# Improvement of old reductions of irregular satellites using the first publications of the data

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# Introduction

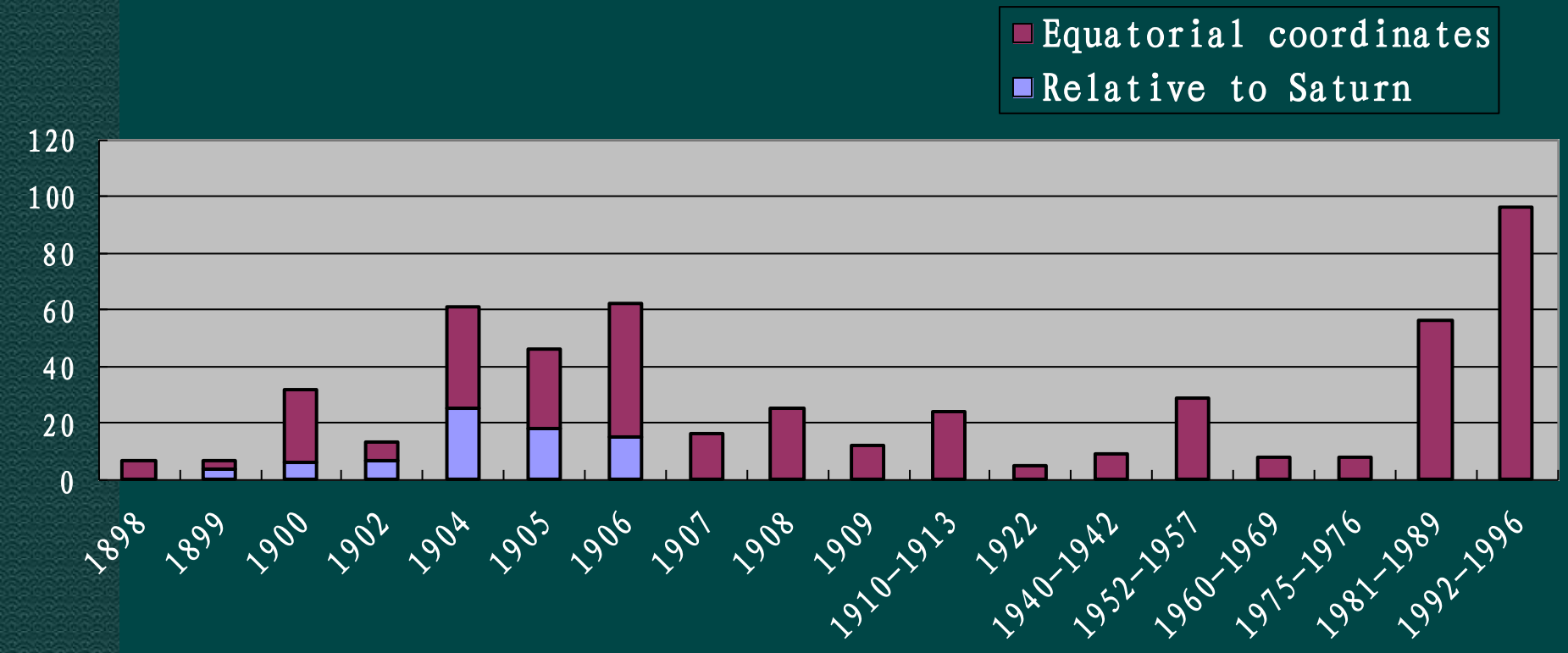
- The use of long-exposure photographic plates made the discovery of additional natural satellites possible. The first satellite to be discovered in this manner, Phoebe, was found in 1899 by W.H. Pickering.

- Some old literatures have given the positions of the natural satellites and mentioned the reference stars for determining its positions.

- We don't have the plates but we can try to reduce the positions of the natural satellites from these articles with modern precise astrometric catalogue, such as PPM, UCAC2...

# Example

- The photographic observations of Phoebe



# Example

## Example: Pickering-1908-AnHar-60-45p

TABLE I.

DATA RELATING TO PLATES.

| Plate. | | Date. | Exp. | Sid. T. | G.M.T. | J.D. 2410000+ | Actual Centre. | | Assumed Centre. | | No. of Meas. | No. of Stars. | Reduction to Arc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A. | D. | | | | | | R.A. 1875. | Dec. 1875. | R.A. 1875. | Dec. 1875. | | | |
| | | y. m. d. | m. | h. m. | h. m. | | h. m. | ° ′ | h. m. | ° ′ | | | |
| 3227 | 10311 | 98 8 16 | 60 | 17 11 | 12 16 | 4518.511 | 16 15.8 | −20 4 | 16 15.9 | −19 59 | 16 | 10 | 2.98,2.98 |
| 3228 | 10315 | 98 8 16 | 120 | 19 13 | 14 18 | 4518.596 | 16 15.8 | −20 4 | " " | " " | 16 | 10 | 2.99,2.98 |

TABLE II.

STANDARD STARS.

| Plate A. | Star. | DM. | Magn. | R.A. 1875. | Dec. 1875. | Computed coörd. | | Measured coörd. | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | X | Y | x | y |
| | | | | h. m. s. | ° ′ ″ | ″ | ″ | | |
| 3227 | 1 | −20° 6322 | 10.0 | 16 14 32.9 | −20 13 18 | −1141.1 | − 859.0 | −1138.9 | − 865.3 |
| | 2 | −19° 5982 | 10.0 | 16 14 40.7 | −19 57 0 | −1033.5 | + 119.0 | −1032.5 | + 123.4 |
| | 3 | −19° 5983 | 9.6 | 16 14 43.2 | −19 4 12 | −1003.8 | +3287.3 | −1002.0 | +3293.8 |
| | 4 | −20° 6325 | 9.3 | 16 15 22.4 | −20 13 24 | − 444.8 | − 864.0 | − 452.6 | − 867.8 |
| | 5 | −20° 6328 | 9.4 | 16 16 13.9 | −20 6 48 | + 279.8 | − 468.0 | + 283.2 | − 468.6 |
| | 6 | −20° 6331 | 9.4 | 16 18 3.6 | −20 1 36 | +1826.5 | − 159.0 | +1824.9 | − 150.4 |
| | 7 | −19° 5985 | 8.4 | 16 18 8.2 | −19 32 48 | +1897.1 | +1569.0 | +1897.8 | +1568.9 |
| | 8 | −20° 6332 | 9.8 | 16 18 12.4 | −20 11 12 | +1948.5 | − 735.0 | +1945.2 | − 740.5 |
| | 9 | −20° 6333 | 10.0 | 16 18 46.7 | −20 9 48 | +2431.4 | − 653.0 | +2437.2 | − 649.0 |
| | 10 | −19° 5986 | 9.8 | 16 21 21.1 | −19 1 18 | +4639.5 | +3444.3 | +4637.0 | +3437.3 |
| 3228 | 1 | −20° 6322 | 10.0 | 16 14 32.9 | −20 13 18 | −1141.1 | − 859.0 | −1137.7 | − 863.4 |
| | 2 | −19° 5982 | 10.0 | 16 14 40.7 | −19 57 0 | −1033.5 | + 119.0 | −1033.2 | + 124.7 |

# Example

The measurement of 42 plates

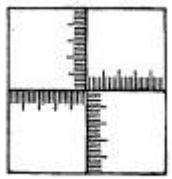


FIG. 1.

TABLE III.

ORIGINAL MEASURES.

| Plate A | Star. | Estimates. | | Scale Readings. | | | | Uncorrected. | | Plate A | Star. | Estimates. | | Scale Readings. | | | | Uncorrected. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $x$ | | A | B | C | D | $x$ | $y$ | | | $x$ | $y$ | A | B | C | D | $x$ | $y$ |
| 3227 | P | 30.7 | 45.5 | 2.5 | 4.9 | 7.6 | 5.1 | 1815.2 | 2699.4 | 3228 | 4 | 14.9 | 9.6 | 0.5 | 5.6 | 9.6 | 4.5 | 867.2 | 543.3 |
| | 2 | 2.2 | 27.6 | 8.1 | 6.0 | 2.0 | 4.1 | 101.8 | 1625.7 | | P | 33.7 | 44.1 | 2.8 | 0.5 | 7.2 | 9.5 | 1993.2 | 2613.2 |
| | 1 | 0.4 | 11.0 | 5.5 | 10.2 | 4.5 | 10.1 | *3.0* | 630.3 | | 6 | 53.1 | 21.6 | 8.9 | 7.0 | 1.1 | 3.0 | 3156.7 | 1271.9 |
| | 3 | 2.6 | 80.7 | 4.2 | 7.9 | 5.9 | 2.1 | 125.1 | 4817.3 | | 5 | 27.3 | 16.3 | 7.5 | 3.0 | 2.6 | 7.1 | 1605.3 | 947.8 |
| | T | 4.8 | 5.4 | 1.9 | 4.0 | 8.1 | 6.1 | 258.5 | 3053.7 | | 8 | 55.2 | 11.8 | 8.2 | 8.0 | 1.9 | 2.1 | 3281.2 | 677.6 |
| | H | 10.6 | 52.3 | 4.3 | 2.9 | 5.9 | 7.2 | 604.8 | 3107.2 | | 9 | 63.4 | 13.4 | 5.9 | 3.5 | 4.1 | 6.5 | 3774.6 | 771.1 |
| | I | 14.3 | 51.4 | 7.1 | 3.9 | 2.9 | 6.2 | 827.5 | 3053.1 | | 7 | 54.3 | 50.6 | 6.9 | 5.5 | 3.1 | 4.5 | 3228.6 | 3003.0 |
| | P | 30.8 | 45.5 | 2.4 | 5.0 | 7.8 | 5.1 | 1816.1 | 2699.7 | | 10 | 100.1 | 82.1 | 8.5 | 0.5 | 1.5 | 9.6 | 5979.1 | 4892.9 |
| | 4 | 11.9 | 10.9 | 0.3 | 9.9 | 9.7 | 0.1 | 688.0 | 629.2 | | J | 17.3 | 49.9 | 6.9 | 9.4 | 3.1 | 0.8 | 1008.6 | 2965.6 |
| | 5 | 24.3 | 17.7 | 7.1 | 7.1 | 3.0 | 2.9 | 1427.8 | 1032.5 | | P | 33.7 | 44.1 | 3.0 | 0.4 | 7.1 | 9.7 | 1992.3 | 2612.3 |
| | 6 | 50.1 | 23.1 | 8.5 | 1.0 | 1.6 | 9.1 | 2979.4 | 1355.9 | 3230 | P | 31.2 | 46.6 | 7.9 | 6.0 | 2.1 | 4.2 | 1842.7 | 2765.4 |
| | 8 | 52.2 | 13.2 | 8.1 | 2.0 | 2.0 | 8.0 | 3101.8 | 762.1 | | 1 | 2.3 | 28.6 | 8.0 | 7.1 | 2.1 | 3.0 | 102.4 | 1692.2 |
| | 7 | 51.4 | 51.9 | 6.9 | 9.5 | 3.1 | 0.5 | 3048.7 | 3086.8 | | 2 | 2.0 | 81.9 | 10.1 | 9.9 | 10.1 | 0.2 | 90.0 | 4888.9 |
| | 9 | 60.4 | 14.7 | 5.5 | 7.6 | 4.5 | 2.5 | 3597.0 | 855.2 | | T | 4.6 | 52.6 | 3.0 | 6.8 | 7.1 | 3.3 | 252.3 | 3130.4 |
| | 10 | 97.2 | 83.4 | 8.0 | 3.9 | 2.1 | 6.2 | 5802.4 | 4973.1 | | I | 15.1 | 52.1 | 9.9 | 0.5 | 0.2 | 9.5 | 871.0 | 3093.2 |
| | P | 30.7 | 45.5 | 2.5 | 4.9 | 7.6 | 5.1 | 1815.2 | 2699.4 | | 3 | 0.6 | 12.1 | 3.1 | 0.9 | 7.0 | 9.2 | 11.7 | 695.3 |
| 3228 | P | 33.7 | 44.1 | 2.9 | 0.5 | 7.1 | 9.6 | 1992.6 | 2612.9 | | 4 | 12.3 | 12.3 | 7.9 | 1.9 | 2.1 | 8.2 | 702.7 | 701.2 |

# Example

7 of 42 positions of Phoebe in the article

TABLE IX.

POSITIONS OF PHOEBE.

| Plate A. | Date. | | | J. D. 241000+ | $x$ | $y$ | R. A. 1875.0. | | | Declination 1875.0. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *y.* | *m.* | *d.* | | | | *h.* | *m.* | *s.* | ° | ′ | ″ |
| 3227 | 1898 | 8 | 16 | 4518.511 | + 672.1 | +1186.6 | 16 | 16 | 41.6 | −19 | 38 | 12 |
| 3228 | " | " | " | 4518.596 | + 670.8 | +1184.8 | 16 | 16 | 41.5 | 19 | 39 | 14 |
| 3230 | " | " | 17 | 4519.539 | −8027.5 | +1349.1 | 16 | 16 | 54.0 | 19 | 39 | 35 |
| 3233 | " | " | 18 | 4520.550 | + 740.7 | +1140.0 | 16 | 16 | 46.5 | 19 | 40 | 0 |
| 3304 | " | 9 | 15 | 4548.531 | +1550.4 | − 22.2 | 16 | 20 | 31.9 | 19 | 55 | 20 |
| 3308 | " | " | 16 | 4549.528 | +1742.2 | − 66.3 | 16 | 20 | 45.5 | 19 | 56 | 3 |
| 3312 | " | " | 17 | 4550.528 | +1934.7 | − 109.1 | 16 | 20 | 59.2 | 19 | 56 | 38 |

# Procedures

- The information about the telescopes and the photographs:
- Observatory Name: Arequipa
- W. Longitude (deg): 71.55
- Latidude (deg): -16.375
- Aperture (m): 0.6
- Scale: (arcsec/mm) 59.57
- Telescope: 24-inch Bruce Doublet, letter A

# Procedures

- The relationship among the measured coordinates of a star on the plate, the standard coordinates and the spherical coordinates are the same as what we use now.

$$\xi = \frac{\tan(\alpha - A)\sin q}{\cos(P - q)}, \qquad \eta = \tan(P - q),$$

where

$$\tan q = \tan p \cos(\alpha - A).$$

$$\kappa\xi = (1 + \alpha)x + \beta y + \gamma, \qquad \kappa\eta = \delta x + (1 + \epsilon)y + \zeta,$$

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P, A: Right Ascension and N.P.D( North Polar Distance) of the centre of the plate;

p, a: RA and NPD of a star

ξ, η: The standard coordinates;

x, y: The measured coordinates;

# Procedures

- If in the article they gave the positions of the satellite and the reference stars: (start from procedure2)

- If the article didn't mention the potions of the reference stars;

1, find the stars in the old catalogue which were used at that time, with the distance to the satellite less than 1 degree and the magnitude of 9 or 10, choose these stars as the reference stars(at least 6 stars);

# Procedures

2, reduce all the positions to the same reference system such as the J2000 mean equatorial coordinate system or ICRS;(using the IAU1976 precession parameters to transform the reference system )

3, use the proper motions in new catalogue to calculate the positions of the stars at the epoch of the old catalogue;

4, identify the reference stars in new catalogue ($d<15$mas, $\Delta m<1$, to be decided).

# Procedures

5, choose the natural satellite mentioned in the article as the centre of the plate if we don't know the centre, with the positions of the stars and the satellite in the article(not necessary to transform the reference system), calculate the tangent coordinates of the stars,

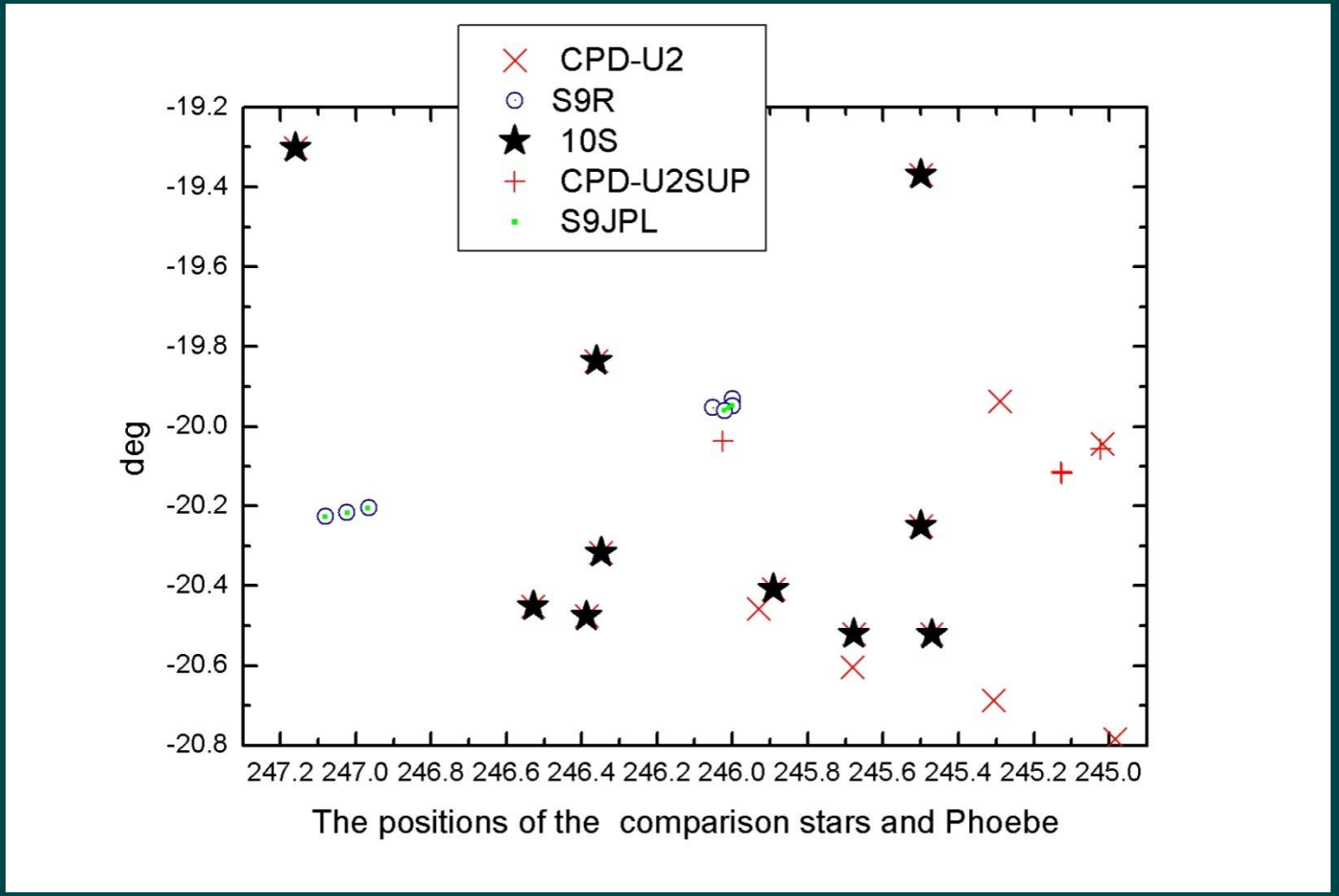
6, use these coordinates as the measured coordinates, then determine the center of the plate, the parameters of the plate (4 parameters at least or more if we have more stars) and the standard coordinates of them.

# Procedures

6, with the standard coordinates and the positions of the stars in new catalogue, after the reduction astrometric, the positions of the satellite can be calculated.

# Procedures

## Example



# Limitations

- The precision of the proper motions of the new catalogue is not good enough;
- Because of the bad precision of the old catalogue, it is difficult to identify some stars in new one.

# Result of the example: Comparisons o-c

- With 10 mentioned reference stars

| DATE | 1875-J2000(S,") | | PPM(S,") | | UCAC2(S,") | |
|---|---|---|---|---|---|---|
| 1898 8 17.011 | 0.225 | -63.89 | 0.0833 | -62.1092 | 0.1093 | -62.7261 |
| 1898 8 17.096 | -0.014 | -3.47 | -0.1485 | -1.6152 | -0.1216 | -2.2422 |
| 1898 8 18.039 | 10.366 | -3.14 | 10.2496 | -1.5398 | 10.2743 | -2.1497 |
| 1898 8 19.050 | 0.164 | 2.4 | 0.0402 | 4.2009 | 0.066 | 3.5746 |
| 1898 9 16.031 | -0.553 | 1.1 | -0.2818 | -1.0073 | -0.3 | -1.4116 |
| 1898 9 17.028 | -0.183 | 0.53 | 0.1101 | -1.8303 | 0.0894 | -2.2191 |
| 1898 9 18.028 | -0.09 | -8.66 | 0.2248 | -11.2834 | 0.2016 | -11.6552 |

# Result of the example: Comparisons o-c

- With the stars at the same time in the old and new catalogue

I, 1 degree, d<10mas, m<1, UCAC2 and CPD---Find 10 stars

II, 1 degree, d<15mas, UCAC2 and CPD-----Find 16 stars

| DATE | With stars(S,") | | I(S,") | | II(S,") | |
|---|---|---|---|---|---|---|
| 1898 8 17.011 | 0.1093 | -62.7261 | 0.2529 | -63.4158 | 0.2146 | -61.951 |
| 1898 8 17.096 | -0.1216 | -2.2422 | 0.0206 | -3.0097 | -0.0194 | -1.5121 |
| 1898 8 18.039 | 10.2743 | -2.1497 | 10.4008 | -2.9381 | 10.3669 | -1.362 |
| 1898 8 19.050 | 0.066 | 3.5746 | 0.2018 | 2.7517 | 0.1632 | 4.3009 |
| 1898 9 16.031 | -0.3 | -1.4116 | -0.4502 | -3.2781 | -0.3911 | -0.0281 |
| 1898 9 17.028 | 0.0894 | -2.2191 | -0.078 | -4.1321 | -0.0126 | -0.7867 |
| 1898 9 18.028 | 0.2016 | -11.6552 | 0.0167 | -13.6046 | 0.0887 | -10.1674 |

# Result of the example: Comparisons o-c

| | 1875-J2000 (S,") | | PPM(S,") | | UCAC2(S,") | | I(S,") | | II(S,") | |
|---|---|---|---|---|---|---|---|---|---|---|
| μ | 0.222 | 1.805 | 0.145 | 2.132 | 0.144 | 2.075 | 0.188 | 2.334 | 0.163 | 1.904 |
| σ | 0.530 | 4.383 | 0.310 | 4.960 | 0.315 | 4.838 | 0.476 | 5.454 | 0.404 | 4.520 |

# Conclusions

- Some ancient photographic observations are good to improve the orbit;
- If the article didn't mention the reference stars, we can still find the stars to improve the positions of the natural satellites;
- It is necessary to choose a catalogue with high precision in proper motions and positions.

Thank You