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THE METHODS AND EXPERIENCE OF DETECTING SMALL AND WEAKLY-CONTRASTING SPACE OBJECTS

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ABSTRACT

New optimum methods for acquisition of a weak signal with the help of narrow-angle and narrow-beam optical and radar tracking facilities by a-priori information on space object's (SO) motion are discussed. The methods are based on topological analysis of the SO current position uncertainty domain and of its dynamics and effective use of this information together with the tracking facility characteristics for establishing the optimal search strategy. The methods are implemented in the software for different optical-electronical sensors and, using them, several series of experiments were carried out. The analysis of the results are presented.

1. INTRODUCTION

The process of usual sounding (scanning) the space with the aim of acquisition of a weak intelligence signal is found to be too energy-consuming and retarded owing to a great range to SO, the necessity of accumulating a weak signal energy and also to indispensable requirement of sufficiently accurate compensation of SO motion for concentrating the signal energy at the same spot of the reciever. Fulfilment of the last one practically is possible only if a-priori information on the object's movement parameters is available. If only rough information is available it becomes problematical.

Constructively, the search problem comes to choosing a sequence of conditional ephemerides and the related (supposed) conditional velocities of the SO visible motion - optimal with respect to the adopted efficiency criterion under the restrictions laid by technical capabilities and properties of the facility used.

Strictly theoretically this sequence of conditional ephemerides and velocities is at first to meet the requirements of completeness and non-redundancy - i.e. in the end to completely cover not the field of space but the continuously drifting and topologically deforming the object's current position uncertainty domain and nothing more.

Secondly, the condition of the most economicity is to be provided - for example the sequence must be minimal.

Thirdly, after realization of the sequence in one and only one case it must be provided the complex of necessary favourable conditions for concentrating and accumulating the SO signal energy.

The traditional search methods as a rule do not meet the requirements mentioned, and mainly do not provide with necessary accuracy the compensation of the SO motion (for normalizing the process of summation of a weak signal energy) in case of rough information on the objects motion. If the exact information is available there is no problem.

2. GENERAL APPROACH TO OPTIMUM PLAN CONSTRUCTION

It seems that all these requirements can be met with the recently formulated set theory statement of the problem and the search plans equivalence principle [1, 2, 3]. Initially they were developed as a contemporary theoretical base for constructing the most economical search methods with the use of incomplete a-priori information (regardless of a SO size).

But it appeared to be very convenient for creating the optimum search methods for detecting small and weakly-contrasting SO.

The incomplete a-priori information on every object's orbit is available practically always (more or less exactly). This may be the information on a calculated orbit, statistical data on the movement parameters, the estimation of orbital parameters by rough measurements, outdated informaton about an orbit, computed or simulated data after an explosion in orbit, collision, breakup, experement and so on.

Making this information available is equal to giving in a 6-dimential phase space $X6$ a domain $D6(to)$ of possible values of the object's motion parameters vector on the time to

$$R6(t_o) = \{|x1, x2, x3, \dot{x}1, \dot{x}2, \dot{x}3|\} \in D6(t_o) \subseteq X6$$

and the related probability distribution density function fto(R6) defined on the domain D6(to).

The celestial mechanics laws define on the domain D6(to) a homeomorphic mapping F wich transfers each point of D6 at time t_o to another point of the phase space X6 at time t_1:

$$R6(t1) = F(to, R6(to), t1),$$

id est the domain D6(to) one-to-one and to-and-fro continuously is transfered by F into the domain D6(t1):

$$D6(t1) = \bigcup_{R_6 \in D_6(t_o)} F(to, R6(to), t1) = F(to, D6(to), t1).$$

Now let us formulate the search plan equivalence principle. Checking the point R6(to) at the time t_o is equivalent to checking the point R6(t1) at the time t1 in the sense that it is not necessary to accomplish the both acts of checking - it is sufficient to check only one of the two equivalent points. Similarly, checking the domain D6(to) at the time t_o is equivalent to checking the domain D6(t1) at the time t1 in the same sense.

By definition, a search plan M6 is refered to as a set of pairs

$$M6 = \{(R6, t)\}, \; R6 \in X6,$$

chosen by some principle, each pair meaning checking the point R6 at the time t. Plan M6 is refered to as non-redundant if among all the pairs of this set there are no equivalent ones. Plan M6 is defined as complete if realization of all its pairs garantees a "coverage" of the sought for SO in the phase space.

A real sensor can sound not the 6-dimentional phase space but its real K-dimentional projection (K = 2 for optical, K = 3 for a radar sensor). With this, the projectional equation looks as it is shown here:

$$DK(t1) = PD6(t1) = P \bigcup_{R_6 \in D_6(t_o)} F(to, R6(to), t1) =$$

$$= \bigcup_{R_6 \in D_6(t_o)} PF(to, R6(to), t1) = \bigcup_{R_6 \in D_6(t_o)} FK(to, PR6(to), t1) =$$

$$= \bigcup_{R_K \in D_K(t_o)} FK(to, RK(to), t1), \quad DK(to) = PD6(to),$$

where P is a projection operator: PR6(t)=RK(t), FK is a K-dimentional projection of F, which is already not a homeomorphism because of relationships (1) and (2):

$$FK(to, RK(to), t1) = \bigcup_{R_6 : PR_6 = R_K(t_o)} PF(to, R6(to), t1) = D'K(t1), \quad (1)$$

$$RK(to) \neq R'K(to) \not\Rightarrow FK(to, RK(to), t1) \cap \cap FK(to, R'K(to), t1) = 0. \quad (2)$$

According to (1) the FK-image of the point RK(to) is not a point but a domain. According to (2) the FK-images of two different points may intersect.

So the mapping FK is not one-valued in the both sides, not to speak about continuity.

The technical capabilities of a narrow-angle or narrow-beam facility allows it to check every time the compact elementary K-dimentional domain $d^o_K(t)$ practically invariant in time and space. At the same time during the transit from t_o to t_1 the equivalent domain $dK(t1) = FK(to, d^o_K(t_o), t1)$ may be essentially deformed because of known error transformation laws. Besides, according to (2), points RK not belonging to the elementary domain $d^o_K(t_o)$ may transit into its image dK(t1).

Such essential topological difference between F and FK (also complicated by time-dependence of the projection plane position) really makes difficult the transition from equivalence of M6 in the 6-dimentional phase space to equivalence of MK in real 2- or 3-dimentional space of search.

The most complete and constructive theoretical base and the applied mathematical, technical and methodical tool, using the equivalence principle, were developed for one important class of real search situations. The class is confined to highly orbital SO and to the supposition of predominant error propagation along the track. It gave the possibility to adopt the assumptions essentially simplifying formulation and solving the problem.

3. OPTIMUM STRATEGY PRACTICE

The corresponding software was elaborated and several series of natural experiments were carried out with it with the help of different electro-optical facilities. The results have shown the following:

1) in quickness and economicity the tested methods excel the known traditional ones of sequential scanning and spiral search (4). In the most typical 1-dimentional search situations they were 7 to 10 and more times as effective. When there are significant errors in several motion parameters the proposed methods are found to be else more times as effective;

2) the implemented and investigated methods unlike the traditional ones have the properties of completeness and non-redundency;

3) there were found SOs in geosynchronous and highly elliptical orbits ("Molnya" and SDS types) which were in a wrong phase of solar illumination and

which had not been found by the classic methods - including the cases of very durable missing of SO (for about a half-year and more).

There were some cases of SO detection in 10 to 12 minutes after having been lost for about 6 to 9 months and after numerous unsucsessful searching attempts using the traditional methods.

4. CONCLUSION

At conclusion I shall underline once more the next. The proposed methods achieve simultaneously the two important aims: the utmost economicity of the search strategy (this concerns not only small objects) and creation of the necessary favourable conditions for concentration and summation of a weak signal energy taking into account the significant uncertainties in the orbital parameters of a SO. The last property allows detection of very weak signals which would be missed by the traditional search methods.

5. REFERENCES

1. С.С.Вениаминов, Оптимизация поиска объекта, движущегося циклически по замкнутой траектории, Известия АН СССР, Техническая кибернетика, 1984, N 1.

2. С.С.Вениаминов, Оптимальное планирование поиска ИСЗ группой пунктов наблюдения, Астрометрия и астрофизика, 1983, N 49.

3. С.С.Вениаминов, Оптимизация поиска ИСЗ узкопольным телескопом по критерию времени обнаружения, Кинематика и физика небесных тел, 1987, т.3, N 1.

4. С.Е.Здор, В.Б.Широков, Оптический поиск и распознавание, "Наука", 1979.