Minor planet recovery: analysis and verification of data obtained by OrbFit and Edipo software

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Abstract. We investigate the use of ephemeris uncertainties computed by *OrbFit* software for planning observation campaigns for the recovery of lost asteroids, with the help of the new program *Edipo*. We present a series of real and simulated cases of asteroid recovery; the analysis of the results suggests that, although the method is essentially correct and helpful, the error model presently adopted underestimates reality.

Minor planets recovery at the second opposition has always been a matter involving different aspects, both from an instrumental (instrument limit magnitude and field of view) and computational point of view. Ephemeris calculations useful for this purpose are expected to supply both a prediction of the nominal position and an estimate of the the error in the sky associated with it.

Software package *OrbFit* produced by *OrbFit Consortium* (A. Milani, S.R. Chesley, M. Carpino, Z. Knezevic, G.B. Valsecchi) can be used to calculate the position error in the sky, starting from the set of observations available for the object to be recovered. Output data produced by *OrbFit* in order to quantify the error are contained in a file named `objectname.cbd`; it consists of a series of data points giving the astrometric coordinates (right ascension and declination) of the borders of the confidence region inside which the recovery could be expected. Sometimes the estimated area is very big (more than 10 degrees); in this case the plot area is not necessarily an ellipse and could have a complex shape. During several tests we have realized that the graphic and numerical prediction could lead to error of interpretation, among which:

- uncertainty calculations in right ascension, over-estimated at first, were in reality correct because located at high declination;
- very often the position angle of the object with respect to the nominal position appeared perpendicular to the principal axis of the error ellipse;
- in some cases the error was increased by fast motion, creating many troubles in the recovery.

Thanks to the help provided the *OrbFit Consortium* in teaching us the different aspects of *OrbFit*, Augusto Testa has developed a software for the graphic representation of the error region in the sky. The program is called *Edipo* and uses as input a file `objectname.erd` which is a slightly modified version of the file `objectname.cbd` produced by *OrbFit* (it includes the nominal ephemeris along with the information on the uncertainty region). The user must also specify some parameters (saved in an option file):

- focal length of the telescope (in mm);
- CCD specification (number and physical dimension of pixels).

Running *Edipo* it is possible to plot on the screen of the PC the uncertainty region in the sky with the position of all CCD fields needed to cover it. In the output file created by the program are also available the ephemerides needed to point the telescope without any further computation.

Objects : numbered (04660) , 77 days of obs. arc (from February 28, 1982 to May 16,1982) recovery made on September 16,1990 (after 3045 days).

output : output data from Sw EDIPO. Ephemeris compute at the recovery's epoch for Observatory code 413 (where the object was reobserved)

16 9 1990 13.9833 3.0 22 58 46.5 - 4 10 18.4 Nominal Ephemeris.

```
22 58 46.5   - 4 10 17.5   0.60749    22 58 46.6   - 4 10 19.4   0.60753
23  0  8.3   - 4  0 57.7   0.60544    22 57 25.2   - 4 19 35.0   0.60960
23  1 27.0   - 3 51 58.4   0.60348    22 56  7.9   - 4 28 22.3   0.61159
23  2 39.1   - 3 43 44.1   0.60171    22 54 57.9   - 4 36 19.2   0.61342
23  3 41.2   - 3 36 37.5   0.60020    22 53 58.1   - 4 43  5.9   0.61499
23  4 30.6   - 3 30 58.4   0.59902    22 53 10.9   - 4 48 25.8   0.61624
23  5  4.8   - 3 27  3.0   0.59820    22 52 38.4   - 4 52  6.4   0.61710
23  5 22.3   - 3 25  2.5   0.59778    22 52 21.8   - 4 53 58.7   0.61754
23  5 22.3   - 3 25  2.8   0.59779    22 52 21.8   - 4 53 58.5   0.61754
23  5  4.8   - 3 27  3.7   0.59821    22 52 38.4   - 4 52  5.8   0.61709
23  4 30.6   - 3 30 59.5   0.59903    22 53 10.9   - 4 48 25.0   0.61622
23  3 41.2   - 3 36 38.9   0.60023    22 53 58.0   - 4 43  4.7   0.61497
23  2 39.1   - 3 43 45.8   0.60174    22 54 57.8   - 4 36 17.8   0.61339
23  1 27.1   - 3 52  0.3   0.60351    22 56  7.9   - 4 28 20.7   0.61156
23  0  8.4   - 4  0 59.6   0.60547    22 57 25.2   - 4 19 33.2   0.60957
```

input : output file *.erd, added ephemeris for the next 2 days just to show motion and P.A.

'Edipo'

```
& 04660 ------ Observatory Code 413
  $ 1.0
  % 16 09 1990     13.9833 (0.58264) sigma=3.00
    22 58 46.5   - 4 10 18.4  effem. nominale
    17  9 1990     13.9833 (0.58264) sigma=3.00
    22 56 55.1   - 4 20  7.0  effem. nominale
    18  9 1990     13.9833 (0.58264) sigma=3.00
    22 55  3.6   - 4 29 56.7  effem. nominale
  #
    +22 58 46.5  - 4 10 17.5  0.60749    +22 58 46.6  - 4 10 19.4  0.60753
     ..........................          ..............................
    23  0  8.4   - 4  0 59.6  0.60547    +22 57 25.2  - 4 19 33.2  0.60957
    22 58 46.5   - 4 10 18.4  Nominal Ephemeris
    22 56 55.1   - 4 20  7.0  Nominal Ephemeris
    22 55  3.6   - 4 29 56.7  Nominal Ephemeris
```

output : Object : 04660

'Edipo'

```
date        : 1990-09-16.582
  tipo CCD  : ST6
  foc.Tel.  : 1746
  22 58 46  -04 10 18 pos.effem.   22 58 46  -04 10 18 pos.effem.
  22 57 49  -04 16 38              22 59 46  -04 03 34
  22 56 51  -04 23 10              23 00 45  -03 56 31
  22 55 52  -04 30 12              23 01 43  -03 49 58
  22 54 54  -04 36 43              23 02 42  -03 43 25
  22 53 55  -04 43 14              23 03 40  -03 36 52
  22 52 57  -04 49 45              23 04 39  -03 29 48
  22 51 58  -04 56 15              23 05 37  -03 23 14
```

Fig. 1. An extract of the files used for the recovery of asteroid 4660. The first listing is the nominal ephemeris generated by *OrbFit*, the other two are the input and the output file of *Edipo*.

This procedure has been already tested at the Sormano Astronomical Observatory to recover both Main Belt Asteroids (MBA) discovered by us and Near Earth Asteroids (NEA); it will be of paramount importance in order to set up an effective, automated recovery program with the new telescope under construction for our observatory and could be used also in other sites.

Program *Edipo* performs the representation of the sky map (in stereoscopic projection) using the software *Mappa2* (also created by Augusto Testa) which plots all minor planets and comets for a specific epoch using monthly updates from MPC.

In order to test this procedure we have selected several object from the lists of multi-opposition MBA discovered at Sormano and NEAs. For each object we have computed an orbit using all the observations available *before* the recovery and estimated the confidence region (at the 3-σ level) for the ephemeris at the epoch of the recovery; we have then compared the confidence region with the actual position at which the object was recovered. We include here few examples of those tests.

As an example we show here how this procedure works for asteroid 4660 Nereus (1982 DB), discovered on September 30, 1981, observed for about 8 months, lost and subsequently recovered in September 16, 1990 after a period of more than 8 years. In Fig. 1 we show the result of the computation of an ephemeris based on an orbit determined using only the first 8 months of data for the epoch of the actual recovery. In other words we are simulating the use of the procedure by an observer who, in September 16, 1990, wished to find the asteroid on the basis of the observations of 1981–1982.

In Fig. 2 we show the output displayed on the screen by program *Edipo*, computed from the input shown in Fig. 1. The blue line near the center of the image is the representation of the

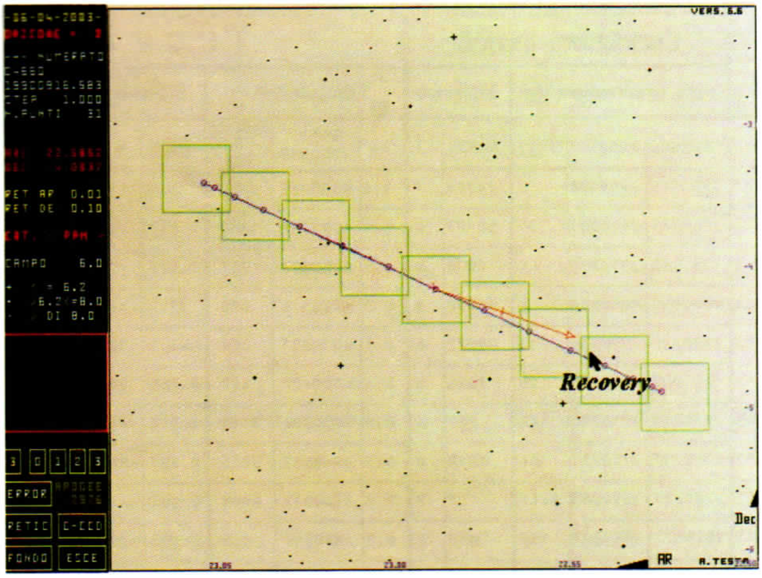

Fig. 2. Screen output of program *Edipo* for the simulated recovery of asteroid 4660 (from data shown in Fig. 1). The contour of the confidence region is shown in blue, its coverage with the exposure fields is shown as a series of green rectangles. The position at which the asteroid has been actually recovered. The red arrow shows the apparent motion of the object at the epoch of recovery.

boundaries of the confidence region at the significance level of 3-σ. The region has approximately the shape of an ellipse but is extremely elongated and, at the scale of the plot, looks like a segment. The green squares are the proposed coverage of the confidence region with separate and partially overlapping exposures (assuming a field of view of the telescope of approximately 30×30 arcmin). As it can be seen, in this case the adoption of the proposed observational procedure would have led to a successful recovery.

An overview of several cases we have tested is shown in Fig. 3. For each object the table reports:

- the MPC code of the asteroid (*Sigla*);
- its semimajor axis in Astronomical Units (*a (UA)*);
- its orbital eccentricity (*e*);
- information on the initial conditions used for generating the ephemeris (*Condizioni Iniziali*):
  - date of the beginning (*Iniziali*) and the end (*Finali*) of the timespan covered by the observations used for the computation of the orbital elements, and arc duration in days (*n° gg*);
  - values of orbital uncertainty supplied by the Minor Planet Center (*RunOff* and *U*);
- circumstances of the recovery (*Temporale*):
  - apparent motion in the sky in arcsec/minute (*"/m*);
  - date (*data Trovata*);
  - time elapsed since the last observation used for ephemeris generation in days (*Trovato – Fine (gg)*);
- description of the confidence region for the recovery (3-σ level) computed by *OrbFit*, approximated as an ellipse (*ERRORE*):
  - dimension of the semimajor axis of the ellipse in degrees (*LE°*);
  - position angle of the semimajor axis of the ellipse with respect to the direction of apparent motion, in degrees (*A°*);
- position of the point of actual recovery with respect to the nominal orbit (center of the confidence region ellipse)(*Geometrico*):
  - distance in degrees (*DT°*);
  - distance as percentage of the semimajor axis of the confidence ellipse (*%*);
  - position angle with respect to the direction of apparent motion, in degrees (*B°*);

ASTRO $n = \frac{0.9856076686}{a\sqrt{a}}$			Condizioni Iniziali					TROVATO								
			Arco Osservazioni (gg)			statistica		Temporale			ERRORE		Geometrico			in ellisse
Sigla	a (UA)	e	Iniziali	Finali	n°gg	RunOff	U	°/m	data Trovato	Trovato - Fine (gg)	LE°	A°	dist.Trov-Eff DT°	%	B°	
J95W03C	3.08	0.167	J951119	J951128	9	24794	7	0.3	K000825	1732	75.5	+7	1.130	2	+7	SI
J97F010	3.02	0.045	J970331	J970501	31	50192	8	0.4	K001101	1280	4.842	+5	1.132	47	+6	SI
J95U07T	3.06	0.043	J951027	J951210	44	1831	6	0.5	K000822	1717	2.543	+7	0.385	30	+188	SI
K000G5G	2.73	0.064	K000831	K000906	6	40010	8	0.5	K980316	899	33.1	-14	0.269	2	-180	SI
J98D23L	2.73	0.064	J980227	J980316	17	99632	8	0.6	K000831	899	43.7	+18	0.242	1	+196	SI
J98X02Y	2.66	0.114	J981207	J990116	40	2626	6	0.6	K000427	467	0.769	-38	0.123	32	-38	SI
J91D00B	1.72	0.402	J910213	J910710	147	819	5	0.8	K000204	3131	3.896	-44	0.296	16	-225	SI
2608	2.49	0.582	J780217	J780731	164	1712	6	0.8	J940512	5764	0.697	-25	0.426	122	-25	NO
2608	2.49	0.582	J780217	J820203	1447	7	2	0.8	J940512	4481	0.001	---	0.002	400	---	NO
3671	2.20	0.543	J840527	J841027	153	670	5	0.8	J870219	845	0.108	+23	0.063	116	+204	NO
7753	1.47	0.482	J881205	J890217	74	3074	6	1.0	J930302	1474	0.247	+1	0.067	53	+184	SI
4660	1.49	0.360	J820228	J820516	77	4687	6	1.2	J900916	3045	3.566	+5	1.132	64	+5	SI
J98S36F	1.33	0.281	J980926	J981111	46	9991	7	1.4	K000731	628	0.173	+1	0.056	64	+180	SI
J97W22S	1.27	0.121	J971124	J980619	207	133	4	1.8	K000612	724	0.021	---	0.002	20	---	SI
J93G00D	1.10	0.238	J930415	J930514	29	6012	6	2.0	K000503	2546	2.323	+47	0.620	54	+47	SI
J98W24T	0.72	0.418	J981125	J981227	32	32082	7	2.0	K000207	407	0.104	+0	0.038	68	+6	NO
7236	2.72	0.564	J870801	J871026	86	896	5	2.4	J960609	3149	9.496	+12	0.811	17	+10	SI
J98B10B	1.27	0.425	J980125	J980705	52	4172	6	3.5	K000705	840	4.566	+15	0.594	26	+196	SI
J97U02S	1.67	0.661	J971023	J971228	66	6010	6	3.6	K000609	894	0.287	-49	0.031	23	-48	SI
2608	2.49	0.582	J780217	J780731	164	1712	6	3.6	J820202	1282	1.077	+4	0.656	122	+4	NO
5797	1.89	0.444	J800113	J800223	40	60656	8	5.4	J930121	4716	126.0	+19	28.1	44	+18	SI
J96F03R	2.17	0.796	J960326	J960621	87	1602	5	6.5	J990405	1018	2.441	+9	0.684	56	+9	SI

Fig. 3. Summary of 22 cases of recovery of lost asteroids (for the explanation of the content of the columns of the Table see the text).

– indication whether the asteroid was observed within the confidence region or not (*in ellisse*).

Although the number of examples we have studied is very small as to allow a final statement, we note that the percentage of cases for which the actual position of the recovered object is outside the confidence ellipse (approximately 23 %) is well in excess of the fraction one would expect for a 3-σ confidence level. For a normal distribution a similar percentage would correspond to a 1.21-σ level, while the percentage expected for 3-σ would be 0.26 %. Also in the cases in which the asteroid is observed outside the the confidence region, however, the forecast of the *direction* of the error is correct, namely the position of the object is along the major axis of a quite elongated ellipse. This suggests that the procedure for estimating ephemeris uncertainties implemented in *OrbFit* is substantially correct but the error model presently adopted leads to an underestimate of real prediction errors. From a practical point of view this means that the procedure presented here is not optimal but is nevertheless useful since it identifies correctly a very narrow region in the sky in which to look for the object, although the *length* of the region itself can be underestimated.