)
×10^4
2.5
2
1.5
1
0.5
0
p-N distance (km)
0
100
200
300
400
500
600
t (day)
S1-D
S2-D
S3-D
S1c-D
S2c-D
S3c-D

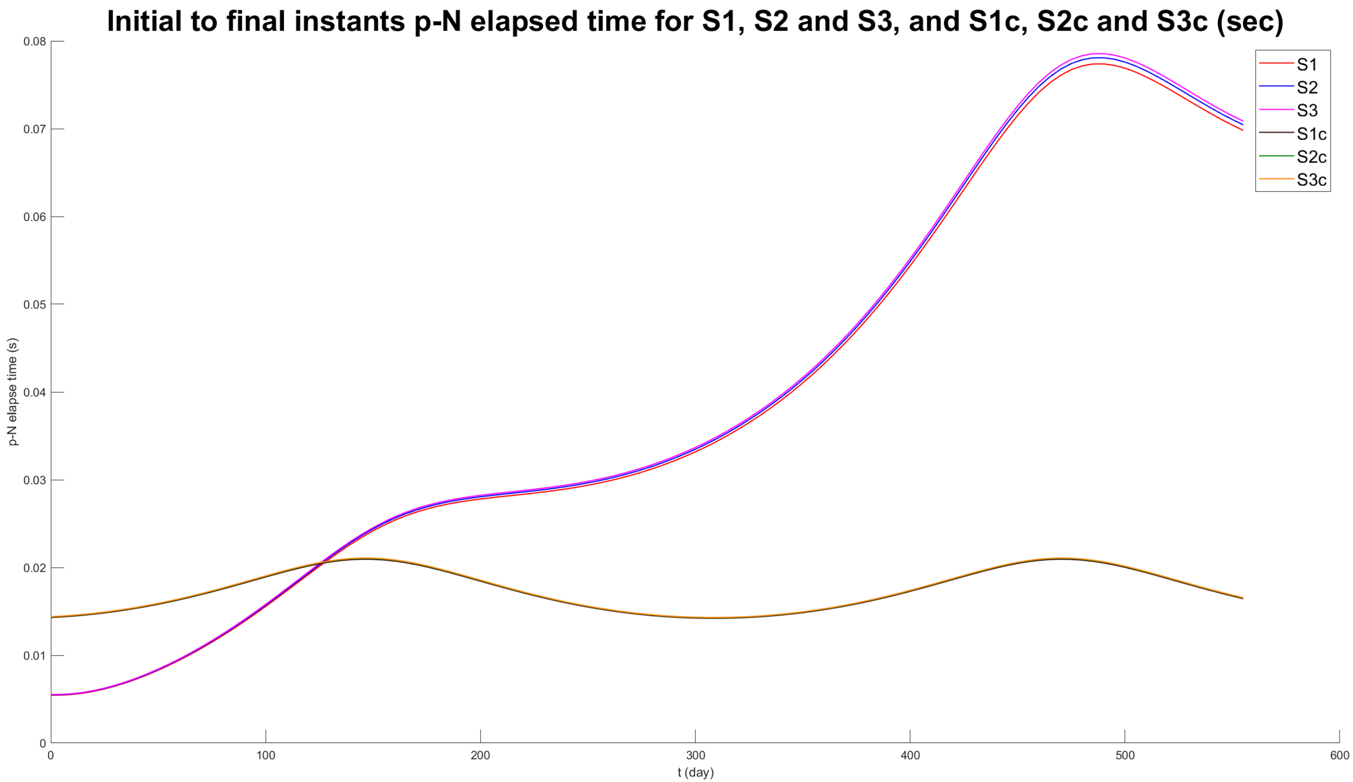

p-N distances S1-S2, S1-S3 and S2-S3 (km)
S1-S2
S1-S3
S2-S3
p-N distance (km)
t (day)
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600


p-N distances S1c-S2c, S1c-S3c and S2c-S3c (km)
S1c-S2c
S1c-S3c
S2c-S3c
p-N distance (km)
t (day)
0
100
200
300
400
500
600
5
10
15
20
25
30
35
40

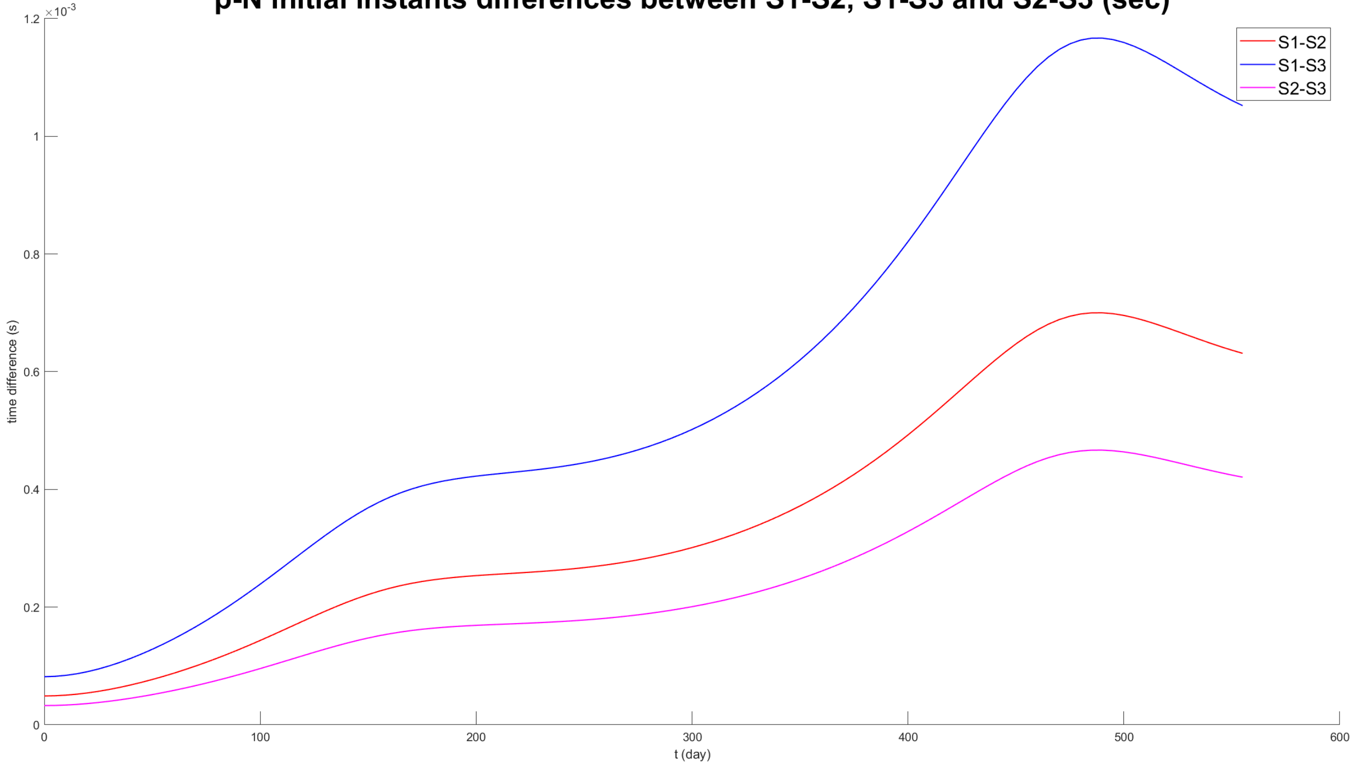


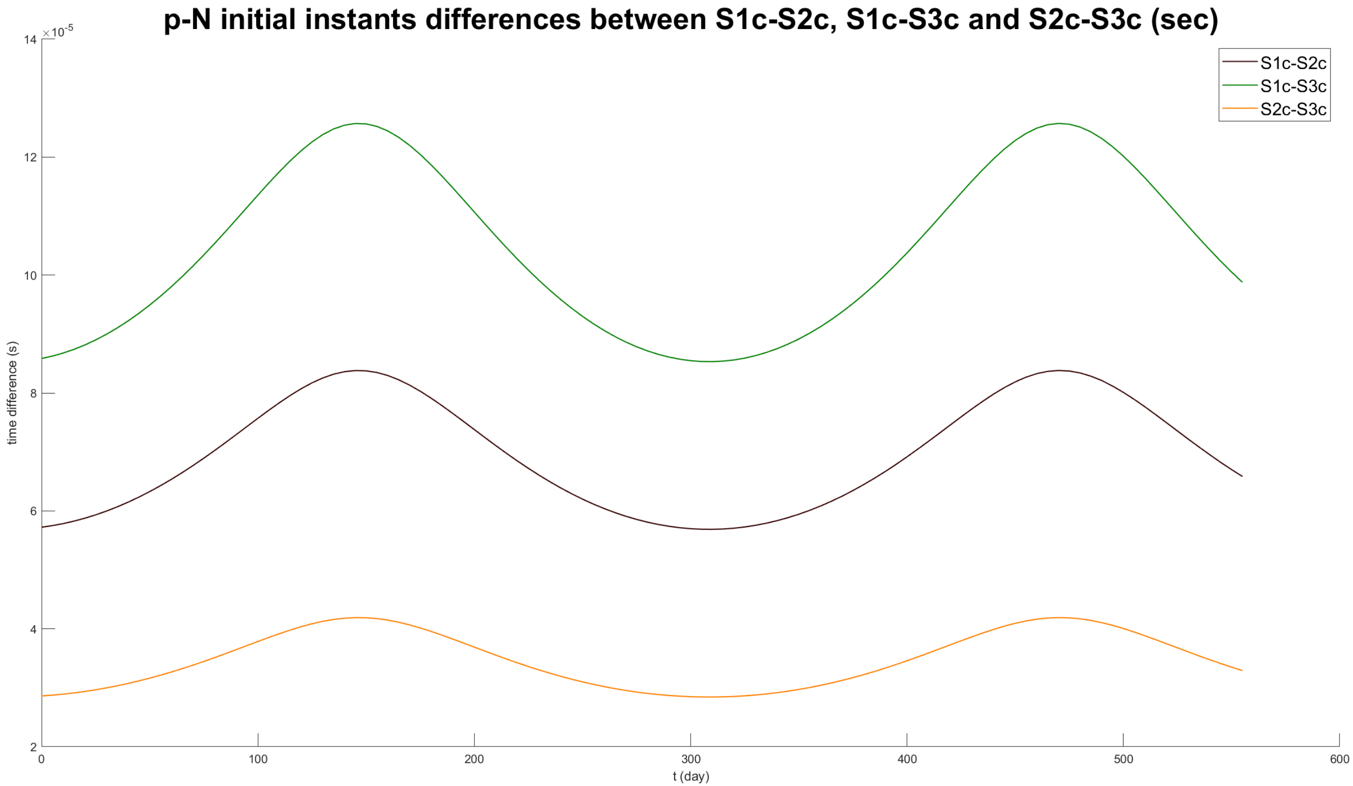
p-N corrections to relative positions of D w.r.t. S1, S2 and S3, and S1c, S2c and S3c (cm)
p-N correction (cm)
t (day)
S1-D
S2-D
S3-D
S1c-D
S2c-D
S3c-D
0
100
200
300
400
500
600
700
800
900


S1-D, S2-D and S3-D, and S1c-D, S2c-D and S3c-D p-N ranging corrections (cm)
p-N correction (cm)
t (day)
50
0
-50
-100
-150
-200
0
100
200
300
400
500
600
S1-D
S2-D
S3-D
S1c-D
S2c-D
S3c-D


Initial to final instants p-N elapsed time for S1, S2 and S3, and S1c, S2c and S3c (sec)
p-N elapse time (s)
t (day)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0
100
200
300
400
500
600
S1
S2
S3
S1c
S2c
S3c

p-N initial instants differences between S1-S2, S1-S3 and S2-S3 (sec)




p-N initial instants differences between S1c-S2c, S1c-S3c and S2c-S3c (sec)
×10-5
14
12
10
8
6
4
2
time difference (s)
0
100
200
300
400
500
600
t (day)
S1c-S2c
S1c-S3c
S2c-S3c