motion of the eighth to the twelfth satellites of Jupiter. Mello is engaged in the theoretical study on the interaction of three satellites of Jupiter.

Kondurar (6) has considered the motion of a satellite in Hill's problem of three bodies around a planet having a spheroidal shape.

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ARTIFICIAL SATELLITES

Apart from the theories of the motion of an artificial satellite by King-Hele, Brouwer, Garfinkel, Kozai and others, Vinti (1) has succeeded in integrating the equations of motion of

$$U = -\frac{\mu}{r}\left[1 - \sum_{n=1}^{\infty} J_n \left(\frac{R}{r}\right)^n P_n(\sin\beta)\right]$$

by means of Hamilton-Jacobi's method in the separation of variables. According to this idea Izsak (2) has considered as his intermediary orbit for the motion of an artificial satellite the motion in the gravitational potential of the Earth by taking into account the coefficients of the zonal harmonics as far as the second order with respect to J_2. The ingenious assumption which Vinti made leads to the separation of variables if $J_{2n} = (-1)^{n+1} J_2^n$, $J_{2n+1} = (-1)^n J_1 J_2^n$. Observations show that the error $J_4 + J_2^2 \sim -10^{-6}$. Since J_1 is practically zero, the potential

$$U = -\frac{\mu}{r}\left[1 + \sum_{n=1}^{\infty} (-J_2)^n \left(\frac{R}{r}\right)^{2n} P_{2n}(\sin\beta)\right]$$

is a good approximation. If oblate-spheroidal co-ordinates are used, then the Hamilton-Jacobi equation of the problem is of Stäckel's type. The solution can be expressed in elliptic integrals. By referring to the theory of elliptic functions with a linear fractional transformation in the complex domain Izsak expressed the solution in Fourier series and the integration constants as funtions of the Keplerian elements.

Vinti (3) tried to simplify Izsak's process of solution and expressed it in terms of the complete elliptic integrals by avoiding the use of complicated elliptic functions, that is, by obtaining the solution as the sum of integrals containing quartics which are evaluated by convergent Fourier series, and then transformed by uniformizing with the eccentric anomaly. Vinti (4) deduced the mean motion in such a conditionally periodic separable system. Then he (5) removed the restriction on the orbital inclination $I_c < I < 180° - I_c$, where I_c might be as large as 1° 54′ for an orbit sufficiently close to the Earth. Many of the formulae for the periodic terms are simplified when the orbit is equatorial or almost equatorial.

Bonavito (6) announces that Vinti's solution goes very fast on the IBM 7090. Shapiro (7) discussed the prediction of satellite orbits.

Callander (8) shows the motion of an artificial close satellite to be quasi-periodic by obtaining the bounds of the variation of the radial distance and the variation of the inclination. Poritsky (9) has shown that the satellite orbit is forever confined to the interior of a certain toroidal region by judging from an integral analogous to the energy integral obtained after a reduction of the differential equations.

Barrar (**10**) estimated to be of the order J_2^3 the difference between the two procedures: to average the potentials and solve the problem or to solve the problem for the given potential and average the answers.

Hori (**11**) studied the hyperbolic case of the motion of artificial satellites. He extended Delaunay's variables to this hyperbolic case and transformed the canonical equations by von Zeipel's theory.

Popovič (**12**) wrote me that he had given the disturbing force of an ellipsoid of revolution with coefficients J_2 and J_4. Zagar (**13**) describes the general method of perturbation of the orbit of an artificial satellite by the spheroidal figure of the Earth. He has organized a working group for the mathematical study of the trajectories of artificial celestial bodies and for the associated physical and geophysical problems. The orbit perturbations of an artificial satellite caused by the Earth's gravitational force and the influence of high atmosphere have been studied, together with the method of calculation on an IBM electronic computer for the orbit problem. Kovalevsky (**14**) discussed the general method for computing the effects of more general origin, including non-sphericity of the Earth potential, atmospheric drag and radiation pressure, and recommended von Zeipel's method but without attention to the convergence of the solution.

Sconzo (**15**) published the differential orbit correction and ephemerides tables for the motion of an artificial Earth satellite, based on Brouwer's theory and the drag effect on empirical procedure. Using the best available observational data, such as by Baker-Nunn cameras, several sets of orbital mean elements at different epochs are obtained. They are expressed as empirical functions of time by means of a general least square fitting procedure. Then the values of the orbital elements at any assigned epoch and then the ephemerides are computed.

Since very accurate observations on the motion of artificial satellites are now available, Petty and Breakwell (**16**) and Struble (**17**) derived the second-order periodic perturbations as functions of the true longitude. Kozai (**18**) went farther and discussed the second-order periodic perturbations with third-order secular perturbations in satellite motions derived by von Zeipel's method. The potential of the Earth is developed into a series of zonal spherical harmonics by assuming that J_2 is a small quantity of the first order, J_3 and J_4 are of the second order, and J_5, J_6, J_7, and J_8 are of the third order. The final expressions of the short-period perturbations are given in the radius, the argument of latitude, the inclination, and the longitude of the ascending node. Izsak (**19**) transformed the variables from Delaunay's to the canonical system ($\dot{r}$, G, H; r, u, h), where u is the argument of latitude, for computing the short-period perturbation of the co-ordinates.

Kovalevsky (**20**) described various analytical methods for computing the coefficients of the expansion of the Earth potential. Most of the results are inconsistent, because the differences are due to the imperfections in the definition of the integration constants, especially the so-called mean elements. He proposes a mathematical definition of the constants, and some principle which should be followed in any complete study of the orbit in order to compare the theory with observations. He prefers the osculating elements to the mean elements for their determination by observations.

Garfinkel (**21**) describes a historical survey of the theory of the motion of an artificial satellite. He wrote me that he had built up an improved theory of the motion (**22**).

The coefficients of zonal and tesseral spherical harmonics of the Earth's gravitational potential have been derived from the minitrack and field-reduced Baker-Nunn observations of artificial satellites by Kozai (**23, 31**) Izsak (**24, 33**), Kaula (**25, 26**), King-Hele (**27, 32**), Smith (**28**), Newton *et al* (**29**). The mathematics has been worked out by Kozai (**30**) both for the zonal and the tesseral coefficients. The tesseral and sectorial harmonics cannot cause secular perturbations of the first order in any orbital element of the satellite, but they can cause periodic perturbations of two kinds: short-period perturbations of which the arguments depend on the mean anomaly and the long-period perturbations of which the periods are nearly integral fractions of a day. The amplitudes of the long-period perturbations are usually almost ten times larger than those of the short-period.

The up-to-date determinations are listed in Table 1 for the zonal and in Table 2 for the

Table 1. Coefficients of zonal spherical harmonics

Kozai, 1962 (**31**)	King-Hele, Cook, Rees, 1963 (**32**)
$J_2 = +1082{\cdot}48 \times 10^{-6}$	$J_2 = +1082{\cdot}78 \times 10^{-6}$
$J_4 = -1{\cdot}84 \times 10^{-6}$	$J_4 = -0{\cdot}78 \times 10^{-6}$
$J_6 = +0{\cdot}39 \times 10^{-6}$	$J_6 = +0{\cdot}70 \times 10^{-6}$
$J_8 = -0{\cdot}02 \times 10^{-6}$	$J_8 = +0{\cdot}24 \times 10^{-6}$
	$J_{10} = -0{\cdot}50 \times 10^{-6}$
	$J_{12} = +0{\cdot}28 \times 10^{-6}$
$J_3 = -2{\cdot}562 \times 10^{-6}$	$J_3 = -2{\cdot}44 \times 10^{-6}$
$J_5 = -0{\cdot}064 \times 10^{-6}$	$J_5 = 0$
$J_7 = -0{\cdot}470 \times 10^{-6}$	$J_7 = -0{\cdot}45 \times 10^{-6}$
$J_9 = +0{\cdot}117 \times 10^{-6}$	

Table 2. Coefficients of tesseral spherical harmonics

Izsak, 1963 (**33**)		Kaula, 1963 (**26b**)	
		$\Delta\bar{C}_{00} = -2{\cdot}46$	$\Delta\bar{C}_{20} = -0{\cdot}03$
$C_{22} = +9{\cdot}68 \times 10^{-7}$	$S_{22} = -4{\cdot}00 \times 10^{-7}$	$\bar{C}_{22} = +1{\cdot}88$	$\bar{S}_{22} = -1{\cdot}38$
		$\bar{C}_{30} = +0{\cdot}97$	
$C_{31} = +1{\cdot}12 \times 10^{-6}$	$S_{31} = +6{\cdot}16 \times 10^{-8}$	$\bar{C}_{31} = +1{\cdot}52$	$\bar{S}_{31} = +0{\cdot}14$
$C_{32} = +9{\cdot}12 \times 10^{-8}$	$S_{32} = -1{\cdot}83 \times 10^{-7}$	$\bar{C}_{32} = -0{\cdot}02$	$\bar{S}_{32} = +0{\cdot}42$
$C_{33} = +7{\cdot}17 \times 10^{-8}$	$S_{33} = +1{\cdot}24 \times 10^{-7}$	$\bar{C}_{33} = +0{\cdot}70$	$\bar{S}_{33} = +0{\cdot}76$
		$\bar{C}_{40} = +0{\cdot}67$	
$C_{41} = -2{\cdot}88 \times 10^{-7}$	$S_{41} = -3{\cdot}21 \times 10^{-7}$	$\bar{C}_{41} = -0{\cdot}33$	$\bar{S}_{41} = +0{\cdot}37$
$C_{42} = +3{\cdot}51 \times 10^{-8}$	$S_{42} = +1{\cdot}23 \times 10^{-7}$	$\bar{C}_{42} = +0{\cdot}01$	$\bar{S}_{42} = +0{\cdot}35$
$C_{43} = +2{\cdot}15 \times 10^{-8}$	$S_{43} = +1{\cdot}48 \times 10^{-8}$	$\bar{C}_{43} = +0{\cdot}17$	$\bar{S}_{43} = +0{\cdot}41$
$C_{44} = +9{\cdot}72 \times 10^{-9}$	$S_{44} = +1{\cdot}63 \times 10^{-8}$	$\bar{C}_{44} = -0{\cdot}01$	$\bar{S}_{44} = +0{\cdot}18$

tesseral harmonic coefficients. The formula for the zonal harmonic expansion has been given. For the tesseral harmonic expansion, Izsak (**33**) adopts

$$U = \frac{\mu}{r}\left\{1 + \sum_{n=2}^{\infty}\left(\frac{R}{r}\right)^{n}\sum_{m=0}^{n}\left[C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right] P_{nm}(\sin\beta)\right\},$$

$$P_{nm}(x) = (1-x^2)^{m/2}\,\frac{d^m P_n(x)}{dx^m}\;,$$

in accordance with the resolution of the IAU Commission 7 at Berkeley in 1961, while Kaula refers to his formula (**26**)

$$R_{nm} = \frac{\mu R}{a^{n+1}} \sqrt{\frac{(n-m)!\,(2n+1)\kappa_m}{(n+m)!}} \sum_{p=0}^{n} F_{nmp}(i) \sum^{\infty} G_{npg}(\rho)$$

$$\times \left[\begin{Bmatrix} \bar{C}_{nm} \\ -\bar{S}_{nm} \end{Bmatrix}_{(n-m)\ odd}^{(n-m)\ even} \cos\{(n-2p)\omega + (n-2p+\epsilon)M + m(\Omega-\theta)\} \right.$$

$$\left. + \begin{Bmatrix} \bar{S}_{nm} \\ \bar{C}_{nm} \end{Bmatrix}_{(n-m)\ odd}^{(n-m)\ even} \sin\{(n-2p)\,\omega + (n-2p+\epsilon)\,M + m(\Omega-\theta)\} \right],$$

where $\kappa_0 = 1$, $\kappa_m = 2$, $m \neq 0$. $\Delta\bar{C}_{00}$, $\Delta\bar{C}_{20}$ mean the corrections to $0{\cdot}3986032 \times 10^{21}$ $(1{\cdot}0 - 0{\cdot}001\,082\,36\, P_2)$ c.g.s. The mean equatorial radius by Kaula is 6 378 196 ± 11 metres, while Kozai's value is $R = 6{\cdot}378\,165 \times 10^6$ metres.

There is scarcely any work published in the theory of rotation of an artificial satellite during its flight along its orbit. Colombo (**34**) analyzed the rotation of Explorer XI around its axis from the point of view of the gravitational and the magnetic torques and computed the period of its tumbling. Hagihara (**35**) computed analytically the effects on the rotation due to the gravitational, gasdynamical and magnetic torques with complicated algebra.

Belorizky determined, in a homogeneous ellipsoid of rotation of small oblateness, the precise parallel where the force of attraction is the same as if the ellipsoid were replaced by a sphere of the same density. The theory is applied to the Hayford ellipsoid currently accepted. At the parallel of 35° 25′ 10″, one finds that the attraction is that of a sphere with the mass of the Earth less 3×10^{-6} of its value.

Kalitzin (**36**) studied Poincaré's limit of the maximum angular velocity of a rotating celestial body when the angular velocity depends on the distance from the rotation axis and examined Roche's model with central condensation. He proved the existence of a unique solution for a generalized problem of a non-uniformly rotating fluid in the case of small angular velocities, by means of an integro-differential equation, which is a generalization of the equation of Clairaut and Liapounov.

The following has been taken from the report of Soviet astronomers.

(*a*) *Motion of AES* (*Artificial Earth Satellite*) *in the Gravitational Field of the Earth.* A precise solution for the problem of the motion of an artificial satellite in the normal gravitational field of the Earth has been obtained by Kislik (**37**). For solving the same question Aksenov, Grebenikov and Demin (**38**) have used a generalized problem of two fixed centres. Zhongolovich (**39**) has presented closed formulae with respect to the eccentricity and inclination of the orbits for AES perturbations. Zhongolovich and Pellinen (**40**) have given a new description of the term 'mean AES elements'. Chebotarev (**41**) has considered the AES motion for the case of small eccentric orbits.

(*b*) *Periodic Orbits of AES.* Volkov (**42**) has proved the existence of the first, second and third sort periodic solutions of Poincaré for the problem of a particle moving in the gravitational field of a flattened planet and its satellite. Orlov (**43**) has proved the existence of almost-circular periodic orbits in the gravitational field of a spheroid for the case of a critical inclination of the orbit relative to the equatorial plane of the spheroid.

(*c*) *Perturbations in AES movement caused by the Moon and the Sun.* Noteworthy results concerning the stability and evolution of orbits of artificial satellites of a planet have been obtained by Lidov (**44**). As a particular numerical example he has considered the orbit evolution of a polar Earth satellite whose semi-major axis and eccentricity are equal, respectively, to the semi-major axis and eccentricity of the Moon. It has been shown that such a satellite would drop to the surface of the Earth in four years' time after only 52 revolutions. Egorova (**45**) has obtained the first order perturbations in AES orbital elements precise to the first order of the Earth's compression, and secular perturbations up to the second order of the compression.

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Perturbations by the Sun and the Moon have been made precise to the second order in the ratios of the mean motions of the Moon and Sun to the mean motion of the satellite. Chebotarev and Gontkovskaya (**46**) have considered in detail the perturbations caused by the Moon and the Sun in the motion of Lunik 3, the third Soviet space rocket.

(*d*) *Translational-Rotational Motion of AES.* Duboshin (**47**) has considered a general problem of integrating the differential equations for the rotational motion of an artificial celestial body whose inertia-centre is moving along an assigned trajectory. The same question has been considered by Beletski (**48**). Kondurar (**49**) has attacked a general problem of the progressive-rotational motion of two absolutely rigid bodies whose ellipsoids of inertia differ from a sphere. For small characteristics, the dynamical compression of the bodies is assumed. He has also discussed (**50**) the influence of the satellite shape on the motion of the centre of masses around a spherical planet under the assumption that a non-disturbed orbit is either a circle or an ellipse. The satellite is supposed to be a rotating body with dynamical symmetry about the axis of rotation. Magnaradze (**51**) has considered the translational-rotational motion of a space vehicle relative to the Earth by taking the air resistance into account. The space vehicle has a rod-like shape and a variable mass. Volkov (**52**) has developed an approximate general solution in the vicinity of the periodic solution for the translational-rotational motion of a satellite in the gravitational field of a sphere. The stability of a rotational motion relative to the various disturbing factors has been studied by Beletski (**53**). He has also determined the characteristics of the rotation and the orientation of the third Soviet Satellite over an extensive lapse of time.

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