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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Russian Satellite Navigation System

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The Russian satellite navigation system

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Since 1972, systematic analysis of Cosmos satellites, having near-circular orbits and periods close to 105 min, has revealed that several groups have had the necessary orbital plane spacing to give the global coverage suitable for satellite navigation systems. Replacements have been launched at regular intervals. The current systems comprise three satellites with 60° spacing, six with 30° spacing and three with 45° spacing.

These satellites have been shown to transmit on frequencies close to 150 and 400 MHz. The modulation of the 150 MHz carrier frequencies is explained together with the techniques employed to decode Standard Moscow Time, the satellite's position in geocentric Cartesian coordinates with corresponding rates of change at 3 min intervals, plus the orbital parameters of all satellites forming the system.

Introduction

Although the Soviet Union's Five Year Plan, announced in 1966, made direct reference to the use of space for navigation, no Russian satellite was specifically identified as having such a mission until the launch of Cosmos 1000 on 31 March 1978.

In an attempt to identify the particular satellites concerned, a programme of orbital analysis, based on Norad two-line orbital elements, was commenced in 1972. This revealed the rudimentary global coverage required for a navigation system (Perry 1972). Positive confirmation was obtained by reception of the radio transmissions and by subsequent analysis of the transmitted data which showed position and standard time. The historical aspects of this ambitious task, employing no sophisticated equipment, have been reported elsewhere (Perry & Wood 1976; Perry 1976, 1978).

The obvious place to look was within the Cosmos programme, and particularly at those satellites with orbital parameters characteristic of those of the U.S. Navy's Transit system: near-circular orbits with periods of the order of 100 min.

Orbital plane spacings

The position of the orbital plane in space relative to the fixed stars is specified by the right ascension, r.a., of the ascending node. For satellites in circular orbits at 1000 km altitude, the rate of change of r.a. remains reasonably constant over long periods of time, and thus it is possible to compute values of r.a. at given epochs from known values of r.a. at two widely separated epochs.

By computing the r.a.s of operational satellites at an epoch close to the launch-date of a new satellite, it is possible to observe the relative orbital plane spacings and note which satellite has the same r.a. as the newcomer. It is not unreasonable to assume that this satellite has been

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replaced at the end of its operational life, and decoding of radio transmissions in recent years confirms the assumption.

The first operational system

Strong candidates for the navigation role were Cosmos satellites with an orbital inclination of 74° to the equator and periods close to 105 min.

Table 1. Development of first operational system

(Values are R.A.s of ascending node in degrees.)

Cosmos	385	422	465	475	489
385	284				
422	17	258			
465	37	279	159		
475	(278)	159	40	281	
489		(37)	278	158	39

Table 1 gives the R.A.s of such satellites at epochs close to their launch-dates. It can be seen that the orbital planes are spaced at 120° intervals, thus giving rudimentary global coverage. The satellites fall into three groups. Cosmos 475 and 489 replaced Cosmos 385 and 422 after intervals of 440 and 350 days respectively, pointing to an operational life of about 1 year.

The second operational system

Cosmos 514, launched on 16 August 1972, differed from these satellites only in having an inclination of 83° instead of 74°. In 1973 it was joined by Cosmos 574 and 586 with a 60° spacing between their orbital planes. Table 2 shows the development of this new system up to the present day. It will be seen that replacement satellites have been launched at regular intervals.

Table 2. Development of second operational system

(Values are R.A.s of ascending node in degrees.)

Cosmos	514	574	586	627	628	663	689	729	800	823	846	890	962	994	1027
514	199														
574	330	31													
586	266	327	29												
627	(187)	250	311	189											
628		236	(297)	175	297										
663		118		57	(178)	179									
689		(35)		334		96	35								
729				(197)		318	258	197							
800						(106)	47	346	285						
823							319	(258)	197	258					
846							(277)		156	216	277				
890									27	(88)	147	90			
962									182		(299)	244	305		
994									(81)			143	204	81	
1027												(45)	104	342	45

A major change occurred on 3 February 1976, with the launch of Cosmos 800. Instead of directly replacing Cosmos 663, it was placed in a plane separated from that of Cosmos 663 by 180°. This had the effect of moving the orbital planes of the second operational system away from those of the third system, which had been introduced at the end of 1974 and was being extended to a six-satellite system.

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The near-polar inclination of 83° meant, in effect, that satellites in orbital planes spaced 180° apart were virtually in the same orbital plane but travelling in opposite directions. Thus it was only necessary to cover an arc of 180° with the orbital planes in order to achieve complete global coverage.

The third operational system

Cosmos 700, launched on 26 December 1974, did not fit the general pattern of replacement for the second operational system, being offset by 20° from Cosmos 627. Cosmos 726 was also offset from the second system and was 120° away from Cosmos 700. The gap in this third system was filled by Cosmos 755, placed midway between them.

Table 3. Development of third operational system

(Values are R.A.s of ascending node in degrees.)

Cosmos	700	726	755	778	789	864	887	894	928	951	971	985	991	996	1011
700 (1)	303														
726 (2)	225	347													
755 (3)	132	255	193												
778 (4)	72	194	132	225											
789 (5)	15	137	75	168	45										
864 (6)	165	288	226	320	197	256									
887 (7)	121	(244)	181	276	153	212	243								
894 (8)	(77)		137	232	109	168	198	77							
928 (1)			(35)	132	9	66	97	336	35						
951 (2)				86	(324)	21	51	290	349	321					
971 (3)				(12)		306	336	215	275	247	7				
985 (4)						288	318	(197)	256	229	348	196			
991 (5)						256	(288)		225	198	317	165	287		
996 (7)						(236)			204	177	297	144	266	236	
1011 (6)									(163)	136	255	103	225	194	164

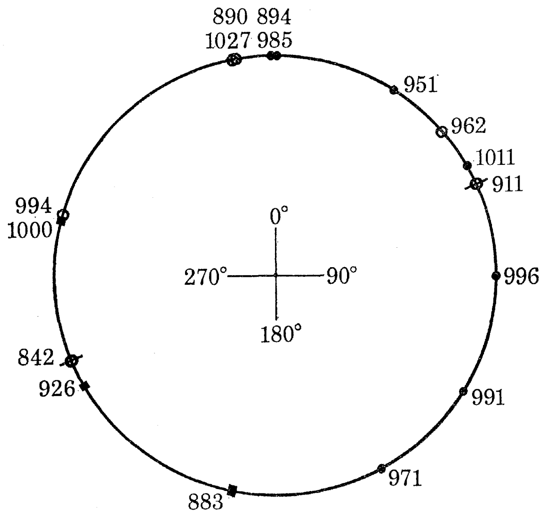
The development of the third operational system is given in table 3. A further development came with the launch of Cosmos 778 on 4 November 1975. Placed midway between Cosmos 726 and 755, it marked the extension of the third system into a six-satellite system with 30° orbital plane spacings. Russian identity numbers, decoded from the radio transmissions, are given in parentheses following the Cosmos designation in table 3.

A fourth operational system

An additional group of satellites with identity numbers 11, 12 and 13 has recently appeared and must be considered to be a fourth operational system. Their orbital planes are spaced 45° apart and the ascending nodes fall within the quadrants opposite to those occupied by the third system.

Locations of the ascending nodes of satellites currently transmitting are indicated diagrammatically in figure 1. It will be seen that two of the satellites that have been 'replaced' are still transmitting along with their 'replacements'.

Two satellites which, from orbital parameters alone, appear to be members of the set of navigation satellites described, are included although they do not fit the patterns of orbital plane spacings and have not been observed to transmit on the same frequencies as the others. It is of interest that their orbital planes are spaced 180° apart.



second system		third system		fourth system	
Cosmos	890	Cosmos	894	Cosmos	883
	962		951		926
	994		971		1000
	1027		985		
			991		
			996		
			1011		

Figure 1. Right ascensions of ascending nodes of Russian navigation satellites, 10 October 1978.

Radio transmissions

Like the U.S. Transit satellites, the Cosmos navigation satellites transmit simultaneously in the v.h.f. and u.h.f. bands. Frequencies of 150.00 and 400.00 MHz were used initially. As the number of operational satellites increased, channels above and below 150 MHz were brought into operation, the 3:8 frequency ratio of v.h.f. and u.h.f. channels being maintained. Table 4 gives the approximate frequencies employed. Signals are not continuous but, when received, have indicated an effective radiated power in the order of 10 W. The u.h.f. carrier is unmodulated.

Table 4. Navigation satellite frequencies

v.h.f./MHz	u.h.f./MHz	system
149.9625	399.9	Cosmos
149.975	399.933	Cosmos
149.988	399.968	Transit
150.00	400.00	Cosmos
150.0375	400.1	Cosmos

Carrier modulation

Two kinds of 50 bit s^{-1} modulation, designated types A and B for convenience, are employed. Type A modulation is used exclusively by the second operational system. In both types, the data to be transmitted selects a low frequency and the resulting sequence amplitude modulates the v.h.f. carrier. Their frequency spectra are shown in figure 2.

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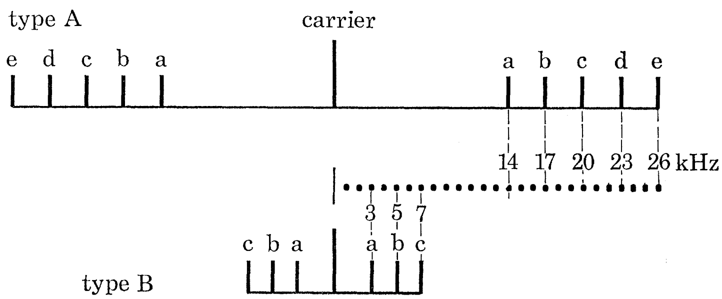

FIGURE 2. Signal spectra.

Type A modulation

The data to be transmitted select either 14, 17, 20 or 23 kHz producing side bands a, b, c or d after modulating the carrier. Binary 1 alternately selects 14 or 17 kHz and binary 0 alternately selects 20 or 23 kHz, e.g. the transmission of binary 1011001 would result in sideband sequence a, c, b, a, d, c, b. This arrangement permits the extraction of data timing information even when long sequences of binary 1 and 0 are present. It also permits a limited degree of error correction.

A 26 kHz time synchronization pulse of 20 ms duration is inserted every second and produces side bands e.

Type B modulation

Most of these satellites employ this method using only two frequencies, 3 and 5 kHz, to convey the binary information. The 7 kHz provides time synchronization every second. Transitional encoding is employed, binary 1 being represented by a change from 3 to 5 kHz or vice versa. Binary 0 produces no frequency shift. The low amplitude odd and even harmonics of sidebands a and b that are normally present are not shown in figure 2.

Owing to the widespread use of type B modulation, the remainder of this paper relates, unless otherwise stated, to type B.

DATA FORMAT

Every second of the v.h.f. transmission is punctuated by the time synchronization pulse shown in figure 3; 17 binary bits are used to give a statement of real time in hours, minutes and seconds (Moscow Time) referred to the start of the pulse. This pulse can extend from its minimum 20 ms length up to the first binary 1 of the time statement, occupying the full 17 bits at midnight.

The last 32 bits of each second form an information word.

The 1 min *frame and information blocks*

Sixty 1 s lines of data produce a 1 min data frame. The seven information words starting from second 02 contain related data. Similarly, seven other words of related data begin during seconds 09, 16, 23, 30, 37, 44 and 51. It is convenient to consider the 1 min frame as having eight information blocks, as illustrated in figure 4.

When a word is received, the block, its position within the block, and hence its purpose, are defined by the preceding seconds value of the time count.

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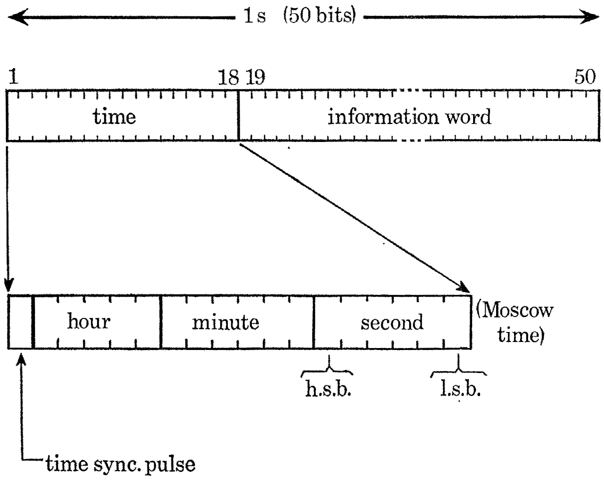

FIGURE 3. Position of encoded time information within each second.

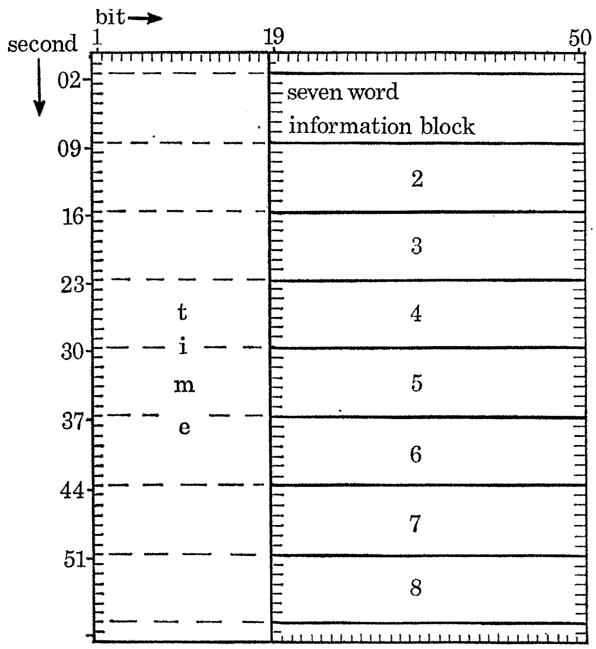

FIGURE 4. Composition of 1 min time frame.

The first two words of the frame each have 32 bits of binary 0 and hence contain no information. Binary values in the last two words of each frame are also 0 with the exception of bit 35.

Utilization of information blocks

The first four information blocks define the transmitting satellite's position in geocentric Cartesian coordinates; blocks 1 and 3 are identical, as are blocks 2 and 4. Even numbered blocks define the position 3 min after that given by the odd blocks.

On a basis of one block per satellite, the remaining four blocks in the frame contain the orbital parameters of the satellites in the system. The parameters of the transmitting satellite always appear in block 5.

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Progression of information blocks

The coordinate blocks for t and $t+3$ min are repeated for three frames. In the next three frames the information for $t+3$, previously occupying blocks 2 and 4, move up to blocks 1 and 3, with $t+6$ min being inserted into blocks 2 and 4. Three frames later, coordinates are inserted for $t+9$. Thus coordinates of the satellite at intervals of 3 min are given in any frame and are updated every 3 min.

A system employing a 30° orbital plane spacing involves six satellites requiring six parameter blocks. Since only four blocks are available in each frame, parameter blocks are repeated every 2 min making eight available. The use of seven or even eight parameter blocks is not unusual, occurring when replacements are launched before the withdrawal of older satellites. These progressions are shown in figure 5.

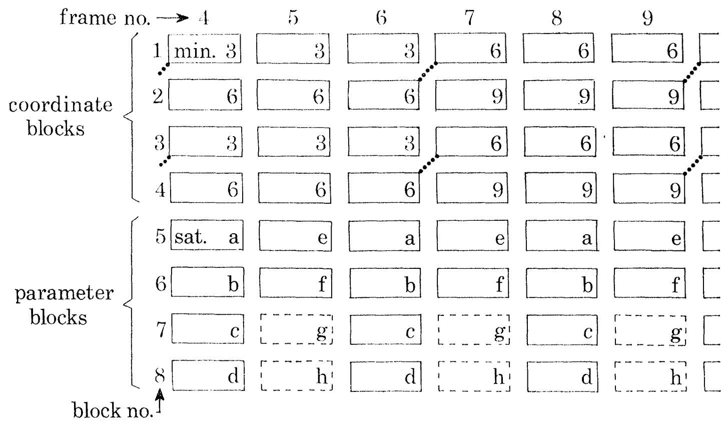

Figure 5. Block progression, frame by frame.

Satellite identity numbers

To avoid confusion, particularly in the parameter blocks, each satellite has an identity number. These numbers are not unique, only relating to a particular satellite during its operational lifetime, and are subsequently re-allocated but not to the replacement.

Identity numbers for the 30° system are in the range 1–8. The fourth system with 45° spacing currently uses identity numbers 11, 12 and 13.

Information decoding

Generally, information words employ normalized binary floating point notation. The allocation of the 32 bits to the mantissa and exponent is shown in figure 6. The arrangement caters for decimal values ranging from $+32768$ to -32768 but excludes values smaller than $\pm 1.52587 \times 10^{-6}$.

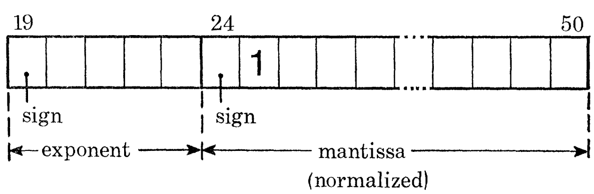

Figure 6. Allocation of bits in floating-point words.

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Words not using the above technique are split into two or more sub-words and employ normal binary notation with the highest significant bit being transmitted first.

Coordinate block details

As indicated above, the satellite's position in space is defined at a given time, in terms of X, Y and Z coordinates. X is in the direction from the origin through 00° latitude – 00° longitude, Y from origin through 00° latitude – 90° E, and Z through 90° N. To enable the satellite's intermediate positions to be computed, each block also contains the rates of change of the coordinates (see table 5).

TABLE 5. ALLOCATION OF COORDINATE BLOCK WORDS

word	quantity	unit
1	X coordinate	kilometres
2	Y coordinate	kilometres
3	Z coordinate	kilometres
4	dx/dt	kilometres per second
5	dy/dt	kilometres per second
6	dz/dt	kilometres per second
7	(*a*) bits 27–37, time t	minute of day
	(*b*) remaining bits; see text	

Words 1–6 use floating point notation and relate to the time t derived from a sub-word (bits 27–37) of the seventh word; the remaining sub-words are described later.

Satellite parameter block details

The orbital parameters are contained in words and sub-words as shown in table 6. The transmitted values remain constant for a week and in the 30° system normally refer to the first ascending node occurring after Friday midnight Moscow time. Direct comparison, where possible, with values given in NORAD two-line orbital elements shows good positive correlation between both data sets.

TABLE 6. ALLOCATION OF PARAMETER BLOCK WORDS

word	quantity		unit	parity bit
1	ascending node longitude (east)		radians	50
2	inclination of orbit		radians	24
3	(*a*) bits 19–23 identity number		—	24
	(*b*) bits 25–50 semi-major axis		kilometres	
4	constant, K_1, $+e \sin \omega$		—	19
5	constant, K_2, $+e \cos \omega$		—	19
6	orbital period		minutes	19
7	(*a*) bits 20–23 month	time of ascending node	—	19
	(*b*) bits 24–28 day			
	(*c*) bits 29–33 hour			
	(*d*) bits 34–39 minute			
	(*e*) bits 40–50 part minute			

The plot of $e \sin \omega$ against $e \cos \omega$ normally produces a circle with the centre slightly offset from the origin. Word 4 plotted against word 5 also produces a circle but with greater offsets than those obtained from NORAD figures. Constants K_1 and K_2 represent the difference between the two offsets having approximate values of $+1.04 \times 10^{-3}$ and $+4.5 \times 10^{-4}$ respectively.

Parity and error checks

Parameter blocks

Binary 1 occurs an odd number of times in each of the seven words of a parameter block. While the normal position for a parity bit would be at the end of the word, there is strong evidence to suggest that its position may be elsewhere. Such positions are indicated in table 6 and are those normally allocated to the exponent or mantissa sign. There is no conflict as such signs are redundant in the particular words. For example, the inclination given in word 2 is naturally positive, irrespective of the bit preceding the mantissa. Similarly the exponent of lines 4 and 5 should always be considered negative, irrespective of the sign derived from bit 19.

In view of the repetition rate of parameter blocks, more sophisticated error checking is probably unnecessary.

Coordinate blocks

Parity bits are not included in the coordinate block words. In view of the importance of these words in defining the satellite's position, it is probable that more sophisticated error checking techniques are employed. Word 7 has two undefined sub-words, each of eight bits, whose values follow no logical sequence. It is possible that cyclic coding of the block is employed with the remainder, after modulo 2 division, being contained in one or both sub-words. The most suitable generating polynomial is dependent on the number of bits included in the block before the addition of the remainder and is still undetermined.

Information from type A satellites

Type A transmissions differ from those using type B modulation in having no parameter blocks and consequently no identity numbers. Each 1 min frame consists of six coordinate blocks separated by three blank words. Floating point notation is used throughout to give X, Y and Z coordinates, their rates of change and the time of the day to which they relate.

Type A data differs in general terms from type B in that the lowest significant bits and values are transmitted first. The real-time statement contained in the first 18 bits is read in the sequence: second, minute, hour, The mantissa of the information word occupies bits 20–45, bit 19 being its sign, and the exponent occupies bits 47–50, its sign being bit 46. Parity bits are not provided.

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