

# Primer - Potential outside a Oblate Spheroid

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Notes on a satellite orbiting a non-rotating uniform spheroid.

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# 1 Gravitational Potential $V$ in terms of $r$ and $\phi$

Outside the spheroid, the gravitational potential satisfies Laplace's equation  $\nabla^2 V = 0$ . The solution to this is found by separation of variables - looking for a solution, in spherical coordinates, of the form  $V = R(r)\Phi(\phi)\Lambda(\lambda)$ .

Note the use of geodetic notation for coordinates  $[r, \phi, \lambda]$  as opposed to the usual Physics convention of  $[r, \theta, \phi]$ . The solution can be written as below [Kaula]

$$V = \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{1}{r^{l+1}} P_{lm}(\sin \phi) [C_{lm} \cos m\lambda + S_{lm} \sin m\lambda] \quad (1)$$

where  $P_{lm}$  are Legendre associated functions and  $C_{lm}$  and  $S_{lm}$  are constants. Note the  $\sin \phi$  term rather than the usual  $\cos \theta$  we normally see in Physics books when discussing Legendre polynomials in spherical coordinates. This is because  $\phi$  is the latitude rather than the usual co-latitude  $\theta$  we use in spherical coordinates.

$$\sin \phi = \sin \left( \frac{\pi}{2} - \theta \right) = \cos \theta$$

Terms involving  $m = 0$  i.e.  $P_{l0}$  are called zonal terms. Terms involving  $m \geq 1$  are called tesseral terms [GeoPotential Model]. I'm interested in the uniform spheroid case, only considering terms  $l \leq 2$ , where the potential has no  $\lambda$  dependency i.e.  $m = 0$ . For  $m = 0$ , the Legendre associated functions  $P_{lm}(\sin \phi)$  become the Legendre Polynomials  $P_l(\sin \phi)$ . The above reduces to (where Legendre Polynomial  $P_0(\sin \phi) = 1$ )

$$V = C_{00} \frac{1}{r} + C_{20} \frac{1}{r^3} P_2(\sin \phi) \quad (2)$$

Note there is no  $l = 1$  term as expected, i.e.  $P_1$ , due to symmetry of the spheroid around the equator. At this point we just have a general solution of  $\nabla^2 V = 0$ .

## 1.1 Laplacian Check

Laplacian in polar coordinates [Kaula]

$$r^2 \nabla^2 = \frac{\partial}{\partial r} \left( r^2 \frac{\partial}{\partial r} \right) + \frac{1}{\cos \phi} \frac{\partial}{\partial \phi} \left( \cos \phi \frac{\partial}{\partial \phi} \right) + \frac{1}{\cos^2 \phi} \frac{\partial^2}{\partial \lambda^2}$$

There is no  $\lambda$  dependency so we can ignore the last term,  $V$  is

$$\begin{aligned} V &= C_{00} \frac{1}{r} + C_{20} \frac{1}{r^3} P_2(\sin \phi) \\ &= C_{00} \frac{1}{r} + C_{20} \frac{1}{r^3} \left( \frac{1}{2} [3 \sin^2 \phi - 1] \right) \end{aligned}$$

Applying the Laplacian to this gives

$$\begin{aligned} r^2 \nabla^2 V &= \frac{\partial}{\partial r} \left[ r^2 C_{00} \left[ -\frac{1}{r^2} \right] + r^2 C_{20} \left( \frac{1}{2} [3 \sin^2 \phi - 1] \right) \left( -\frac{3}{r^4} \right) \right] + \left[ \left( \frac{3}{2} C_{20} \frac{1}{r^3} \right) \frac{1}{\cos \phi} \frac{\partial}{\partial \phi} \left( \cos \phi \frac{\partial}{\partial \phi} \sin^2 \phi \right) \right] \\ &= \frac{\partial}{\partial r} \left( -C_{00} - C_{20} \left( \frac{1}{2} [3 \sin^2 \phi - 1] \right) \left( \frac{3}{r^2} \right) \right) + \left[ C_{20} \left( \frac{3}{r^3} \right) \frac{1}{\cos \phi} \frac{\partial}{\partial \phi} (\cos^2 \phi \sin \phi) \right] \\ &= C_{20} ([3 \sin^2 \phi - 1]) \left( \frac{3}{r^3} \right) + C_{20} \left( \frac{3}{r^3} \right) \frac{1}{\cos \phi} (\cos^3 \phi - 2 \sin^2 \phi \cos \phi) \\ &= C_{20} \left( \frac{3}{r^3} \right) ([3 \sin^2 \phi - 1]) + C_{20} \left( \frac{3}{r^3} \right) (\cos^2 \phi - 2 \sin^2 \phi) \\ &= C_{20} \left( \frac{3}{r^3} \right) ([3 \sin^2 \phi - 1]) + C_{20} \left( \frac{3}{r^3} \right) (\cos^2 \phi + \sin^2 \phi - 3 \sin^2 \phi) \\ &= C_{20} \left( \frac{3}{r^3} \right) ([3 \sin^2 \phi - 1]) + C_{20} \left( \frac{3}{r^3} \right) (1 - 3 \sin^2 \phi) = 0 \end{aligned}$$

## 1.2 Gravitational Potential for a Spheroid

The above is a general solution of  $\nabla^2 V = 0$ . Let us see what the gravitational potential is for a spheroid - but this time starting from the basic formula for the gravitational potential for a distributed body, which is (from [Potential Uniform Spheroid]). This derivation uses the typical Physics convention for the potential - note the -ve sign)

$$\Phi(\mathbf{r}) = \Phi(r, \theta, \phi) = -G \int \frac{\rho(\mathbf{r}')}{|\mathbf{r}' - \mathbf{r}|} d^3\mathbf{r}'$$

and given that

$$d^3\mathbf{r}' = r'^2 \sin \theta' dr' d\theta' d\phi'$$

and I'm assuming *constant* density  $\rho$  and from axial symmetry there is no dependence on  $\phi$

$$\Phi(r, \theta) = -G\rho \int_0^\infty \int_0^\pi \int_0^{2\pi} \frac{r'^2 \sin \theta'}{|\mathbf{r}' - \mathbf{r}|} dr' d\theta' d\phi'$$

Note that  $|\mathbf{r}' - \mathbf{r}|$  varies over  $\phi'$  for a given  $\theta'$ .

$$\Phi(r, \theta) = -G\rho \int_0^\infty \int_0^\pi \left[ \int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' \right] r'^2 \sin \theta' dr' d\theta'$$

### 1.2.1 Integration over azimuthal angel

Looking at the term  $\left[ \int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' \right]$

$$\frac{1}{|\mathbf{r}' - \mathbf{r}|} = [(\mathbf{r}' - \mathbf{r}) \bullet (\mathbf{r}' - \mathbf{r})]^{-\frac{1}{2}} = [r^2 - 2\mathbf{r}' \bullet \mathbf{r} + r'^2]^{-\frac{1}{2}}$$

From

$$x = r \sin \theta \cos \phi$$

$$y = r \sin \theta \sin \phi$$

$$z = r \cos \theta$$

$$r' \bullet r = rr' (\sin \theta \cos \phi \sin \theta' \cos \phi' + \sin \theta \sin \phi \sin \theta' \sin \phi' + \cos \theta \cos \theta')$$

but this is a calculation for  $\Phi(r, \theta)$  which is independent of  $\phi$  which means  $r' \bullet r$  must be independent of  $\phi$  so we can evaluate this at  $\phi = 0$

$$r' \bullet r = rr' (\sin \theta \sin \theta' \cos \phi' + \cos \theta \cos \theta') = rr' F$$

where

$$F = \sin \theta \sin \theta' \cos \phi' + \cos \theta \cos \theta'$$

giving

$$\frac{1}{|\mathbf{r}' - \mathbf{r}|} = [r^2 - 2rr'F + r'^2]^{-\frac{1}{2}} = \frac{1}{r} \left[ 1 - 2\left(\frac{r'}{r}\right)F + \left(\frac{r'}{r}\right)^2 \right]^{-\frac{1}{2}}$$

Binomially expand using  $(1+x)^{-\frac{1}{2}} = 1 - \frac{x}{2} + \frac{3}{8}x^2$  and  $x = -2\left(\frac{r'}{r}\right)F + \left(\frac{r'}{r}\right)^2$  and keeping terms up to  $\left(\frac{r'}{r}\right)^2$

$$\left[ 1 - 2\left(\frac{r'}{r}\right)F + \left(\frac{r'}{r}\right)^2 \right]^{-\frac{1}{2}} \approx 1 + \left(\frac{r'}{r}\right)F - \frac{1}{2}\left(\frac{r'}{r}\right)^2 + \frac{3}{8}\left(\frac{r'}{r}\right)^2 F^2 = 1 + \left(\frac{r'}{r}\right)F + \frac{1}{2}\left(\frac{r'}{r}\right)^2 [3F^2 - 1]$$

so

$$\int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' = \frac{1}{r} \int_0^{2\pi} \left[ 1 + \left(\frac{r'}{r}\right)F + \frac{1}{2}\left(\frac{r'}{r}\right)^2 [3F^2 - 1] \right] d\phi'$$

First term is

$$\frac{1}{r} \int_0^{2\pi} [1] d\phi' = 2\pi \frac{1}{r}$$

Second term - using  $\int_0^{2\pi} \cos \phi' d\phi' = 0$  - is

$$\begin{aligned} \frac{1}{r} \int_0^{2\pi} \left[ \left( \frac{r'}{r} \right) F \right] d\phi' &= \frac{1}{r} \left( \frac{r'}{r} \right) \int_0^{2\pi} [(\sin \theta \sin \theta' \cos \phi' + \cos \theta \cos \theta')] d\phi' = \frac{1}{r} \left( \frac{r'}{r} \right) (\cos \theta \cos \theta') \phi' \Big|_0^{2\pi} \\ &= 2\pi \frac{1}{r} \left( \frac{r'}{r} \right) \cos \theta \cos \theta' \end{aligned}$$

Third term - using  $\int_0^{2\pi} \cos^2 \phi' d\phi' = \pi$  - is

$$\begin{aligned} \frac{1}{r} \int_0^{2\pi} \left[ \frac{1}{2} \left( \frac{r'}{r} \right)^2 [3F^2 - 1] \right] d\phi' &= \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \int_0^{2\pi} [3F^2 - 1] d\phi' \\ &= \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \int_0^{2\pi} [3 \sin^2 \theta \sin^2 \theta' \cos^2 \phi' + 3 \cos^2 \theta \cos^2 \theta' + 6 \sin \theta \sin \theta' \cos \phi' \cos \theta \cos \theta' - 1] d\phi' \\ &= \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 [3\pi \sin^2 \theta \sin^2 \theta' + 2\pi 3 \cos^2 \theta \cos^2 \theta' - 2\pi] \\ &= 2\pi \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \left[ \frac{3}{2} \sin^2 \theta \sin^2 \theta' + 3 \cos^2 \theta \cos^2 \theta' - 1 \right] \\ &= 2\pi \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \left[ \frac{3}{2} (1 - \cos^2 \theta) (1 - \cos^2 \theta') + 3 \cos^2 \theta \cos^2 \theta' - 1 \right] \\ &= 2\pi \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \left[ \frac{3}{2} (1 + \cos^2 \theta \cos^2 \theta' - \cos^2 \theta - \cos^2 \theta') + 3 \cos^2 \theta \cos^2 \theta' - 1 \right] \\ &= 2\pi \frac{1}{r} \frac{1}{2} \left( \frac{r'}{r} \right)^2 \left[ \frac{1}{2} + \frac{9}{2} \cos^2 \theta \cos^2 \theta' - \frac{3}{2} \cos^2 \theta - \frac{3}{2} \cos^2 \theta' \right] \\ &= 2\pi \frac{1}{r} \left( \frac{r'}{r} \right)^2 \frac{1}{2} (3 \cos^2 \theta - 1) \frac{1}{2} (3 \cos^2 \theta' - 1) \end{aligned}$$

Putting the 3 terms together

$$\int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' = 2\pi \frac{1}{r} \left[ 1 + \left( \frac{r'}{r} \right) \cos \theta \cos \theta' + \left( \frac{r'}{r} \right)^2 \frac{1}{2} (3 \cos^2 \theta - 1) \frac{1}{2} (3 \cos^2 \theta' - 1) \right]$$

but these are just the Legendre Polynomials

$$\begin{aligned} \int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' &= 2\pi \frac{1}{r} \left[ P_0(\cos \theta) P_0(\cos \theta') + \left( \frac{r'}{r} \right) P_1(\cos \theta) P_1(\cos \theta') + \left( \frac{r'}{r} \right)^2 P_2(\cos \theta) P_2(\cos \theta') \right] \\ \int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' &= 2\pi \frac{1}{r} \sum_n \left[ \left( \frac{r'}{r} \right)^n P_n(\cos \theta) P_n(\cos \theta') \right] \end{aligned}$$

### 1.2.2 Potential term

Going back to

$$\Phi(r, \theta) = -G\rho \int_0^\infty \int_0^\pi \left[ \int_0^{2\pi} \frac{1}{|\mathbf{r}' - \mathbf{r}|} d\phi' \right] r'^2 \sin \theta' dr' d\theta'$$

and using the above

$$\begin{aligned} \Phi(r, \theta) &= -G\rho \int_0^\infty \int_0^\pi \left[ 2\pi \frac{1}{r} \sum_n \left[ \left( \frac{r'}{r} \right)^n P_n(\cos \theta) P_n(\cos \theta') \right] \right] r'^2 \sin \theta' dr' d\theta' \\ \Phi(r, \theta) &= \int_0^\infty \int_0^\pi \left[ -2\pi G\rho \sum_n \frac{1}{r^{n+1}} \left[ r'^n P_n(\cos \theta) P_n(\cos \theta') \right] \right] r'^2 \sin \theta' dr' d\theta' \\ \Phi(r, \theta) &= \sum_n \left\{ -\frac{2\pi G\rho}{r^{n+1}} \int_0^\infty \int_0^\pi r'^{n+2} P_n(\cos \theta') \sin \theta' d\theta' dr' \right\} P_n(\cos \theta) \end{aligned}$$

### 1.2.3 Integrating over radius

From G the surface of the spheroid is described by

$$r'(\theta') \simeq R_\mu \left[ 1 - \frac{2}{3} \epsilon P_2(\cos \theta') \right]$$

$$[r'(\theta')]^{n+3} \simeq R_\mu^{n+3} \left[ 1 - \frac{2}{3} \epsilon P_2(\cos \theta') \right]^{n+3} \approx R_\mu^{n+3} \left[ P_0(\cos \theta') - \frac{2(n+3)}{3} \epsilon P_2(\cos \theta') \right]$$

$$\Phi(r, \theta) = \sum_n \left\{ -\frac{2\pi G \rho}{r^{n+1}} \int_0^\pi \frac{r'^{n+3}}{n+3} \Big|_0^{r'(\theta')} P_n(\cos \theta') \sin \theta' d\theta' \right\} P_n(\cos \theta)$$

$$\Phi(r, \theta) = \sum_n \left\{ -\frac{2\pi G \rho R_\mu^3}{r^{n+1}} \int_0^\pi \frac{R_\mu^n \left[ P_0(\cos \theta') - \frac{2(n+3)}{3} \epsilon P_2(\cos \theta') \right]}{n+3} P_n(\cos \theta') \sin \theta' d\theta' \right\} P_n(\cos \theta)$$

The orthogonality of Legendre Polynomials is given by

$$\int_{-1}^1 P_n(x) P_m(x) dx = \frac{\delta_{nm}}{n + \frac{1}{2}}$$

Let  $x = \cos \theta$  so  $dx = -\sin \theta d\theta$

$$\int_\pi^0 P_n(\cos \theta) P_m(\cos \theta) (-\sin \theta) d\theta = \int_0^\pi P_n(\cos \theta) P_m(\cos \theta) \sin \theta d\theta = \frac{\delta_{nm}}{n + \frac{1}{2}}$$

So from the orthogonality above, the only terms that survive the integration are  $n = 0$  and  $n = 2$

$$\Phi(r, \theta) = -\frac{4\pi G \rho R_\mu^3}{3r} + \left\{ -\frac{2\pi G \rho R_\mu^3}{r^3} \frac{R_\mu^2 \left[ -\frac{10}{3} \epsilon \right] 2}{5} \right\} P_2(\cos \theta)$$

$$\Phi(r, \theta) = -\frac{4\pi G \rho R_\mu^3}{3r} + \left\{ \frac{4\pi G \rho R_\mu^3}{3r^3} R_\mu^2 \frac{2}{5} \epsilon \right\} P_2(\cos \theta)$$

For a uniform spheroid  $M = \frac{4\pi}{3} \rho R_\mu^3$

$$\Phi(r, \theta) = -\frac{GM}{r} + \frac{2}{5} \epsilon \frac{GM R_\mu^2}{r^3} P_2(\cos \theta)$$

The derivation in [Potential Uniform Spheroid] uses the typical Physics convention for the potential as (note the -ve sign)

$$V(\mathbf{r}) = -\frac{GM}{r}$$

and the acceleration is (again note the -ve sign)

$$\mathbf{a} = -\nabla V(\mathbf{r})$$

However [Kaula] uses

$$V(\mathbf{r}) = \frac{GM}{r}$$

and

$$\mathbf{a} = \nabla V(\mathbf{r})$$

and states “ $V$  is shown as a positive quantity which is consistent with the sign convention of astronomy and geodesy. In Physics  $V$  is conventionally taken to be negative”

I'll do the same so

$$V(r, \phi) = \frac{GM}{r} - \frac{2}{5} \epsilon \frac{GM R_\mu^2}{r^3} P_2(\sin \phi) + O(\epsilon^2)$$

and the  $V_{20}$  term here is

$$V_{20} = -\frac{2}{5} \epsilon GM R_\mu^2 \frac{1}{r^3} P_2(\sin \phi) \quad (3)$$

### 1.3 Value of $C_{20}$ constant

Comparing 2 with 3 we can see

$$C_{20} = -\frac{2}{5}\epsilon GMR_\mu^2$$

Typically we make  $C_{20}$  nondimensional and introduce a factor  $GMR_\mu^2$  i.e. make

$$C_{20} = -\frac{2}{5}\epsilon$$

and rewrite 3 as

$$V_{20} = C_{20}GMR_\mu^2 \frac{1}{r^3} P_2(\sin \phi) \quad (4)$$

However for below, unless stated otherwise,  $C_{20}$  is the non factored value

### 1.4 $V_{20}$ Zonal Term

The Legendre associated function  $P_{lm}(\sin \phi)$  in 1 is the solution for  $\Phi(\phi)$  in  $V = R(r)\Phi(\phi)\Lambda(\lambda)$ . It can be written as a series expansion [Kaula] where  $k$  is the integer part of  $\frac{(l-m)}{2}$ .

$$P_{lm}(\sin \phi) = \cos^m \phi \sum_{t=0}^k T_{lmt} \sin^{l-m-2t} \phi$$

where

$$T_{lmt} = \frac{(-1)^t (2l-2t)!}{2^l t! (l-t)! (l-m-2t)!}$$

For  $P_{20}$  this expansion gives

$$P_{20}(\sin \phi) = \sum_{t=0}^1 [T_{20t} \sin^{2-2t} \phi] \quad (5)$$

In our case,  $l = 2$  and  $m = 0$  this reduces to

$$T_{20t} = \frac{(-1)^t (4-2t)!}{4t! (2-t)! (2-2t)!}$$

$t$  ranges from 0 to 1 so we have

$$T_{200} = \frac{3}{2} \quad (6)$$

and

$$T_{201} = -\frac{1}{2} \quad (7)$$

so from 5

$$P_{20} = \frac{3}{2} \sin^2 \phi - \frac{1}{2}$$

or (as expected)

$$P_{20} = \frac{1}{2} [3 \sin^2 \phi - 1]$$

The  $l = 2$  term in 2 can now be re-written as

$$V_{20} = \frac{C_{20}}{r^3} \sum_{t=0}^1 T_{20t} \sin^{2-2t} \phi \quad (8)$$

Ultimately I am looking at the potential  $V_{20}$  at the points along an ellipse that a satellite is travelling along. The ellipse might be at an angle to the x-y plane of the spheroid so using  $r$  and  $\phi$  isn't the most convenient. I want to express  $V_{20}$  in terms of orbital elements  $\{a, e, i, M, \omega, \Omega\}$  i.e. semi-major axis of the ellipse  $a$ , eccentricity  $e$ , inclination  $i$ , mean anomaly  $M$ , argument of the pericentre  $\omega$  and longitude of node  $\Omega$ . For an explanation of the orbital elements refer to [Orbital Elements].

I want to replace  $\phi$  and  $r$  in 8.

Starting with the  $\sin \phi$  term. We can use 3-D trigonometry relationships which states that for a triangle on a sphere (see Figure 1)

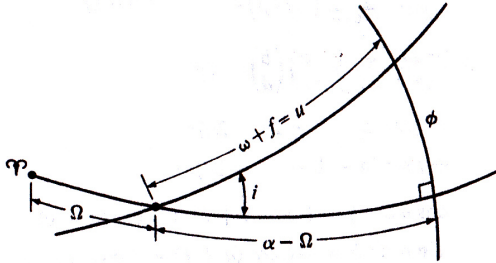


Figure 1: Orbit-equator-meridian triangle (from Fig 4 Kaula)

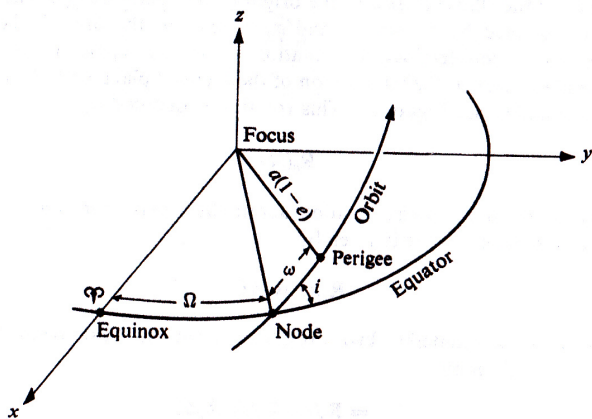


FIGURE 3. Orbital orientation.

Figure 2: Orbital Orientation (from Fig 3 Kaula)



$$\frac{\sin(side)}{\sin(angle)} = const$$

gives

$$\frac{\sin(\omega + f)}{\sin\left(\frac{\pi}{2}\right)} = \frac{\sin\phi}{\sin i}$$

$$\sin\phi = \sin i \sin(\omega + f)$$

where  $f$  is the true anomaly.

If the satellite is moving in an ellipse around a central body, then there will be points where it is closest and furthest away. The pericentre is the position in the elliptic path where the satellite is closest to the central body. The apocentre is where the satellite is furthest away from the central body.  $\omega$  is the argument of the pericentre (see Figure 2). If  $\omega = 0$  then the pericentre is at the point where the elliptical path crosses the equatorial plane of the central body.

Eq 8 becomes

$$V_{20} = \frac{C_{20}}{r^3} \sum_{t=0}^1 T_{20t} \sin^{2-2t} i \sin^{2-2t}(\omega + f) \quad (9)$$

## 2 Inclination Functions $F_{lmp}(i)$

We are now going to introduce some of the inclination functions that are seen in [Kaula]. These are functions of  $i$  i.e. the inclination of the satellite ellipse w.r.t. the spheroid x-y (equatorial) plane. (Imagine the satellite is orbiting in an ellipse in the same plane as the spheroid x-y plane and then tilt the satellite ellipse by an angle  $i$ . See Figure 2).

### 2.1 Prerequisites

#### Binomial Expansion (positive n)

$$(a + b)^n = \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k \quad (10)$$

where

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

Some special cases

$$\binom{n}{0} = \frac{n!}{0!(n-0)!} = 1$$

$$\binom{n}{n} = \frac{n!}{n!(n-n)!} = 1$$

#### Sine Power Expansion

$$e^{i\theta} = \cos \theta + i \sin \theta$$

$$\sin \theta = \frac{e^{i\theta} - e^{-i\theta}}{2i}$$

multiply top and bottom by  $i$  and raise to the power of  $n$

$$\begin{aligned} \sin^n \theta &= \left[ \frac{-i}{2} (e^{i\theta} - e^{-i\theta}) \right]^n \\ &= \frac{(-i)^n}{2^n} (e^{i\theta} - e^{-i\theta})^n \end{aligned}$$

using 10

$$\begin{aligned} &= \frac{(-i)^n}{2^n} \sum_{k=0}^n \binom{n}{k} e^{i\theta(n-k)} e^{-i\theta k} (-1)^k \\ &= \frac{(-i)^n}{2^n} \sum_{k=0}^n \binom{n}{k} (-1)^k e^{i\theta(n-2k)} \\ \sin^n \theta &= \frac{(-i)^n}{2^n} \sum_{k=0}^n \binom{n}{k} (-1)^k \{ \cos[(n-2k)\theta] + i \sin[(n-2k)\theta] \} \end{aligned}$$

### 2.2 $V_{20}$ Inclination Functions

Lets expand the term  $\sin^{2-2t}(\omega + f)$  in 9

$$\sin^{2-2t}(\omega + f) = \frac{(-i)^{2-2t}}{2^{2-2t}} \sum_{k=0}^{2-2t} \binom{2-2t}{k} (-1)^k \{ \cos[(2-2t-2k)(\omega + f)] + i \sin[(2-2t-2k)(\omega + f)] \} \quad (11)$$

From 9,  $t$  can be either 0 or 1 for  $V_{20}$ . For  $t = 0$ ,  $k$  can have the values 0,1,2. For  $t = 1$ ,  $k$  can have the value 0. So writing the permutations gives the table below. (The table also shows a variable  $p$  which will be used later)

$t$	$k$	$2 - 2t - 2k$	$\sin [(2 - 2t - 2k) (\omega + f)]$	$p = t + k$
0	0	2	$\sin 2 (\omega + f)$	0
0	1	0	0	1
0	2	-2	$-\sin 2 (\omega + f)$	2
1	0	0	0	1

From the table above, we can see that when  $t = 0$  then the  $k = 0$  and  $k = 2$  cancel out so we can ignore the sin terms. Also

$(-i)^{2-2t}$  for the two cases we have,  $t = 0 \Rightarrow -1$  and  $t = 1 \Rightarrow 1$ , so lets rewrite  $(-i)^{2-2t}$  as  $(-1)^{t+1}$ . 11 becomes

$$\sin^{2-2t} (\omega + f) = \frac{(-1)^{t+1}}{2^{2-2t}} \sum_{k=0}^{2-2t} \binom{2-2t}{k} (-1)^k \cos [(2 - 2t - 2k) (\omega + f)] \quad (12)$$

Let's introduce a variable  $p = t + k$ . 12 becomes

$$\sin^{2-2t} (\omega + f) = \frac{(-1)^{t+1}}{2^{2-2t}} \sum_{k=0}^{2-2t} \binom{2-2t}{k} (-1)^k \cos [(2 - 2p) (\omega + f)] \quad (13)$$

Equation 9 now becomes

$$V_{20} = \frac{C_{20}}{r^3} \sum_{t=0}^1 T_{20t} \sin^{2-2t} i \frac{(-1)^{t+1}}{2^{2-2t}} \sum_{k=0}^{2-2t} \binom{2-2t}{k} (-1)^k \cos [(2 - 2p) (\omega + f)] \quad (14)$$

From the table above,  $p$  can have the values 0, 1, 2.

### 2.3 Inclination function for $p = 0$ . $F_{200}$

Just looking at the  $p = 0$  term, there is only one  $t$  and  $k$  that gives  $p = 0$  i.e.  $t = 0$  and  $k = 0$ . So the  $p = 0$  term in 14 becomes

$$\frac{C_{20}}{r^3} T_{200} \sin^2 i \frac{-1}{4} \binom{2}{0} (1) \cos [(2 - 2p) (\omega + f)]$$

From 6

$$\begin{aligned} & \frac{C_{20}}{r^3} \frac{3}{2} \frac{-1}{4} \sin^2 i \cos [(2 - 2p) (\omega + f)] \\ & \frac{C_{20}}{r^3} \frac{-3}{8} \sin^2 i \cos [(2 - 2p) (\omega + f)] \end{aligned}$$

So let  $F_{lmp}$  be the inclination function. In this case  $l = 2$ ,  $m = 0$  and  $p = 0$  so

$$F_{200} = \frac{-3}{8} \sin^2 i$$

and the  $p = 0$  term is

$$\frac{C_{20}}{r^3} F_{200}(i) \cos [2 (\omega + f)]$$

### 2.4 Inclination function for $p = 1$ . $F_{201}$

Looking at the  $p = 1$  term, there are two  $t$  and  $k$  permutations that give  $p = 1$  i.e.  $t = 0, k = 1$  and  $t = 1, k = 0$ . So the  $p = 1$  term in 14 becomes

$$\begin{aligned} & \frac{C_{20}}{r^3} \cos [(2 - 2p) (\omega + f)] \left[ T_{200} \sin^2 i \frac{-1}{4} \binom{2}{1} (-1) + T_{201} \right] \\ & \frac{C_{20}}{r^3} \cos [(2 - 2p) (\omega + f)] \left[ \frac{3}{2} \frac{2}{4} \sin^2 i - \frac{1}{2} \right] \\ & \frac{C_{20}}{r^3} \cos [(2 - 2p) (\omega + f)] \left[ \frac{3}{4} \sin^2 i - \frac{1}{2} \right] \end{aligned}$$

$$F_{201} = \frac{3}{4} \sin^2 i - \frac{1}{2}$$

and the  $p = 1$  term becomes

$$\frac{C_{20}}{r^3} F_{201}(i)$$

## 2.5 General Inclination Functions $F_{lmp}$

Generally, we can write  $V_{20}$  as

$$V_{20} = \frac{C_{20}}{r^3} \sum_{p=0}^2 F_{20p}(i) \cos[(2-2p)(\omega + f)] \quad (15)$$

i.e. we are now writing  $V_{20}$  as a sum over  $p$  which contains a function of the inclination  $i$ . So for an elliptic path, this is easier to work with. However the terms with  $f$  and  $r$  are still tricky to work with - so we will look to substitute those. We will attempt to use  $e$  and  $M$  instead i.e. the eccentricity and mean anomaly.

### 3 Eccentricity Functions $G_{lpq}$

We are going to introduce a number of functions of  $e$  called the eccentricity functions i.e.  $G_{lpq}(e)$  where  $l, p$  are as before and  $q$  is a new index. These functions will be different depending on the values of  $l, p, q$  but will still be functions of  $e$  alone. The aim is to produce the same  $G_{lpq}(e)$  as listed in [Kaula].

When expressing  $V_{20}$  in orbital elements [Kaula] gives the below - where he uses  $a_e$  the mean equatorial radius of the earth, rather than  $R_\mu$ . Note that  $C_{20}$  here is the non dimensional value discussed in 1.3.

$$V_{20} = \frac{C_{20}GMa_e^2}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos[(2-2p+q)M] \quad (16)$$

Note in [Kaula], and the above,  $q$  ranges from  $-\infty$  not 0.

#### 3.1 Prerequisites

$e$  is the eccentricity (unless otherwise stated  $\exp()$  is used for exponential).

$$e = \sqrt{\frac{a^2 - b^2}{a^2}}$$

$$E - e \sin E = M \quad (17)$$

where  $E$  is the eccentric anomaly,  $M$  is the mean anomaly.

$$r = a(1 - e \cos E) \quad (18)$$

$$\frac{dM}{dE} = 1 - e \cos E$$

From 18

$$\frac{dM}{dE} = \frac{r}{a}$$

or

$$\boxed{dE = \frac{a}{r} dM} \quad (19)$$

$$\frac{r}{a} = 1 - e \cos E$$

$$\frac{r}{a} = 1 - e \left[ \frac{\exp(iE) + \exp(-iE)}{2} \right]$$

If we define

$$\boxed{e = \frac{2\beta}{(1 + \beta^2)}} \quad (20)$$

$$1 - e^2 = 1 - \frac{4\beta^2}{(1 + \beta^2)^2}$$

$$1 - e^2 = \frac{(1 + 2\beta^2 + \beta^4) - 4\beta^2}{(1 + \beta^2)^2}$$

$$1 - e^2 = \frac{1 - 2\beta^2 + \beta^4}{(1 + \beta^2)^2}$$

\

$$1 - e^2 = \frac{(1 - \beta^2)(1 - \beta^2)}{(1 + \beta^2)(1 + \beta^2)}$$

$$\sqrt{1 - e^2} = \frac{(1 - \beta^2)}{(1 + \beta^2)}$$

$$1 - \sqrt{1 - e^2} = \frac{1 + \beta^2 - (1 - \beta^2)}{(1 + \beta^2)}$$

$$1 - \sqrt{1 - e^2} = \frac{2\beta^2}{(1 + \beta^2)}$$

$$1 - \sqrt{1 - e^2} = \beta e$$

$$\boxed{\beta = \frac{1 - \sqrt{1 - e^2}}{e}} \quad (21)$$

$$\frac{r}{a} = 1 - \frac{2\beta}{(1 + \beta^2)} \left[ \frac{\exp(iE) + \exp(-iE)}{2} \right]$$

$$= 1 - \frac{\beta}{(1 + \beta^2)} [\exp(iE) + \exp(-iE)]$$

$$\boxed{\frac{r}{a} = \frac{1}{(1 + \beta^2)} [(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]} \quad (22)$$

### 3.2 Eccentricity Functions for $G$ where $p = 1$

We have from 15

$$V_{20} = \frac{C_{20}}{r^3} \sum_{p=0}^2 F_{20p}(i) \cos[(2 - 2p)(\omega + f)]$$

Let's look at the  $p = 1$  term initially. We'll use the notation  $V_{20p}$  to represent the potential due to the  $p^{th}$  term.

$$V_{20p} = \frac{C_{20}}{r^3} F_{20p}(i) \cos[(2 - 2p)(\omega + f)]$$

The cos term = 1 for  $p = 1$  so

$$V_{201} = \frac{C_{20}}{r^3} F_{201}(i) \quad (23)$$

We would like to remove the reference to  $r$ . Lets introduce  $a$  the semi-major axis of the ellipse into 23

$$V_{201} = \frac{C_{20}}{a^3} \frac{a^3}{r^3} F_{201}(i)$$

$\frac{a^3}{r^3}$  is a periodic function. Let us expand  $\frac{a^3}{r^3}$  in an exponential Fourier series w.r.t. the mean anomaly  $M$ .

$$\frac{a^3}{r^3} = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

the Fourier coefficients  $c_k$  are got by

$$c_k = \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} \exp(-ikM) dM \quad (24)$$

so

$$V_{201} = \frac{C_{20}}{a^3} F_{201}(i) \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

and the  $k$  term is

$$V_{201k} = \frac{C_{20}}{a^3} F_{201}(i) c_k \exp ikM \quad (25)$$

### 3.2.1 Prerequisites - Fourier Expansions and $p = 1$

The Fourier series of an even function can be expressed as exponential series as above with summation over  $[-\infty, \infty]$

$$f(x) = \sum_{n=-\infty}^{\infty} c_n e^{inx}$$

or as a cosine series as below with summation over  $[0, \infty]$

$$f(x) = a_0 + \sum_{n=1}^{\infty} a_n \cos(nx)$$

If  $f$  is real then  $c_k = \bar{c}_{-k}$  i.e. the complex conjugate.

If  $f$  is even,  $c_k$  is real, so  $c_k = c_{-k}$ .

The relation between the coefficients are

$$a_0 = c_0$$

$$c_k = c_{-k} = \frac{a_k}{2}$$

Since Kaula's formula is a cosine expansion we would expect the coefficients as above.

In the case of  $p = 1$  his equation reduces to a sum of cosine terms  $\cos(qM)$

$$V_{201} = \frac{C_{20} G M a_e^2}{a^3} F_{201}(i) \sum_{q=-\infty}^{\infty} G_{21q}(e) \cos(qM) \quad (26)$$

You'd expect the Fourier cosine coefficient  $a_k$  i.e.  $G_{21q}(e)$  to be related to the Fourier complex coefficient  $c_k$  as above. Also you'd expect the summation for the cosine series to be over  $[0, \infty]$  not  $[-\infty, \infty]$ . However in [Kaula], the summation of the cosine series is over the range  $[-\infty, \infty]$  so he is using  $c_k$  and  $c_{-k}$ . It'd imply that  $G_{21q} = G_{21-q}$ , which is the case.

### 3.2.2 Term $p = 1, k = 0$

For  $k = 0$ , 24 becomes

$$\begin{aligned} c_0 &= \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} dM \\ &= \frac{1}{2\pi} \int_0^{2\pi} \frac{a^2}{r^2} \frac{a}{r} dM \end{aligned}$$

From 19

$$\begin{aligned} &= \frac{1}{2\pi} \int_0^{2\pi} \frac{a^2}{r^2} dE \\ &= \frac{1}{2\pi} \int_0^{2\pi} \left(\frac{r}{a}\right)^{-2} dE \end{aligned}$$

From 22

$$\begin{aligned} &= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} dE \\ &= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[1 + \beta^2 - \beta(\exp(iE) + \exp(-iE))]^2} dE \\ &= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[1 + \beta^2 - 2\beta \cos E]^2} dE \end{aligned}$$

dividing by  $(1 + \beta^2)^2$

$$\begin{aligned}
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{1}{\left[1 - \frac{2\beta}{1+\beta^2} \cos E\right]^2} dE \\
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{1}{[1 - e \cos E]^2} dE
\end{aligned}$$

Using 79

$$c_0 = \frac{1}{2\pi} \frac{2\pi}{(1 - e^2)^{\frac{3}{2}}}$$

$$c_0 = \frac{1}{(1 - e^2)^{\frac{3}{2}}}$$

$$G_{210} = c_0 = (1 - e^2)^{-\frac{3}{2}}$$

This is the same as we see in [Kaula].

### 3.2.3 Term $p = 1, k = 1$

Let us look at  $k = 1$ , so we have

$$\begin{aligned}
c_1 &= \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} \exp(-iM) dM \\
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{a^2}{r^2} \exp(-iM) \frac{a}{r} dM \\
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} \exp(-iM) dE \\
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} \exp(-i(E - e \sin E)) dE \\
&= \frac{1}{2\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} \exp(i(e \sin E - E)) dE \\
&= \frac{(1 + \beta^2)^2}{2\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \exp(i(e \sin E - E)) dE
\end{aligned}$$

Binomial expansion works for negative powers as well but, instead of ending up with a polynomial with a finite  $x^n$  term, we end up with an infinite series.

$$(1 + x)^k = \sum_{n=0}^{\infty} \binom{k}{n} x^n$$

The binomial coefficient is given by

$$\binom{k}{n} = \frac{k(k-1)(k-2)\dots(k-n+1)}{n!}$$

Special case.

$$\binom{k}{0} = 1$$

The cases we will be interested in are

$$\binom{-2}{1} = \frac{(-2)}{1!} = -2$$

$$\binom{-2}{2} = \frac{(-2)(-3)}{2!} = 3$$



$$\binom{-2}{3} = \frac{(-2)(-3)(-4)}{3!} = -4$$

binomially expand

$$c_1 = \frac{(1 + \beta^2)^2}{2\pi} \int_0^{2\pi} \sum_{b=0}^{\infty} \binom{-2}{b} (-1)^b \beta^b \exp(iEb) \sum_{d=0}^{\infty} \binom{-2}{d} (-1)^d \beta^d \exp(-iEd) \exp(i(e \sin E - E)) dE$$

rearrange

$$c_1 = \frac{(1 + \beta^2)^2}{2\pi} \int_0^{2\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-2}{b} \binom{-2}{d} (-1)^{b+d} \beta^{b+d} \exp(iEb) \exp(-iEd) \exp(i(e \sin E - E)) dE$$

combine exp terms

$$c_1 = \frac{(1 + \beta^2)^2}{2\pi} \int_0^{2\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-2}{b} \binom{-2}{d} (-1)^{b+d} \beta^{b+d} \exp(i(e \sin E - (1 - b + d) E)) dE$$

take summations outside integral

$$c_1 = \frac{(1 + \beta^2)^2}{2\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-2}{b} \binom{-2}{d} (-1)^{b+d} \beta^{b+d} \int_0^{2\pi} \exp(i(e \sin E - (1 - b + d) E)) dE \quad (27)$$

The integral is of the form

$$\frac{1}{2\pi} \int_0^{2\pi} \exp(i(e \sin E - nE)) dE \quad (28)$$

where  $n$  is an integer. The solutions to these integrals have a dependency on  $n$  and  $e$  are called Bessel Functions  $J_n(e)$ .

$$c_1 = (1 + \beta^2)^2 \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-2}{b} \binom{-2}{d} (-1)^{b+d} \beta^{b+d} J_{1-b+d}(e)$$

Note that in the above for  $c_1$ , it shouldn't matter if we interchange  $b$  and  $d$  (we'll check this later). so we could also write

$$c_1 = (1 + \beta^2)^2 \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-2}{b} \binom{-2}{d} (-1)^{b+d} \beta^{b+d} J_{1+b-d}(e)$$

The Bessel function can be written as a series solution

$$J_n(e) = \left(\frac{e}{2}\right)^n \sum_{m=0}^{\infty} \frac{(-1)^m \left(\frac{e}{2}\right)^{2m}}{m!(n+m)!} \quad (29)$$

The first few Bessel functions are below. The eccentricity functions are power series in  $e$ . I'll only expand as far as  $e^3$

$$J_0(e) = 1 - \frac{e^2}{4} + O(e^4)$$

$$J_1(e) = \frac{e}{2} - \frac{e^3}{16} + O(e^5)$$

$$J_2(e) = \frac{e^2}{8} + O(e^4)$$

$$J_3(e) = \frac{e^3}{48} + O(e^5)$$

In 27  $\beta$  is defined as

$$\beta = \frac{\left(1 - (1 - e^2)^{\frac{1}{2}}\right)}{e}$$

For small  $e$ , binomially expand and keep terms up to  $e^3$  as that is as much as I'm going to calculate.

$$\beta \simeq \frac{1 - \left(1 - \frac{e^2}{2} - \frac{e^4}{8}\right)}{e} = \frac{e}{2} + \frac{e^3}{8}$$

Similarly

$$(1 + \beta^2)^2 \simeq \left(1 + \frac{e^2}{4}\right)^2 \simeq 1 + \frac{e^2}{2}$$

In 27 there is a term  $\beta^{b+d}$  so  $b + d \leq 3$  otherwise we will have  $O(e^4)$  terms. Below are the possible combinations.

Row No	b	d	b + d	$\binom{-2}{b}$	$\binom{-2}{d}$	$(-1)^{b+d}$	$(\beta)^{b+d}$	1 + b - d	$J_{1+b-d}(e)$	$(\beta)^{b+d} * J_{1+b-d}(e)$ where $O(e^3)$ and less	$\binom{-2}{b} * \binom{-2}{d} * (-1)^{b+d}$	Multiply by $\binom{-2}{b} * \binom{-2}{d} * (-1)^{b+d}$
a	0	0	0	1	1	1	1	1	$\frac{e}{2} - \frac{e^3}{16}$	$\frac{e}{2} - \frac{e^3}{16}$	1	$\frac{e}{2} - \frac{e^3}{16}$
b	0	1	1	1	-2	-1	$\frac{e}{2} + \frac{e^3}{8}$	0	$1 - \frac{e^2}{4}$	$\frac{e}{2} + \frac{e^3}{8} - \frac{e^3}{8} = \frac{e}{2}$	2	$e$
c	0	2	2	1	3	1	$\frac{e^2}{4}$	-1	$-\frac{e}{2} + \frac{e^3}{16}$	$-\frac{e^3}{8}$	3	$-\frac{6e^3}{16}$
d	0	3	3	1	-4	-1	$\frac{e^3}{8}$	-2	$\frac{e^2}{8}$	None		
e	1	0	1	-2	1	-1	$\frac{e}{2} + \frac{e^3}{8}$	2	$\frac{e^2}{8}$	$\frac{e^3}{16}$	2	$\frac{2e^3}{16}$
f	1	1	2	-2	-2	1	$\frac{e^2}{4}$	1	$\frac{e}{2} - \frac{e^3}{16}$	$\frac{e^3}{8}$	4	$\frac{8e^3}{16}$
g	1	2	3	-2	3	-1	$\frac{e^3}{8}$	0	$1 - \frac{e^2}{4}$	$\frac{e^3}{8}$	6	$\frac{12e^3}{16}$
h	2	0	2	3	1	1	$\frac{e^2}{4}$	3	$\frac{e^3}{48}$	None		
i	2	1	3	3	-2	-1	$\frac{e^3}{8}$	2	$\frac{e^2}{8}$	None		
j	3	0	3	-4	1	-1	$\frac{e^3}{8}$	4	$O(e^4)$	None		

From inspection we have a  $\frac{3e}{2}$  term.

For the  $e^3$  term we have

$$\frac{e^3}{16} [-1 - 6 + 2 + 8 + 12] = \frac{15e^3}{16}$$

However, because of the  $\frac{e^2}{2}$  term in  $\left(1 + \frac{e^2}{2}\right)$  there are also  $\frac{e^3}{4}$  and  $\frac{e^3}{2}$  terms for rows a and b respectively when we multiply through by  $\frac{e^2}{2}$  i.e. total of  $\frac{12e^3}{16}$ .

In total  $\frac{27e^3}{16}$ . Therefore

$$c_1 = \frac{3e}{2} + \frac{27e^3}{16} + \dots$$

This is what [Kaula] lists for  $G_{211}$ . Also  $G_{211} = G_{21-1}$

### 3.3 Terms including $p <> 1$

For  $p <> 1$ , we have to deal with the  $\cos((2 - 2p)(\omega + f))$  term as well (which disappeared in the  $p = 1$  case).

#### 3.3.1 Prerequisites

see Appendix E

$$e^{if} = \frac{e^{iE} (1 - \beta e^{-iE})}{1 - \beta e^{iE}} \quad (30)$$

#### 3.3.2 Expansion of $\cos((2 - 2p)(\omega + f))$

$$\frac{a^3}{r^3} \cos((2 - 2p)(\omega + f)) = \frac{a^3}{r^3} \left[ \frac{\exp(i(2 - 2p)(\omega + f)) + \exp(-i(2 - 2p)(\omega + f))}{2} \right]$$

$$\begin{aligned} \frac{a^3}{r^3} \cos((2 - 2p)(\omega + f)) &= \frac{1}{2} \frac{a^3}{r^3} [\exp(i(2 - 2p)\omega) \exp(i(2 - 2p)f)] \\ &\quad + \frac{1}{2} \frac{a^3}{r^3} [\exp(-i(2 - 2p)\omega) \exp(-i(2 - 2p)f)] \end{aligned}$$

From 30

$$\exp(i(2-2p)f) = \frac{\exp(i(2-2p)E)(1-\beta\exp(-iE))^{(2-2p)}}{(1-\beta\exp(iE))^{(2-2p)}}$$

$$\begin{aligned} \frac{a^3}{r^3} \cos((2-2p)(\omega+f)) &= \frac{1}{2} \frac{a^3}{r^3} \exp(i(2-2p)\omega) \frac{\exp(i(2-2p)E)(1-\beta\exp(-iE))^{(2-2p)}}{(1-\beta\exp(iE))^{(2-2p)}} \\ &+ \frac{1}{2} \frac{a^3}{r^3} \exp(-i(2-2p)\omega) \frac{\exp(-i(2-2p)E)(1-\beta\exp(-iE))^{-(2-2p)}}{(1-\beta\exp(iE))^{-(2-2p)}} \end{aligned}$$

$$\begin{aligned} \frac{a^3}{r^3} \cos((2-2p)(\omega+f)) &= \frac{1}{2} \frac{a^3}{r^3} \exp(i(2-2p)\omega) \exp(i(2-2p)E)(1-\beta\exp(-iE))^{(2-2p)}(1-\beta\exp(iE))^{-(2-2p)} \\ &+ \frac{1}{2} \frac{a^3}{r^3} \exp(-i(2-2p)\omega) \exp(-i(2-2p)E)(1-\beta\exp(-iE))^{-(2-2p)}(1-\beta\exp(iE))^{(2-2p)} \end{aligned}$$

It follows from the above that the value for  $p=0$  is the same as  $p=2$ .

i.e.  $\cos(i2(\omega+f)) = \cos(-i2(\omega+f))$  as we'd expect. The first and second terms would just interchange.

### 3.3.3 Expansion of $V_{20p}$

The potential term is given by

$$V_{20p} = \frac{C_{20}}{a^3} \frac{a^3}{r^3} F_{20p}(i) \cos[(2-2p)(\omega+f)]$$

Let's expand the  $r, f$  term in a Fourier series - but use the exponential version of the Fourier expansion - note that sum is from  $-\infty$  not 0 i.e.

$$function = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega+f)] = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

However using

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega+f)] = \frac{1}{2} \frac{a^3}{r^3} [\exp(i(2-2p)(\omega+f)) + \exp(-i(2-2p)(\omega+f))]$$

we can write each term as an exponential series

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(i(2-2p)(\omega+f))] = \sum_{k=-\infty}^{\infty} c_{k_1} \exp ikM$$

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(-i(2-2p)(\omega+f))] = \sum_{k=-\infty}^{\infty} c_{k_2} \exp ikM$$

$$c_k = c_{k_1} + c_{k_2}$$

$$c_{k_1} = \frac{1}{2\pi} \int_0^{2\pi} \left[ \frac{1}{2} \frac{a^3}{r^3} \exp(i(2-2p)\omega) \exp(i(2-2p)E)(1-\beta\exp(-iE))^{(2-2p)}(1-\beta\exp(iE))^{-(2-2p)} \right] \exp -ikM dM$$

$$c_{k_2} = \frac{1}{2\pi} \int_0^{2\pi} \left[ \frac{1}{2} \frac{a^3}{r^3} \exp(-i(2-2p)\omega) \exp(-i(2-2p)E)(1-\beta\exp(-iE))^{-(2-2p)}(1-\beta\exp(iE))^{(2-2p)} \right] \exp -ikM dM$$

(Note the  $\square$  term is an even function of  $E$  i.e.  $f(E) = f(-E)$ )

For brevity let's abbreviate  $f(+\omega) = \exp(i(2-2p)\omega)$  and  $f(-\omega) = \exp(-i(2-2p)\omega)$

Let's look at the first term first

$$c_{k_1} = \frac{1}{2\pi} \int_0^{2\pi} \left[ \frac{1}{2} \frac{a^3}{r^3} f(+\omega) \exp(i(2-2p)E)(1-\beta\exp(-iE))^{(2-2p)}(1-\beta\exp(iE))^{-(2-2p)} \right] \exp -ikM dM$$

From previously, we can substitute  $\frac{a^3}{r^3}$  with  $\frac{a^2}{r^2} \frac{a}{r} dM$  or  $\frac{a^2}{r^2} dE$  and take the factor  $\frac{1}{2}$  out

$$f(+\omega) \frac{1}{4\pi} \int_0^{2\pi} \frac{a^2}{r^2} \left[ \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \right] \exp(-ikM) dE$$

substitute  $\frac{a^2}{r^2}$

$$= f(+\omega) \frac{1}{4\pi} \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} \left[ \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \right] \exp(-ikM) dE$$

(Note that the  $\frac{a^2}{r^2}$  term is also an even function of  $E$ .)

Rearrange  $\beta$  terms

$$= f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \left[ \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \right] \exp(-ikM) dE$$

substitute  $M$

$$= f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \exp(-ik(E - e \sin E)) dE$$

take minus sign inside bracket

$$= f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \exp(ik(e \sin E - E)) dE$$

take  $k$  inside bracket

$$= f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \exp(i(2-2p)E) (1 - \beta \exp(-iE))^{(2-2p)} (1 - \beta \exp(iE))^{-(2-2p)} \exp(ik[e \sin E - E]) dE$$

rearrange

$$= f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(iE))^{-(2-2p)} (1 - \beta \exp(-iE))^{-2} (1 - \beta \exp(-iE))^{(2-2p)} \exp(i(2-2p)E) \exp(ik[e \sin E - E]) dE$$

so the first term is

$$c_{k_1} = f(+\omega) \frac{(1 + \beta^2)^2}{4\pi} \int_0^{2\pi} (1 - \beta \exp(iE))^{-(4-2p)} (1 - \beta \exp(-iE))^{-2p} \exp(i(2-2p)E) \exp(ik[e \sin E - E]) dE$$

The 2nd term in the integral is

$$c_{k_2} = \frac{1}{2\pi} \int_0^{2\pi} \frac{1}{2} \frac{a^3}{r^3} f(-\omega) \left[ \exp(-i(2-2p)E) (1 - \beta \exp(-iE))^{-(2-2p)} (1 - \beta \exp(iE))^{(2-2p)} \right] \exp(-ikM) dM$$

omitting a few steps for brevity leads to

$$= f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} (1-\beta \exp(-iE))^{-(2-2p)} (1-\beta \exp(iE))^{(2-2p)} \exp(-i(2-2p)E) \exp(i(ke \sin E - kE)) dE$$

$$= f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(iE))^{(2-2p)} (1-\beta \exp(-iE))^{-2} (1-\beta \exp(-iE))^{-(2-2p)} \exp(-i(2-2p)E) \exp(i(ke \sin E - kE)) dE$$

$$c_{k_2} = f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2p} (1-\beta \exp(-iE))^{-(4-2p)} \exp(-i(2-2p)E) \exp(i[ke \sin E - kE]) dE$$

Sanity Check 1:

Let  $p = 1$  and look at the  $k = 1$  term

$$c_{1_1} = \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} \exp(i(e \sin E - E)) dE$$

$$c_{1_2} = \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} \exp(i(e \sin E - E)) dE$$

so they are both the same.  $c_1$  below is the same as in the previous section.

$$c_1 = c_{1_1} + c_{1_2} = \frac{(1+\beta^2)^2}{2\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} \exp(i(e \sin E - E)) dE$$

Sanity Check 2: For an exponential Fourier expansion of a real function, the coefficient for  $k = -1$  should be the complex conjugate of  $k = 1$ .

$$c_{-1_1} = \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} \exp(i(-e \sin E + E)) dE$$

$$c_{-1_2} = \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2} (1-\beta \exp(-iE))^{-2} \exp(i(-e \sin E + E)) dE$$

which gives  $c_1$  equal to the complex conjugate as expected

$$c_{-1} = c_{-1_1} + c_{-1_2} = \frac{(1+\beta^2)^2}{2\pi} \int_0^{2\pi} (1-\beta \exp(-iE))^{-2} (1-\beta \exp(iE))^{-2} \exp(-i(e \sin E - E)) dE$$

So continuing with the first term, binomially expand terms

$$c_{k_1} = f(+\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-(4-2p)} (1-\beta \exp(-iE))^{-2p} \exp(i(2-2p)E) \exp(i(ke \sin E - kE)) dE$$

$$c_{k_1} = f(+\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} \sum_{b=0}^{\infty} \binom{-(4-2p)}{b} (-1)^b \beta^b \exp(iEb) \sum_{d=0}^{\infty} \binom{-2p}{d} (-1)^d \beta^d \exp(-iEd) \exp(i(ke \sin E - (k-2+2p)E)) dE$$

$$c_{k_1} = f(+\omega) \frac{(1+\beta^2)^2}{4\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-(4-2p)}{b} \binom{-2p}{d} (-1)^{b+d} \beta^{b+d} \int_0^{2\pi} \exp(i(ke \sin E - (k-2+2p-b+d)E)) dE$$

The 2nd term similarly is

$$c_{k_2} = f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2p} (1-\beta \exp(-iE))^{-(4-2p)} \exp(-i(2-2p)E) \exp(i[ke \sin E - kE]) dE$$

$$c_{k_2} = f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} (1-\beta \exp(iE))^{-2p} (1-\beta \exp(-iE))^{-(4-2p)} \exp(i[ke \sin E - (k+2-2p)E]) dE$$

swapping indices  $b$  and  $d$  around so we have the same range

$$c_{k_2} = f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \int_0^{2\pi} \sum_{d=0}^{\infty} \binom{-2p}{d} (-1)^d \beta^d \exp(iEd) \sum_{b=0}^{\infty} \binom{-(4-2p)}{b} (-1)^b \beta^b \exp(-iEb) \exp(i[ke \sin E - (k+2-2p)E]) dE$$

$$c_{k_2} = f(-\omega) \frac{(1+\beta^2)^2}{4\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-(4-2p)}{b} \binom{-2p}{d} (-1)^{b+d} \beta^{b+d} \int_0^{2\pi} \exp(i[ke \sin E - (k+2-2p+b-d)E]) dE$$

So we have

$$c_{k_1} = \exp(i(2-2p)\omega) \frac{(1+\beta^2)^2}{2} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-(4-2p)}{b} \binom{-2p}{d} (-1)^{b+d} \beta^{b+d} J_{k-2+2p-b+d}(ke)$$

$$c_{k_2} = \exp(-i(2-2p)\omega) \frac{(1+\beta^2)^2}{2} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-(4-2p)}{b} \binom{-2p}{d} (-1)^{b+d} \beta^{b+d} J_{k+2-2p+b-d}(ke)$$

Sanity Check:  $c_k = \bar{c}_{-k}$

$$c_k = \bar{c}_{-k} \implies c_{k_1} + c_{k_2} = \bar{c}_{-k_1} + \bar{c}_{-k_2}$$

Looking at the  $[c_{k_1}, c_{-k_2}]$  combination,

The  $c_{k_1}$  Bessel term for  $k$  is

$$c_{k_1} = \dots \exp(i(2-2p)\omega) J_{(k-2)+2p-b+d}(ke)$$

The  $c_{-k_2}$  Bessel term for  $-k$  is

$$c_{-k_2} = \dots \exp(-i(2-2p)\omega) J_{-(k-2)-2p+b-d}(-ke)$$

so we have terms  $J_n(ke)$  against  $J_{-n}(-ke)$  and a property of Bessel functions where  $n$  is an integer is that  $J_n(ke) = J_{-n}(-ke)$  so  $c_{k_1} = \bar{c}_{-k_2}$  when we also take into account the complex conjugate for the  $\omega$  term. Similarly  $c_{k_2} = \bar{c}_{-k_1}$ .

If we ignore the  $\omega$  term then we see that we just have a real function and that

$$c_{k_1} = c_{-k_2} \tag{31}$$

### 3.3.4 Express as Cosine

Originally we were expanding in an exponential series as follows

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{k=-\infty}^{\infty} c_k \exp(ikM)$$

where  $c_k$  was given by

$$c_k = c_{k_1} + c_{k_2}$$

so the  $kM$  terms of the expansion are for  $c_k$

$$c_k \exp(ikM) = \exp(im\omega) c_{k_1} \exp(ikM) + \exp(-im\omega) c_{k_2} \exp(ikM)$$

and for  $c_{-k}$

$$c_{-k} \exp(-ikM) = \exp(im\omega) c_{-k_1} \exp(-ikM) + \exp(-im\omega) c_{-k_2} \exp(-ikM)$$

Using  $c_{k_1} = c_{-k_2}$  and  $c_{k_2} = c_{-k_1}$

$$c_k \exp(ikM) = \exp(im\omega) c_{k_1} \exp(ikM) + \exp(-im\omega) c_{k_2} \exp(ikM)$$

$$c_{-k} \exp(-ikM) = \exp(im\omega) c_{k_2} \exp(-ikM) + \exp(-im\omega) c_{k_1} \exp(-ikM)$$

Grouping terms

$$\begin{aligned} c_k \exp(ikM) + c_{-k} \exp(-ikM) &= \exp(im\omega) c_{k_1} \exp(ikM) + \exp(-im\omega) c_{k_1} \exp(-ikM) \\ &\quad + \exp(im\omega) c_{k_2} \exp(-ikM) + \exp(-im\omega) c_{k_2} \exp(ikM) \end{aligned}$$

$$= c_{k_1} [\exp(i(m\omega + kM)) + \exp(-i(m\omega + kM))] + c_{k_2} [\exp(i(m\omega - kM)) + \exp(-i(m\omega - kM))]$$

$$c_k \exp(ikM) + c_{-k} \exp(-ikM) = 2c_{k_1} \cos(m\omega + kM) + 2c_{k_2} \cos(m\omega - kM)$$

From the section below 3.3.5 we can relate the  $c_k$  terms to Hansen coefficients i.e.  $2c_{k_1} = X_k^{-3,m}$  and  $2c_{k_2} = X_k^{-3,-m}$

$$c_k \exp(ikM) + c_{-k} \exp(-ikM) = X_k^{-3,m} \cos(m\omega + kM) + X_k^{-3,-m} \cos(m\omega - kM)$$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{k=0}^{\infty} X_k^{-3,m} \cos(m\omega + kM) + X_k^{-3,-m} \cos(m\omega - kM)$$

From Eq 34  $X_k^{-3,m} = X_{-k}^{-3,-m}$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{k=0}^{\infty} X_k^{-3,m} \cos(m\omega + kM) + X_{-k}^{-3,m} \cos(m\omega - kM)$$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{k=-\infty}^{\infty} X_k^{-3,m} \cos(m\omega + kM)$$

If we make a change of variables  $k = m + q$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{q=-\infty}^{\infty} X_{m+q}^{-3,m} \cos((2-2p)\omega + (2-2p+q)M)$$

From  $G_{l pq} = X_{l-2p+q}^{-l-1, l-2p} = X_{m+q}^{-3,m}$

$$\frac{a^3}{r^3} \cos[(2-2p)(\omega + f)] = \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos((2-2p)\omega + (2-2p+q)M)$$

which matches what we had previously for the case  $\omega = 0$

$$V_{20} = \frac{C_{20} G M a_e^2}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos[(2-2p+q)M]$$

We can see that  $G_{2pq}$  are cosine coefficients. However this sum is over  $[-\infty, \infty]$  not the usual  $[0, \infty]$  for a Fourier cosine expansion.

For  $m = 2$ , the terms that contribute to the  $k = 1$  cosine term are from  $k = m + q$ ,  $q = -1$  and  $q = -3$  i.e.  $G_{20-1}$  and  $G_{20-3}$ .

### 3.3.5 Relate $c_k$ to Hansen Coefficients $X_k^{n,m}$

In the previous section we expanded the following in 2 exponential series

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(i(2-2p)(\omega+f))] = \sum_{k=-\infty}^{\infty} c_{k_1} \exp(ikM)$$

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(-i(2-2p)(\omega+f))] = \sum_{k=-\infty}^{\infty} c_{k_2} \exp(ikM)$$

Let us put  $m = (2-2p)$  and set  $\omega = 0$  i.e. ignore the  $\omega$  term in the expansion when calculating  $c_k$  terms, so they will now be real terms.

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(imf)] = \sum_{k=-\infty}^{\infty} c_{k_1} \exp(ikM)$$

$$\frac{1}{2} \frac{a^3}{r^3} [\exp(-imf)] = \sum_{k=-\infty}^{\infty} c_{k_2} \exp(ikM)$$

To relate this to Hansen coefficients, we use the following definition of the Hansen coefficient

$$\left(\frac{r}{a}\right)^n \exp(imf) = \sum_k X_k^{n,m}(e) \exp(ikM) \quad (32)$$

If  $n = -3$  this gives

$$\frac{a^3}{r^3} \exp(imf) = \sum_k X_k^{-3,m}(e) \exp(ikM) \quad (33)$$

we can see immediately that

$$2c_{k_1} = X_k^{-3,m}$$

and

$$2c_{k_2} = X_k^{-3,-m}$$

Also from 31  $c_{k_1} = c_{-k_2}$  and remembering that  $c_{k_1}$  is due to the expansion of the  $\exp(imf)$  term and  $c_{k_2}$  is due to the expansion of the  $\exp(-imf)$  term we see that

$$X_k^{-3,m} = X_{-k}^{-3,-m} \quad (34)$$

For  $p = 0$  or  $(m = 2)$  and  $k = 1$ , we find

```
file:///C:/dev/SpheroidCode/spheroid/bin/Debug/spheroid.EXE
k=1 1st:-1/4e^1 + 1/32e^3, 2nd:1/96e^3
```

$$c_1 = c_{1_1} + c_{1_2} = \left(-\frac{1}{4}e + \frac{1}{32}e^3\right) + \left(\frac{1}{96}e^3\right) = -\frac{1}{4}e + \frac{1}{24}e^3$$

$$X_1^{-3,2} = 2 * c_{1_1} = -\frac{1}{2}e + \frac{1}{16}e^3$$

and

$$X_1^{-3,-2} = 2 * c_{1_2} = \frac{1}{48}e^3$$

## 3.4 General $G_{2pq}$ terms

Going back to the Kaula notation and let  $p = 0$

$$V_{20} = \frac{C_{20}}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos((2-2p+q)M)$$

$$V_{200} = \frac{C_{20}}{a^3} F_{200}(i) \sum_{q=-\infty}^{\infty} G_{20q}(e) \cos((2+q)M)$$



If I look at the  $k = 0$  term,  $c_0$ , this would imply  $q = -2$ . So this would imply that  $c_0 = G_{20-2}$ . If we calculate  $c_0$  we get a  $J_n(ke) = J_n(0)$  term because  $k = 0$  and  $n < 0$

$$c_0 = \frac{(1 + \beta^2)^2}{2\pi} \sum_{b=0}^{\infty} \sum_{d=0}^{\infty} \binom{-4}{b} \binom{0}{d} (-1)^{b+d} \beta^{b+d} [J_{-2-b+d}(0) + J_{2+b-d}(0)]$$

For a Bessel function,  $J_n(0) = 0$  so

$$G_{20-2} = c_0 = 0$$

$G_{20-2} = 0$  agrees with [Kaula]

Similarly if we let  $p = 2$

$$V_{202} = \frac{C_{20}}{a^3} F_{202}(i) \sum_{q=-\infty}^{\infty} G_{20q}(e) \cos((2 - 2 * 2 + q) M)$$

$$V_{202} = \frac{C_{20}}{a^3} F_{202}(i) \sum_{q=-\infty}^{\infty} G_{20q}(e) \cos((-2 + q) M)$$

If I look at the  $k = 0$  term,  $c_0$ , this would imply  $q = 2$ . So this would imply that  $c_0 = G_{222}$ . If we calculate  $c_0$  we similarly have a  $J_n(0)$  term so  $c_0 = 0$ .

$G_{222} = 0$  also agrees with [Kaula]

### 3.5 Conclusion

Ultimately, we have written the potential term  $V_{20}$  at points on the ellipse in terms of the orbital elements  $\{a, e, i, M, \omega, \Omega\}$  - albeit simplified because we have omitted  $\omega, \Omega$ . We have also shown the link between Kaula's formula and our derivation. To recap, here is Kaula's formula.

$$V_{20} = \frac{C_{20}}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos[(2 - 2p + q) M]$$

Using the non dimensional version of  $C_{20}$  we have

$$V_{20} = \frac{GMR_{\mu}^2 C_{20}}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos[(2 - 2p + q) M] \quad (35)$$

#### 3.5.1 Sanity Check

Consider  $i = 0$  and given  $G_{lpq}$  are of  $O(e^{|q|})$

The  $e^0$  term is  $G_{210}$  i.e.  $(1 - e^2)^{-\frac{3}{2}}$ .  $p = 1$  and  $q = 0$ . In the cosine term in 35 we see that  $\cos(2 - 2p + q) M = \cos(2 - 2 * 1 + 0) M = 1$  so the potential related to the  $G_{210}$  term has no dependency on the mean anomaly  $M$  so is the same for all points on the ellipse.

Given that if  $e \neq 0$  we'd expect some variation in the potential  $V_{20}$  along the ellipse path. There are 3  $G_{2pq}$  terms that give a dependency on  $e$  and  $M$ .

1.  $G_{20-1} = G_{221} = -\frac{e}{2}$  and gives a  $\cos M$  term. However we also need to consider  $F_{20p}$  terms as well and  $F_{200} = F_{202} = 0$  for  $i = 0$  so we can ignore  $G_{20-1}$  and  $G_{221}$ .
2.  $G_{201} = G_{22-1} = \frac{7e}{2}$  and gives a  $\cos 3M$  term. However we also need to consider  $F_{20p}$  terms and  $F_{200} = F_{202} = 0$  for  $i = 0$  so we can ignore  $G_{201}$  and  $G_{22-1}$  as well.
3.  $G_{211} = G_{21-1} = \frac{3e}{2}$  and gives a  $\cos M$  term. However we also need to consider  $F_{20p}$  terms and  $F_{201} = -\frac{1}{2}$  for  $i = 0$  so we include  $G_{211}$  and  $G_{21-1}$ .

Therefore in summary we have

$$V_{20} = \frac{GMR_{\mu}^2 C_{20}}{a^3} \left[ \left( -\frac{1}{2} \right) 1 + \left( -\frac{1}{2} \right) \left( \frac{3e}{2} \right) [\cos M + \cos(-M)] \right]$$

$$V_{20} = -\frac{GMR_{\mu}^2 C_{20}}{2a^3} (1 + 3e \cos M)$$

### 3.5.2 Sanity Check II

We can also get a similar answer by substituting the solution for the radius of an elliptical orbit  $r(\lambda)$

$$\frac{1}{r} = \eta (1 + e \cos \lambda)$$

directly into

$$V_{20} = GMR_\mu^2 C_{20} \frac{1}{r^3} P_2(\sin \phi) = GMR_\mu^2 C_{20} \frac{1}{r^3} \frac{1}{2} (3 \sin^2 \phi - 1)$$

where  $\phi = 0$  i.e.

$$V_{20} = GMR_\mu^2 C_{20} \left(-\frac{1}{2}\right) \eta^3 (1 + e \cos \lambda)^3 \approx GMR_\mu^2 C_{20} \left(-\frac{1}{2}\right) \left(\frac{1}{a(1-e^2)}\right)^3 (1 + 3e \cos \lambda)$$

$$V_{20} = -\frac{GMR_\mu^2 C_{20}}{2a^3} (1 - e^2)^{-3} (1 + 3e \cos \lambda)$$

$$V_{20} \approx -\frac{GMR_\mu^2 C_{20}}{2a^3} (1 + 3e \cos \lambda) \tag{36}$$

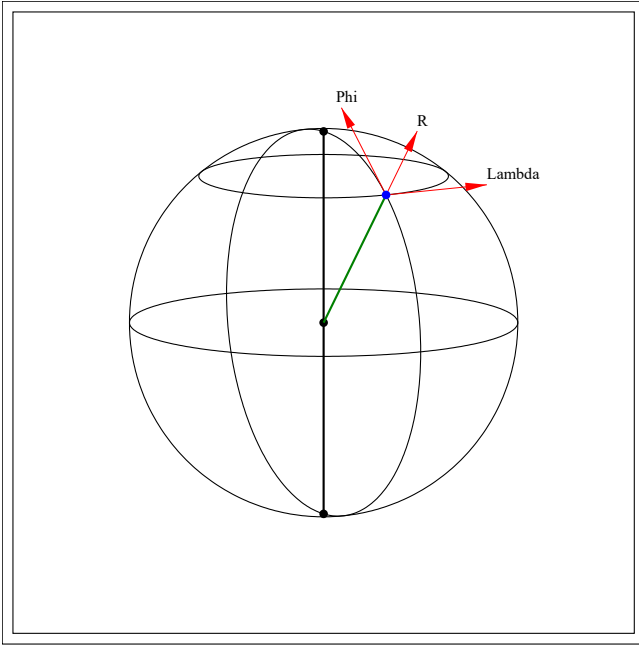


Figure 3: Longitudinal Force Component

## 4 Forces due to $V_{20}$

$$V_{20} = C_{20} \frac{1}{r^3} P_2(\sin \phi)$$

$$V_{20} = C_{20} \frac{1}{2r^3} (3 \sin^2 \phi - 1)$$

$$F_\phi = \frac{1}{r} \frac{\partial V_{20}}{\partial \phi} = C_{20} \frac{1}{r^4} 3 \sin \phi \cos \phi$$

This force is longitudinal. As  $C_{20}$  is negative, it is towards the equator, away from the poles (see Figure 3). When describing the motion of a satellite, we can see two frames of reference in Figure 4.

1. **x** coordinates - based on the equatorial plane of the spheroid  
There is an inertial reference frame **a, b, n** with **a** and **b** in the equatorial plane of the spheroid. Additionally let **a** point to the ascending node of the satellite orbit (the blue dot i.e. the point at which the satellite orbit crosses the equatorial plane of the spheroid)
2. **q** coordinates - based on the orbiting satellite Keplerian ellipse.  
We can see that there is a reference frame **r, t, z** with **r** and **t** in the plane of the satellite orbital Keplerian ellipse.

See Figure 5

Note that we need to be a bit more precise when we include the  $V_{20}$  potential. Without the  $V_{20}$  term then we have a purely inverse square force and the path of the satellite is an ellipse that closes in on itself i.e. it doesn't precess. In this case the meaning of the orbital elements like the semi-major axis  $a$  are clear as the ellipse is fixed in space. The satellite follows a path along this ellipse. When we include  $V_{20}$  the meaning of  $a$  is not so clear. Essentially what we have to do is adjust the ellipse shape at each point in time to reflect how the satellite is actually moving in the inertial **x** frame i.e. the satellite is moving on an time dependent ellipse  $\xi_t(a, e, i, \omega, \Omega)$  at time  $t$ . This instantaneous ellipse is the osculating orbit - still an ellipse. It describes the orbit the satellite would follow if the perturbing force were not there [Osculating Orbit]. Note the orbital elements, e.g.  $a$ , in the osculating orbit may be different to what they would be in the perturbed orbit.

We can describe the motion of the satellite in the inertial frame by position  $\{x, y, z\}$  and velocity  $\{\dot{x}, \dot{y}, \dot{z}\}$ . Alternatively we could describe the motion of the satellite in terms of what are called the Keplerian orbital elements  $\{a, e, i, M, \omega, \Omega\}$ . For an explanation of the orbital elements refer to [Orbital Elements].

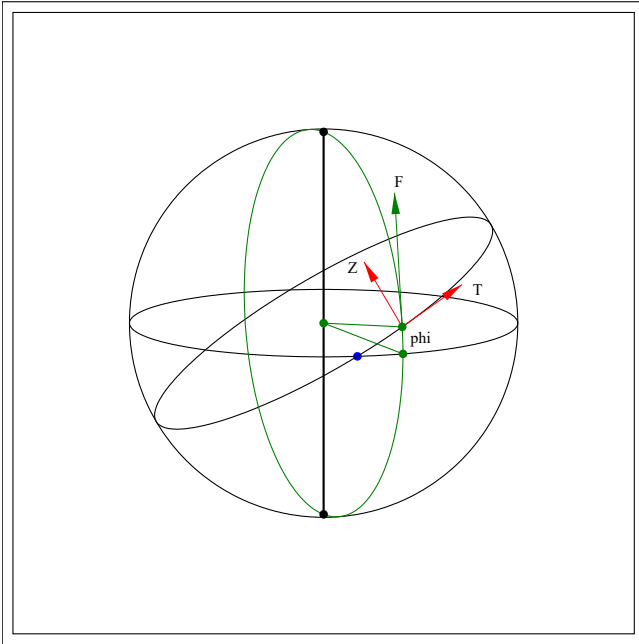


Figure 4: Resolved Longitudinal Force Components along Satellite Ellipse

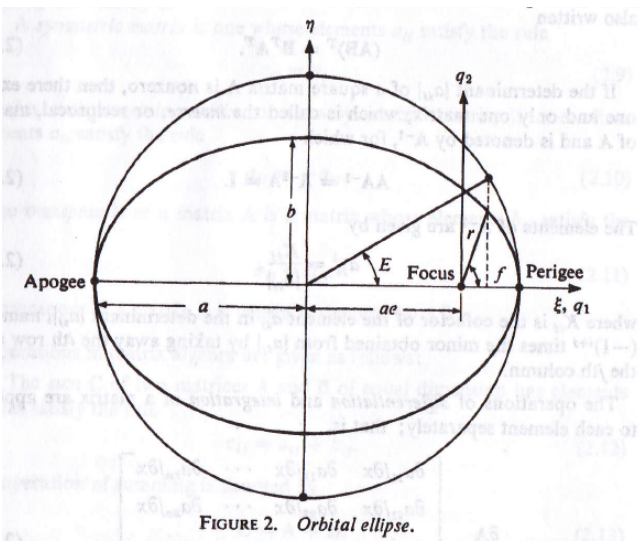


Figure 5: Keplerian Orbital Ellipse (from [Kaula])

## 4.1 Lagrange Bracket

First we will define and calculate a Lagrange bracket and then show why they are useful.

The rotation matrix that relates  $\mathbf{x}$  and  $\mathbf{q}$  coordinates i.e.  $\mathbf{x} = R\mathbf{q}$  is

$$R = \begin{bmatrix} (\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) & (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) & \sin \Omega \sin i \\ (\sin \Omega \cos \omega + \cos \Omega \cos i \sin \omega) & (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) & -\cos \Omega \sin i \\ \sin i \sin \omega & \sin i \cos \omega & \cos i \end{bmatrix}$$

The  $\mathbf{q}$  coordinates are given by

$$q = \begin{bmatrix} a(\cos E - e) \\ a\sqrt{1-e^2} \sin E \\ 0 \end{bmatrix} = \begin{bmatrix} r \cos f \\ r \sin f \\ 0 \end{bmatrix}$$

$$\dot{q} = \begin{bmatrix} -\sin E \\ \sqrt{1-e^2} \cos E \\ 0 \end{bmatrix} \frac{na}{1-e \cos E}$$

The Lagrange bracket is defined as below where  $s_l, s_k$  can be any of the Keplerian orbital elements. We sum over the  $i$  terms i.e.  $i$  has values  $[1, 2, 3]$ .

$$[s_l, s_k] = \frac{\partial x_i}{\partial s_l} \frac{\partial \dot{x}_i}{\partial s_k} - \frac{\partial \dot{x}_i}{\partial s_l} \frac{\partial x_i}{\partial s_k}$$

### 4.1.1 Partial Derivative Meaning e.g. $\frac{\partial x}{\partial e}, \frac{\partial y}{\partial e}, \frac{\partial z}{\partial e}$

The partial derivatives relate changes to coordinates in the inertial frame with changes in the orbital elements e.g.  $\frac{\partial x}{\partial e}$  determines how much the  $x$  coordinate changes if the eccentricity  $e$  changes and we keep all the other orbital elements unchanged.

So, as an example, for the  $x$  coordinate, let  $\Omega = \omega = i = 0$  so we have the elliptic orbit in the  $x, y$  plane of the inertial frame with the pericentre lined up in the direction of the  $x$  axis. An increase in the eccentricity  $\partial e$  means that the ellipse becomes flatter ( $a$  is unchanged) and in effect the focus of the ellipse which was at  $ae$  is now at  $a(e + \partial e)$ . From the point of view of the origin (i.e. the focus) the pericentre - which was at  $a(1 - e)$  is now at  $a(1 - (e + \partial e))$  so the change in the  $x$  coordinate is  $-a\partial e$ .

$$\frac{\partial x}{\partial e} = \frac{\partial (a(\cos E - e))}{\partial e} = -a$$

$$\partial x = -a\partial e$$

For the  $y$  coordinate, we have

$$\frac{\partial y}{\partial e} = \frac{\partial (a\sqrt{1-e^2} \sin E)}{\partial e} = a \sin E \frac{1}{2} (1-e^2)^{-\frac{1}{2}} (-2e) = -a \sin E \frac{e}{\sqrt{1-e^2}}$$

$$\left. \frac{\partial y}{\partial e} \right|_{E=0} = 0$$

$$\left. \frac{\partial y}{\partial e} \right|_{E=\frac{\pi}{2}} = -a \frac{e}{\sqrt{1-e^2}}$$

so in the second case,  $y$  decreases when  $E = 90^\circ$  because if  $e$  increases then the ellipse becomes flatter.

#### 4.1.2 $[a, \omega]$ Lagrange Bracket

So we can see from  $\mathbf{x} = R\mathbf{q}$  that  $x$  and it's derivatives can be written in terms of the orbital elements  $\{a, e, i, M, \omega, \Omega\}$ .

As an example, we'll calculate the  $[a, \omega]$  Lagrange Bracket.

$$[a, \omega] = \frac{\partial x_i}{\partial a} \frac{\partial \dot{x}_i}{\partial \omega} - \frac{\partial \dot{x}_i}{\partial a} \frac{\partial x_i}{\partial \omega}$$

$$[\omega, a] = \frac{\partial x_i}{\partial \omega} \frac{\partial \dot{x}_i}{\partial a} - \frac{\partial \dot{x}_i}{\partial \omega} \frac{\partial x_i}{\partial a}$$

so we can see that  $[s_l, s_k] = -[s_k, s_l]$ . We can also see that  $[s_k, s_k] = 0$ . In the Lagrange Bracket, we sum over the  $i$  terms i.e.

$$[a, \omega] = \left[ \frac{\partial x}{\partial a} \frac{\partial \dot{x}}{\partial \omega} - \frac{\partial \dot{x}}{\partial a} \frac{\partial x}{\partial \omega} \right] + \left[ \frac{\partial y}{\partial a} \frac{\partial \dot{y}}{\partial \omega} - \frac{\partial \dot{y}}{\partial a} \frac{\partial y}{\partial \omega} \right] + \left[ \frac{\partial z}{\partial a} \frac{\partial \dot{z}}{\partial \omega} - \frac{\partial \dot{z}}{\partial a} \frac{\partial z}{\partial \omega} \right]$$

Looking at the  $x_1$  or  $x$  term, the initial position  $x$  and velocity  $\dot{x}$  is given by the below. However the *change* in position and velocity can be due to *any* of the orbital elements  $\{a, e, i, M, \omega, \Omega\}$ . changing

$$x = (\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) a (\cos E - e) - (\cos \Omega \sin \omega + \sin \Omega \cos i \cos \omega) a \sqrt{1 - e^2} \sin E$$

$$\dot{x} = \left[ (\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) (-\sin E) - (\cos \Omega \sin \omega + \sin \Omega \cos i \cos \omega) \sqrt{1 - e^2} \cos E \right] \frac{na}{1 - e \cos E}$$

Lagrange brackets are time invariant [Kaula] so we calculate the Lagrange bracket at the pericentre where  $E = 0$

$$q = \begin{bmatrix} a(1 - e) \\ 0 \\ 0 \end{bmatrix}$$

$$\dot{q} = \begin{bmatrix} 0 \\ \sqrt{1 - e^2} \\ 0 \end{bmatrix} \frac{na}{1 - e} = \frac{na\sqrt{1 - e^2}}{1 - e}$$

so just keeping non-zero terms

$$x = (\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) a (1 - e)$$

$$\dot{x} = (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) \frac{na\sqrt{1 - e^2}}{1 - e}$$

$$\frac{\partial x}{\partial a} = (\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) (1 - e)$$

In the next step be careful with the derivative of  $na$  wrt  $a$  because  $n = \sqrt{\frac{\mu}{a^3}}$  so  $na = \left(\frac{\mu}{a}\right)^{\frac{1}{2}}$  and  $\frac{\partial(na)}{\partial a} = \frac{\mu^{\frac{1}{2}} \frac{\partial(a)^{-\frac{1}{2}}}{\partial a}} = -\frac{1}{2} \mu^{\frac{1}{2}} a^{-\frac{3}{2}} = -\frac{1}{2} n$

$$\frac{\partial \dot{x}}{\partial a} = (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) \left(-\frac{n}{2}\right) \frac{\sqrt{1 - e^2}}{1 - e}$$

$$\frac{\partial x}{\partial \omega} = (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) a (1 - e)$$

$$\frac{\partial \dot{x}}{\partial \omega} = (-\cos \Omega \cos \omega + \sin \Omega \cos i \sin \omega) \frac{na\sqrt{1 - e^2}}{1 - e}$$

Similarly for  $y$

$$y = (\sin \Omega \cos \omega + \cos \Omega \cos i \sin \omega) a (1 - e)$$

$$\dot{y} = (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) \frac{na\sqrt{1-e^2}}{1-e}$$

$$\frac{\partial y}{\partial a} = (\sin \Omega \cos \omega + \cos \Omega \cos i \sin \omega) (1-e)$$

$$\frac{\partial \dot{y}}{\partial a} = (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) \left(-\frac{n}{2}\right) \frac{\sqrt{1-e^2}}{1-e}$$

$$\frac{\partial y}{\partial \omega} = (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) a (1-e)$$

$$\frac{\partial \dot{y}}{\partial \omega} = (-\sin \Omega \cos \omega - \cos \Omega \cos i \sin \omega) \frac{na\sqrt{1-e^2}}{1-e}$$

and for z

$$z = \sin i \sin \omega a (1-e)$$

$$\dot{z} = \sin i \cos \omega \frac{na\sqrt{1-e^2}}{1-e}$$

$$\frac{\partial z}{\partial a} = \sin i \sin \omega (1-e)$$

$$\frac{\partial \dot{z}}{\partial a} = \sin i \cos \omega \left(-\frac{n}{2}\right) \frac{\sqrt{1-e^2}}{1-e}$$

$$\frac{\partial z}{\partial \omega} = \sin i \cos \omega a (1-e)$$

$$\frac{\partial \dot{z}}{\partial \omega} = -\sin i \sin \omega \frac{na\sqrt{1-e^2}}{1-e}$$

Putting this all together

$$[a, \omega] = \left[ \frac{\partial x}{\partial a} \frac{\partial \dot{x}}{\partial \omega} - \frac{\partial \dot{x}}{\partial a} \frac{\partial x}{\partial \omega} \right] + \left[ \frac{\partial y}{\partial a} \frac{\partial \dot{y}}{\partial \omega} - \frac{\partial \dot{y}}{\partial a} \frac{\partial y}{\partial \omega} \right] + \left[ \frac{\partial z}{\partial a} \frac{\partial \dot{z}}{\partial \omega} - \frac{\partial \dot{z}}{\partial a} \frac{\partial z}{\partial \omega} \right]$$

Look at  $na\sqrt{1-e^2}$  terms first  $\frac{\partial x}{\partial a} \frac{\partial \dot{x}}{\partial \omega} + \frac{\partial y}{\partial a} \frac{\partial \dot{y}}{\partial \omega} + \frac{\partial z}{\partial a} \frac{\partial \dot{z}}{\partial \omega}$  i.e. the terms that don't have  $\frac{\partial \dot{x}_i}{\partial a}$ .

$$\begin{aligned} [a, \omega]_1 &= na\sqrt{1-e^2} \\ &(\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) (-\cos \Omega \cos \omega + \sin \Omega \cos i \sin \omega) \\ &+ (\sin \Omega \cos \omega + \cos \Omega \cos i \sin \omega) (-\sin \Omega \cos \omega - \cos \Omega \cos i \sin \omega) \\ &- (\sin^2 i \sin^2 \omega) \end{aligned}$$

$$\begin{aligned} &= na\sqrt{1-e^2} \\ &- (\cos \Omega \cos \omega)^2 - (\sin \Omega \cos i \sin \omega)^2 + \cos \Omega \cos \omega \sin \Omega \cos i \sin \omega + \sin \Omega \cos i \sin \omega \cos \Omega \cos \omega \\ &- (\sin \Omega \cos \omega)^2 - (\cos \Omega \cos i \sin \omega)^2 - \sin \Omega \cos \omega \cos \Omega \cos i \sin \omega - \cos \Omega \cos i \sin \omega \sin \Omega \cos \omega \\ &- (\sin^2 i \sin^2 \omega) \end{aligned}$$

$$= na\sqrt{1-e^2} \cdot (-\cos^2 \omega - \cos^2 i \sin^2 \omega - \sin^2 i \sin^2 \omega)$$

$$[a, \omega]_1 = -na\sqrt{1-e^2}$$

Now look at  $\left(-\frac{na}{2}\right) \sqrt{1-e^2}$  terms  $-\frac{\partial \dot{x}}{\partial a} \frac{\partial x}{\partial \omega} - \frac{\partial \dot{y}}{\partial a} \frac{\partial y}{\partial \omega} - \frac{\partial \dot{z}}{\partial a} \frac{\partial z}{\partial \omega}$

$$\begin{aligned}
[a, \omega]_2 &= \left(-\frac{na}{2}\right) \sqrt{1-e^2} \\
&\quad - (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) (-\cos \Omega \sin \omega - \sin \Omega \cos i \cos \omega) \\
&\quad - (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) (-\sin \Omega \sin \omega + \cos \Omega \cos i \cos \omega) \\
&\quad - (\sin i \cos \omega \sin i \cos \omega) \\
&= \left(-\frac{na}{2}\right) \sqrt{1-e^2} \\
&\quad - (\cos \Omega \sin \omega)^2 - (\sin \Omega \cos i \cos \omega)^2 - 2 \sin \Omega \cos i \cos \omega \cos \Omega \sin \omega \\
&\quad - (\sin \Omega \sin \omega)^2 - (\cos \Omega \cos i \cos \omega)^2 + 2 \sin \Omega \sin \omega \cos \Omega \cos i \cos \omega \\
&\quad - (\sin^2 i \cos^2 \omega) \\
&= \left(-\frac{na}{2}\right) \sqrt{1-e^2} \\
&\quad - \sin^2 \omega - \cos^2 i \cos^2 \omega \\
&\quad - \sin^2 i \cos^2 \omega
\end{aligned}$$

$$[a, \omega]_2 = \frac{na}{2} \sqrt{1-e^2}$$

So putting it together

$$[a, \omega] = [a, \omega]_1 + [a, \omega]_2 = -\frac{na}{2} \sqrt{1-e^2}$$

#### 4.1.3 All Lagrange Brackets

The full list of non zero Lagrange Brackets are

$$\begin{aligned}
[\Omega, i] &= -[i, \Omega] = -na^2 (1-e^2)^{\frac{1}{2}} \sin i \\
[\Omega, a] &= -[a, \Omega] = (1-e^2)^{\frac{1}{2}} \frac{na}{2} \cos i \\
[\Omega, e] &= -[e, \Omega] = -\frac{na^2 e \cos i}{(1-e^2)^{\frac{1}{2}}} \\
[\omega, a] &= -[a, \omega] = \frac{na}{2} (1-e^2)^{\frac{1}{2}} \\
[\omega, e] &= -[e, \omega] = -\frac{na^2 e}{(1-e^2)^{\frac{1}{2}}} \\
[a, M] &= -[M, a] = -\frac{na}{2}
\end{aligned}$$

#### Sample Case - Circular motion

$$x = a \cos M$$

$$y = a \sin M$$

$$\dot{x} = -a \sin M \frac{dM}{dt} = -na \sin M$$

$$\dot{y} = a \cos M \frac{dM}{dt} = na \cos M$$

$$[a, M] = \left[ \frac{\partial x}{\partial a} \frac{\partial \dot{x}}{\partial M} - \frac{\partial \dot{x}}{\partial a} \frac{\partial x}{\partial M} \right] + \left[ \frac{\partial y}{\partial a} \frac{\partial \dot{y}}{\partial M} - \frac{\partial \dot{y}}{\partial a} \frac{\partial y}{\partial M} \right]$$



$$\begin{aligned}
&= \left[ \cos M (-na \cos M) - \left( \frac{n}{2} \sin M \right) (-a \sin M) \right] + \left[ \sin M (-na \sin M) - \left( -\frac{n}{2} \cos M \right) (a \cos M) \right] \\
&= \left[ (-na \cos^2 M) + \left( \frac{na}{2} \sin^2 M \right) \right] + \left[ (-na \sin^2 M) + \left( \frac{na}{2} \cos^2 M \right) \right] \\
&= [-na] + \left[ \frac{na}{2} \right] \\
[a, M] &= -\frac{na}{2}
\end{aligned}$$

Note  $n$  isn't constant since  $n = \sqrt{\frac{GM}{a^3}}$  so when we are calculating e.g.  $\frac{\partial \dot{x}}{\partial a}$  we have to take this into account i.e. if we change  $a$  and calculate the change in the length of the arc at  $M = 0$  for angle  $dM$

$$\begin{aligned}
ds_{before} &= adM = andt \\
ds_{after} &= (a + da) \sqrt{GM} \frac{1}{\sqrt{(a + da)^3}} dt \\
&= (a + da) \sqrt{GM} a^{-3} \frac{1}{\sqrt{\left(1 + \frac{da}{a}\right)^3}} dt \\
&\approx (a + da) n \left( 1 - \frac{3}{2} \frac{da}{a} \right) dt \\
&\approx andt + ndadt - n \frac{3}{2} dadt \\
&\approx andt - \frac{n}{2} dadt \\
\dot{x}_{before} &= \frac{ds_{before}}{dt} = an \\
\dot{x}_{after} &= \frac{ds_{after}}{dt} = an - \frac{n}{2} da \\
\frac{\partial \dot{x}}{\partial a} &= -\frac{n}{2}
\end{aligned}$$

## 4.2 Rationale for Lagrange Brackets

In the inertial frame we have

$$\begin{aligned}
\frac{dx_i}{dt} &= \dot{x}_i \\
\frac{d\dot{x}_i}{dt} &= \frac{\partial V}{\partial x_i}
\end{aligned}$$

We want to express this in terms of Keplerian orbital elements so we can write

$$\sum_{k=1}^6 \frac{\partial x_i}{\partial s_k} \frac{ds_k}{dt} = \dot{x}_i$$

and

$$\sum_{k=1}^6 \frac{\partial \dot{x}_i}{\partial s_k} \frac{ds_k}{dt} = \frac{\partial V}{\partial x_i}$$

On the RHS we still have inertial parameters i.e.  $\dot{x}_i$  and  $\frac{\partial V}{\partial x_i}$ . The trick is to multiply the first equation by  $-\frac{\partial \dot{x}_i}{\partial s_l}$  and the second equation by  $\frac{\partial x_i}{\partial s_l}$  giving the below

$$\sum_{k=1}^6 -\frac{\partial \dot{x}_i}{\partial s_l} \frac{\partial x_i}{\partial s_k} \frac{ds_k}{dt} = -\frac{\partial \dot{x}_i}{\partial s_l} \dot{x}_i = -\frac{1}{2} \frac{\partial (\dot{x}_i \dot{x}_i)}{\partial s_l}$$

$$\sum_{k=1}^6 \frac{\partial x_i}{\partial s_l} \frac{\partial \dot{x}_i}{\partial s_k} \frac{ds_k}{dt} = \frac{\partial x_i}{\partial s_l} \frac{\partial V}{\partial x_i}$$

In the above, let  $i$  range over range  $[1, 2, 3]$  i.e.  $x, y, z$  and add the two equations together

$$\sum_{k=1}^6 \left[ \left[ \frac{\partial x}{\partial s_l} \frac{\partial \dot{x}}{\partial s_k} - \frac{\partial \dot{x}}{\partial s_l} \frac{\partial x}{\partial s_k} \right] + \left[ \frac{\partial y}{\partial s_l} \frac{\partial \dot{y}}{\partial s_k} - \frac{\partial \dot{y}}{\partial s_l} \frac{\partial y}{\partial s_k} \right] + \left[ \frac{\partial z}{\partial s_l} \frac{\partial \dot{z}}{\partial s_k} - \frac{\partial \dot{z}}{\partial s_l} \frac{\partial z}{\partial s_k} \right] \right] \frac{ds_k}{dt}$$

$$= -\frac{1}{2} \frac{\partial (\dot{x}^2 + \dot{y}^2 + \dot{z}^2)}{\partial s_l} + \frac{\partial x}{\partial s_l} \frac{\partial V}{\partial x} + \frac{\partial y}{\partial s_l} \frac{\partial V}{\partial y} + \frac{\partial z}{\partial s_l} \frac{\partial V}{\partial z}$$

Let  $T = \frac{1}{2} (\dot{x}^2 + \dot{y}^2 + \dot{z}^2)$

$$\sum_{k=1}^6 \left[ \left[ \frac{\partial x}{\partial s_l} \frac{\partial \dot{x}}{\partial s_k} - \frac{\partial \dot{x}}{\partial s_l} \frac{\partial x}{\partial s_k} \right] + \left[ \frac{\partial y}{\partial s_l} \frac{\partial \dot{y}}{\partial s_k} - \frac{\partial \dot{y}}{\partial s_l} \frac{\partial y}{\partial s_k} \right] + \left[ \frac{\partial z}{\partial s_l} \frac{\partial \dot{z}}{\partial s_k} - \frac{\partial \dot{z}}{\partial s_l} \frac{\partial z}{\partial s_k} \right] \right] \frac{ds_k}{dt} = \frac{\partial [V - T]}{\partial s_l}$$

Use convention that summation happens over the repeated subscript  $i$ .

$$\sum_{k=1}^6 \left[ \frac{\partial x_i}{\partial s_l} \frac{\partial \dot{x}_i}{\partial s_k} - \frac{\partial \dot{x}_i}{\partial s_l} \frac{\partial x_i}{\partial s_k} \right] \frac{ds_k}{dt} = \frac{\partial [V - T]}{\partial s_l}$$

and introducing  $[s_l, s_k]$  for the Lagrange Bracket (using the convention the we sum over the repeated  $k$  subscript), we finally have

$$[s_l, s_k] \frac{ds_k}{dt} = \frac{\partial [V - T]}{\partial s_l}$$

If we let  $H = V - T$

$$[s_l, s_k] \frac{ds_k}{dt} = \frac{\partial H}{\partial s_l}$$

The key thing in this equation is  $\frac{ds_k}{dt}$ . We have the possibility now to calculate the change in orbital elements i.e  $\frac{d\omega}{dt}$ ,  $\frac{dM}{dt}$ ,  $\frac{d\Omega}{dt}$ , etc if we know (1) the values of the Lagrange Brackets and (2) how  $(V - T)$  depends on the orbital elements. We have 6 equations and we can solve for  $\frac{ds_l}{dt}$  e.g.

$$[a, a] \frac{da}{dt} + [a, e] \frac{de}{dt} + [a, i] \frac{di}{dt} + [a, \omega] \frac{d\omega}{dt} + [a, \Omega] \frac{d\Omega}{dt} + [a, M] \frac{dM}{dt} = \frac{\partial H}{\partial a}$$

$$[i, a] \frac{da}{dt} + [i, e] \frac{de}{dt} + [i, i] \frac{di}{dt} + [i, \omega] \frac{d\omega}{dt} + [i, \Omega] \frac{d\Omega}{dt} + [i, M] \frac{dM}{dt} = \frac{\partial H}{\partial i}$$

etc

### 4.3 Lagrangian Equations - Solutions of $\frac{ds_l}{dt}$

I shall just quote them here

$$\begin{aligned}
\frac{da}{dt} &= \frac{2}{na} \frac{\partial H}{\partial M} \\
\frac{de}{dt} &= \frac{1-e^2}{na^2e} \frac{\partial H}{\partial M} - \frac{(1-e^2)^{\frac{1}{2}}}{na^2e} \frac{\partial H}{\partial \omega} \\
\frac{d\omega}{dt} &= -\frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}} \sin i} \frac{\partial H}{\partial i} + \frac{(1-e^2)^{\frac{1}{2}}}{na^2e} \frac{\partial H}{\partial e} \\
\frac{di}{dt} &= \frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}} \sin i} \frac{\partial H}{\partial \omega} - \frac{1}{na^2(1-e^2)^{\frac{1}{2}} \sin i} \frac{\partial H}{\partial \Omega} \\
\frac{d\Omega}{dt} &= \frac{1}{na^2(1-e^2)^{\frac{1}{2}} \sin i} \frac{\partial H}{\partial i} \\
\frac{dM}{dt} &= -\frac{1-e^2}{na^2e} \frac{\partial H}{\partial e} - \frac{2}{na} \frac{\partial H}{\partial a}
\end{aligned}$$

#### 4.4 Disturbing Function $R$

Let us write the potential  $V$  as

$$V = \frac{GM}{r} + R$$

i.e. the central term  $\frac{GM}{r}$  plus  $R$  (the disturbing function) which is the other terms, including  $V_{20}$  - which is the only one we are considering, then

$$H = \frac{GM}{r} + R - T$$

However  $-\frac{GM}{r} + T$  is the total energy of a unit mass orbiting in the (osculating) ellipse 73. This is equal to  $-\frac{GM}{2a}$  so

$$H = \frac{GM}{2a} + R$$

so in the solutions above to  $\frac{ds_l}{dt}$  we can replace  $\frac{\partial H}{\partial s_l}$  by  $\frac{\partial R}{\partial s_l}$  except for  $\frac{\partial H}{\partial a}$  where

$$\frac{2}{na} \frac{\partial H}{\partial a} = \frac{2}{na} \frac{GM}{2} \frac{\partial}{\partial a} \left( \frac{1}{a} \right) + \frac{2}{na} \frac{\partial R}{\partial a} = -\frac{2}{na} \frac{GM}{2a^2} + \frac{2}{na} \frac{\partial R}{\partial a} = -\frac{1}{n} \frac{GM}{a^3} + \frac{2}{na} \frac{\partial R}{\partial a}$$

However using Keplers law  $n^2 a^3 = GM$  or  $n^2 = \frac{GM}{a^3}$  gives

$$\frac{2}{na} \frac{\partial H}{\partial a} = -n + \frac{2}{na} \frac{\partial R}{\partial a}$$

so

$$\frac{dM}{dt} = n - \frac{1-e^2}{na^2e} \frac{\partial R}{\partial e} - \frac{2}{na} \frac{\partial R}{\partial a}$$

#### 4.5 Apisidal Precession $\frac{d\omega}{dt}$ using orbital elements

Intuitively, if  $i = 0$  then the satellite orbits around the equator of the spheroid and due to symmetry we might expect no change in the orientation of the ellipse. However lets do the calculation

##### 4.5.1 Inclination $i = 0$

The full  $V_{20}$  term is

$$V_{20} = \frac{GMR_\mu^2 C_{20}}{a^3} \sum_{p=0}^2 F_{20p}(i) \sum_{q=-\infty}^{\infty} G_{2pq}(e) \cos[(2-2p+q)M]$$

The only term in the above that doesn't have a  $\cos M$  dependency is  $G_{210}$ . Terms  $G_{20-2} = G_{222} = 0$ . The remaining terms have a cosine dependency so over a full orbit will average to zero. Lets consider only the  $p = 1, q = 0$  term.

$$R = \frac{GMR_\mu^2 C_{20}}{a^3} F_{201}(i) G_{210}(e)$$

$$\frac{d\omega}{dt} = -\frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}}\sin i}\frac{\partial R}{\partial i} + \frac{(1-e^2)^{\frac{1}{2}}}{na^2e}\frac{\partial R}{\partial e}$$

Calculating  $\frac{\partial F_{201}}{\partial i}$  term when  $i = 0$

$$\begin{aligned}\frac{\partial F_{201}}{\partial i} &= \frac{\partial \left(\frac{3}{4}\sin^2 i - \frac{1}{2}\right)}{\partial i} = \frac{3}{4}2\sin i \cos i \\ -\frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}}\sin i}G_{210}\frac{\partial F_{201}}{\partial i} &= -\frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}}\sin i}(1-e^2)^{-\frac{3}{2}}\frac{3}{2}\sin i \cos i \\ &= -\frac{\cos^2 i}{na^2(1-e^2)^2}\frac{3}{2} \\ \frac{GMR_\mu^2 C_{20}}{a^3} \left( -\frac{\cos i}{na^2(1-e^2)^{\frac{1}{2}}\sin i} \right) G_{210} \frac{\partial F_{201}}{\partial i} &= \frac{GMR_\mu^2 C_{20}}{a^3} \left( -\frac{\cos^2 i}{na^2(1-e^2)^2}\frac{3}{2} \right) \\ &= n^2 R_\mu^2 C_{20} \left( -\frac{\cos^2 i}{na^2(1-e^2)^2}\frac{3}{2} \right)\end{aligned}$$

evaluating at  $i = 0$

$$= -\frac{3nR_\mu^2 C_{20}}{2a^2(1-e^2)^2}$$

Calculating  $\frac{\partial G_{210}}{\partial e}$  term when  $i = 0$

$$\begin{aligned}\frac{\partial G_{210}}{\partial e} &= \frac{\partial (1-e^2)^{-\frac{3}{2}}}{\partial e} = -\frac{3}{2}(1-e^2)^{-\frac{5}{2}}(-2e) \\ F_{201}\frac{\partial G_{210}}{\partial e} &= \left(\frac{3}{4}\sin^2 i - \frac{1}{2}\right)3(1-e^2)^{-\frac{5}{2}}e \\ F_{201}\frac{\partial G_{210}}{\partial e} &= \left(-\frac{1}{2}\right)3(1-e^2)^{-\frac{5}{2}}e \\ \frac{(1-e^2)^{\frac{1}{2}}}{na^2e}F_{201}\frac{\partial G_{210}}{\partial e} &= \frac{(1-e^2)^{\frac{1}{2}}}{na^2e}\left(-\frac{1}{2}\right)3(1-e^2)^{-\frac{5}{2}}e \\ &= -\frac{3}{2(1-e^2)^2na^2} \\ \frac{GMR_\mu^2 C_{20}}{a^3}\frac{(1-e^2)^{\frac{1}{2}}}{na^2e}F_{201}\frac{\partial G_{210}}{\partial e} &= -\frac{GMR_\mu^2 C_{20}}{a^3}\frac{3}{2(1-e^2)^2na^2}\end{aligned}$$

Using  $n^2 = \frac{GM}{a^3}$

$$= -\frac{3nR_\mu^2 C_{20}}{2a^2(1-e^2)^2}$$

Summing both terms together

$$\frac{d\omega}{dt} = -\frac{3nR_\mu^2 C_{20}}{(1-e^2)^2 a^2}$$

So we see there is apsidal precession around a spheroid object (but not around a spherical object because  $C_{20} = 0$ ).

The precession over one period is

$$\begin{aligned}\frac{d\omega}{dt} \cdot T_0 &= \frac{d\omega}{dt} \cdot \frac{2\pi}{n} = -\frac{3nR_\mu^2 C_{20}}{(1-e^2)^2 a^2} \cdot \frac{2\pi}{n} = -\frac{6\pi R_\mu^2 C_{20}}{(1-e^2)^2 a^2} \\ \Delta\omega_p &= -\frac{6\pi R_\mu^2 C_{20}}{(1-e^2)^2 a^2}\end{aligned}\tag{37}$$

## 4.6 Apical Precession using Inertial Frame

Because we are looking at  $i = 0$  lets see what this looks like in the inertial frame. To recap, we are putting  $\phi = 0$  and  $C_{20}$  is negative. We'll use the dimensionless  $C_{20}$  in what follows. From 4

$$V_{20} = GM R_\mu^2 C_{20} \frac{1}{r^3} P_2(\sin \phi)$$

$$V_{20} = GM R_\mu^2 C_{20} \frac{1}{r^3} \frac{1}{2} (3 \sin^2 \phi - 1)$$

$$F_r = \frac{\partial V_{20}}{\partial r} = GM R_\mu^2 C_{20} \frac{-3}{r^4} \frac{1}{2} (3 \sin^2 \phi - 1) = \frac{3}{2} GM R_\mu^2 C_{20} \frac{1}{r^4}$$

$$F_\phi = \frac{1}{r} \frac{\partial V_{20}}{\partial \phi} = GM R_\mu^2 C_{20} \frac{1}{r^4} 3 \sin \phi \cos \phi = 0$$

So we have an extra inward radial acceleration at the equator due to the negative  $F_r$  that we wouldn't have had if the satellite were orbiting a spherical object.

### 4.6.1 Prerequisites

From  $\mathbf{r} = r\mathbf{e}_r$  in polar coordinates and differentiating (see [Newtonian Mechanics]), we have

$$a_r = \frac{d^2 r}{dt^2} - r \left( \frac{d\lambda}{dt} \right)^2$$

$$a_\lambda = r \frac{d^2 \lambda}{dt^2} + 2 \frac{dr}{dt} \frac{d\lambda}{dt}$$

For a central force  $a_\lambda = 0$

$$r \frac{d^2 \lambda}{dt^2} + 2 \frac{dr}{dt} \frac{d\lambda}{dt} = 0$$

Multiply through by  $r$

$$r^2 \frac{d^2 \lambda}{dt^2} + 2r \frac{dr}{dt} \frac{d\lambda}{dt} = \frac{d}{dt} \left( r^2 \frac{d\lambda}{dt} \right) = 0$$

$$r^2 \frac{d\lambda}{dt} = \text{const} = C = \frac{L}{m} = 2 \frac{dA}{dt}$$

where  $L$  is the angular momentum of the mass  $m$

$$\frac{d\lambda}{dt} = \frac{C}{r^2}$$

Let  $r = \frac{1}{u}$

$$\frac{d\lambda}{dt} = C u^2$$

$$\frac{dr}{dt} = -\frac{1}{u^2} \frac{du}{dt} = -\frac{1}{u^2} \frac{du}{d\lambda} \frac{d\lambda}{dt} = -\frac{1}{u^2} \frac{du}{d\lambda} C u^2 = -C \frac{du}{d\lambda}$$

$$\frac{d^2 r}{dt^2} = -C \frac{d^2 u}{d\lambda^2} \frac{d\lambda}{dt} = -C \frac{d^2 u}{d\lambda^2} C u^2 = -C^2 u^2 \frac{d^2 u}{d\lambda^2}$$

Putting this all together

$$a_r = \frac{d^2 r}{dt^2} - r \left( \frac{d\lambda}{dt} \right)^2 = -C^2 u^2 \frac{d^2 u}{d\lambda^2} - \frac{1}{u} C^2 u^4 = -C^2 u^2 \left( \frac{d^2 u}{d\lambda^2} + u \right)$$

$$F_r = m a_r = -m C^2 u^2 \left( \frac{d^2 u}{d\lambda^2} + u \right)$$

#### 4.6.2 Period $T_u$

$$F_r = ma_r = -mC^2u^2 \left( \frac{d^2u}{d\lambda^2} + u \right)$$

where  $C = \frac{L}{m}$

$$\begin{aligned} F_r &= \frac{-mL^2u^2}{m^2} \left( \frac{d^2u}{d\lambda^2} + u \right) \\ \frac{d^2u}{d\lambda^2} + u &= -\frac{m}{L^2u^2} F(u) \end{aligned} \quad (38)$$

Aside - from the above we can see that for an inverse square force  $-\frac{GMm}{r^2} = -GMmu^2$ , we have  $\frac{d^2u}{d\lambda^2} + u = \frac{GMm^2}{L^2}$ . The RHS is a constant with units  $m^{-1}$  as expected.

$$\begin{aligned} \frac{d^2u}{d\lambda^2} + u &= -\frac{m}{L^2u^2} \left[ -GMmu^2 + \frac{3}{2}GMmR_\mu^2C_{20}\frac{1}{r^4} \right] \\ \frac{d^2u}{d\lambda^2} + u &= -\frac{m}{L^2u^2} \left[ -GMmu^2 + \frac{3}{2}GMmR_\mu^2C_{20}u^4 \right] \\ \frac{d^2u}{d\lambda^2} + u &= \frac{GMm^2}{L^2} - \frac{3GMm^2}{2L^2}R_\mu^2C_{20}u^2 \end{aligned}$$

Let  $\eta_p = \frac{GMm^2}{L_p^2}$  where  $L_p$  is the angular momentum of the satellite

$$\frac{d^2u}{d\lambda^2} + u = \eta_p - \frac{3}{2}\eta_p R_\mu^2 C_{20} u^2$$

Let

$$g(u) = \frac{3}{2}\eta_p R_\mu^2 C_{20} u^2$$

so

$$\frac{d^2u}{d\lambda^2} + u = \eta_p - g(u)$$

Let the perturbed solution  $u$  be in the vicinity of  $\eta_p$ . Let us expand  $g(u)$  around  $u = \eta_p$ .

$$\begin{aligned} g_0 &= g(\eta_p) = \frac{3}{2}\eta_p R_\mu^2 C_{20} \eta_p^2 \\ g_1 &= \left. \frac{dg}{du} \right|_{u=\eta_p} = 3\eta_p R_\mu^2 C_{20} \eta_p \\ \Delta u &= u - \eta_p \end{aligned}$$

$$g(u) = g_0 + g_1 \Delta u = \frac{3}{2}R_\mu^2 C_{20} \eta_p^3 + 3R_\mu^2 C_{20} \eta_p^2 (u - \eta_p)$$

So

$$\begin{aligned} \frac{d^2u}{d\lambda^2} + u &= \eta_p - \frac{3}{2}R_\mu^2 C_{20} \eta_p^3 - 3R_\mu^2 C_{20} \eta_p^2 (u - \eta_p) \\ \frac{d^2u}{d\lambda^2} + (1 + 3R_\mu^2 C_{20} \eta_p^2) u &= \eta_p - \frac{3}{2}R_\mu^2 C_{20} \eta_p^3 + 3R_\mu^2 C_{20} \eta_p^3 \\ \frac{d^2u}{d\lambda^2} + (1 + 3R_\mu^2 C_{20} \eta_p^2) u &= \eta_p + \frac{3}{2}R_\mu^2 C_{20} \eta_p^3 \\ \frac{d^2u}{d\lambda^2} + (1 + 3R_\mu^2 C_{20} \eta_p^2) u &= \eta_p \left( 1 + \frac{3}{2}R_\mu^2 C_{20} \eta_p^2 \right) \end{aligned} \quad (39)$$

This is an equation of the form  $\frac{d^2u}{d\lambda^2} + k^2u = \text{const}$  so  $u$  is a periodic function  $\cos k\lambda$

$$k = \sqrt{1 + 3R_\mu^2 C_{20} \eta_p^2}$$

so  $u(\lambda)$  reaches it's maximum at

$$\lambda = \frac{2\pi}{\sqrt{1 + 3R_\mu^2 C_{20} \eta_p^2}} \approx 2\pi \left( 1 - \frac{3}{2} R_\mu^2 C_{20} \eta_p^2 \right)$$

$$\lambda = 2\pi \left( 1 - \frac{3R_\mu^2 C_{20}}{2a^2 (1 - e_0^2)^2} \right)$$

a increased angle of

$$\Delta\lambda_p = -\frac{3\pi R_\mu^2 C_{20}}{a^2 (1 - e_0^2)^2} \quad (40)$$

#### 4.7 Apparent Discrepancy in Orbital and Inertial Calculations

Comparing 37 and 40 we seem to have a discrepancy as they differ by a factor 2.

$$\Delta\omega_p = -\frac{6\pi R_\mu^2 C_{20}}{(1 - e^2)^2 a^2}$$

$$\Delta\lambda_p = -\frac{3\pi R_\mu^2 C_{20}}{a^2 (1 - e_0^2)^2}$$

To see why this is, we need to revisit the calculation using orbital elements. Instead of using  $\Omega = \omega = i = 0$ , let us instead use  $\Omega = \omega = 0$  but have  $i \approx 0$  i.e. very small but not 0. In this case, we have a well defined ascending node  $\Omega$ . However  $\Omega$  also precesses in the following way

$$\frac{d\Omega}{dt} = \frac{3nR_e^2 C_{20}}{2a^2 (1 - e^2)^2} \cos i$$

For small  $i$ , in one period

$$\Delta\Omega_p = \frac{d\Omega}{dt} \cdot \frac{2\pi}{n} = \frac{3\pi R_e^2 C_{20}}{a^2 (1 - e^2)^2}$$

$$\Delta\Omega_p + \Delta\omega_p = -\frac{3\pi R_e^2 C_{20}}{a^2 (1 - e^2)^2}$$

i.e.

$$\Delta\lambda_p = \Delta\Omega_p + \Delta\omega_p$$

See also Figure 6

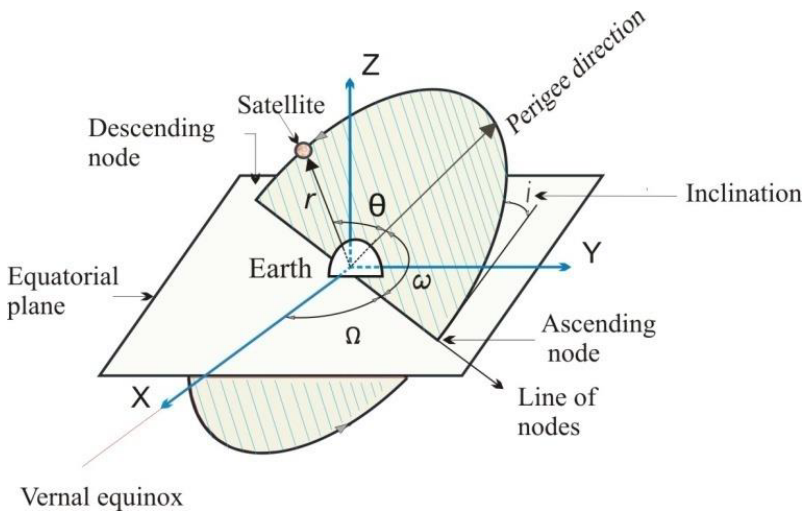


Figure 6: Space orbital parameters (ref [Apsidal Precession Low Earth])

## 4.8 Lagrangian Equations and Small Eccentricity

If we consider the  $G_{211}$  and  $G_{21-1}$  terms, we have for the disturbing function component

$$R = \frac{GMR_\mu^2 C_{20}}{a^3} \left( \frac{3 \sin^2 i}{4} - \frac{1}{2} \right) \left( \frac{3}{2} e \right) (\cos(M) + \cos(-M))$$

$$R = \frac{GMR_\mu^2 C_{20}}{a^3} 3e \left( \frac{3 \sin^2 i}{4} - \frac{1}{2} \right) \cos M \quad (41)$$

If we look at  $\frac{d\omega}{dt}$

$$\frac{d\omega}{dt} = -\frac{\cos i}{na^2 (1-e^2)^{\frac{1}{2}} \sin i} \frac{\partial R}{\partial i} + \frac{(1-e^2)^{\frac{1}{2}}}{na^2 e} \frac{\partial R}{\partial e}$$

$\frac{\partial R}{\partial e}$  on the  $\frac{3}{2}e$  gives  $\frac{3}{2}$  so we have removed the  $e$  from the numerator and we can see that there will now be a division by  $e$  (and  $e$  is small for the case we are considering)

$$\frac{d\omega}{dt} \approx \dots + \frac{(1-\frac{1}{2}e^2)}{na^2 e} \frac{\partial R}{\partial e} = \frac{\partial R}{\partial e} \left[ \frac{1}{na^2 e} - \frac{e}{2na^2} \right]$$

So we would have a huge increase in the argument of the pericentre  $\omega$ . However we also have  $\frac{dM}{dt}$  which has the same  $\frac{\partial R}{\partial e}$  term

$$\frac{dM}{dt} = n - \frac{1-e^2}{na^2 e} \frac{\partial R}{\partial e} - \frac{2}{na} \frac{\partial R}{\partial a}$$

$$\frac{dM}{dt} \approx \dots - \frac{(-1+e^2)}{na^2 e} \frac{\partial R}{\partial e} - \dots = \frac{\partial R}{\partial e} \left[ -\frac{1}{na^2 e} + \frac{e}{na^2} \right]$$

As  $e \rightarrow 0$  the  $\frac{d\omega}{dt}$  and the  $\frac{dM}{dt}$  terms cancel. I think this is what Kaula refers to in section 3.6 Resonance of his book.

## 4.9 Semi-Major Axis Time Dependency

The total energy of a satellite in an ellipse (osculating or not) is (using subscript  $_o$  to indicate osculating)

$$E_o = T - \frac{GM}{r} = -\frac{GM}{2a}$$

However there is also a potential due to the  $V_{20}$  term. The total energy for the satellite is therefore

$$E = E_o + V_{20}$$

Using Physics convention for the  $V_{20}$  potential ( $C_{20}$  is -ve)

$$V_{20} \approx \frac{GMR_\mu^2 C_{20}}{2a^3} (1 + 3e \cos \lambda)$$

$$E = -\frac{GM}{2a} + \frac{GMR_\mu^2 C_{20}}{2a^3} (1 + 3e \cos \lambda) \quad (42)$$

However the difference in  $V_{20}$  between the apocentre and the pericentre is

$$\Delta V_{20} = V_{20\text{apo}} - V_{20\text{peri}} = -\frac{3GMR_\mu^2 C_{20}}{a^3} e > 0$$

So we have an increase in  $V_{20}$  as we go from pericentre to apocentre (it's less negative). Therefore, the semi-major axis  $a$  cannot be constant otherwise energy  $E$  in 42 would not be conserved.

Lagrange equation for the change in semi-major axis  $a$ , due to the disturbing potential, is

$$\frac{da}{dt} = \frac{2}{na} \frac{\partial R}{\partial M}$$

In previous calculations 4.5 to calculate the apsidal precession  $\frac{d\omega}{dt}$ , we considered the disturbing potential due to the  $G_{210}$  term, which has no dependency on the mean anomaly  $M$ . Therefore



$$\frac{da}{dt} = 0$$

Let us consider the  $G_{211}$  and  $G_{21-1}$  terms. From 41 and letting  $i = 0$

$$R = \frac{GM R_\mu^2 C_{20}}{a^3} 3e \left( -\frac{1}{2} \right) \cos M$$

$$\frac{da}{dt} = \frac{2}{na} \frac{\partial R}{\partial M}$$

$$\frac{da}{dt} = \frac{2}{na} \left( \frac{GM R_\mu^2 C_{20}}{a^3} 3e \left( \frac{1}{2} \right) \sin M \right)$$

$$\frac{da}{dt} = \frac{GM R_\mu^2 C_{20}}{na^4} 3e \sin M$$

$$\int a^4 da = \int \frac{GM R_\mu^2 C_{20}}{n} 3e \sin(nt) dt$$

So calculating  $\delta a$  between pericentre and apocenter.

$$\frac{(a + \delta a)^5 - a^5}{5} = - \frac{GM R_\mu^2 C_{20}}{n^2} 3e \cos(M) \Big|_0^\pi$$

Keep  $O(\delta a)$

$$a^4 \delta a = \frac{GM R_\mu^2 C_{20}}{n^2} 6e$$

$$\delta a = \frac{GM R_\mu^2 C_{20}}{n^2 a^4} 6e$$

From  $n^2 = \frac{GM}{a^3}$

$$\delta a = \frac{R_\mu^2 C_{20}}{a} 6e$$

so  $a$  has decreased. Lets work out the change in energy in the osculating ellipse. (From the below it will be more -ve since  $a$  is smaller).

$$E_o = -\frac{GM}{2a}$$

$$\frac{dE_o}{da} = \frac{GM}{2a^2}$$

$$\Delta E_o = \frac{GM}{2a^2} \delta a$$

$$= \frac{GM R_\mu^2 C_{20}}{2a^3} 6e$$

$$\Delta E_o = \frac{3GM R_\mu^2 C_{20}}{a^3} e$$

#### 4.10 Mercury Precession due to Sun Oblateness

For Mercury we have the following (see [Mercury: Planet and Orbit]).

Sun Radius (km) $R_{\odot}$	695,700
Mercury $e$	0.2056
Mercury semi-major axis (km) $a$	57.91E6
Orbital Period (days) $T$	87.969
Mean angular velocity $n$	$\frac{2\pi}{T}$
Inclination $i$	$7^\circ$
Sun $J_2$ (or $-C_{20}$ )	2.0E-7

$$\omega_{prec} = \frac{3nR_{\odot}^2 J_2}{2a^2 (1 - e^2)^2} = \frac{3nR_{\odot}^2 (10^{-7})}{2a^2 (1 - e^2)^2} \left( \frac{J_2}{10^{-7}} \right)$$

$$\omega_{prec} = 1.68575E - 12 \left( \frac{J_2}{10^{-7}} \right) \text{ radians per day}$$

$$\omega_{prec} = 6.15299E - 08 \left( \frac{J_2}{10^{-7}} \right) \text{ radians per century}$$

$$\omega_{prec} = 3.5254E - 06 \left( \frac{J_2}{10^{-7}} \right) \text{ degrees per century}$$

$$\omega_{prec} = 3.5254E - 06 \left( \frac{J_2}{10^{-7}} \right) * 60 * 60 \approx 0.012 \left( \frac{J_2}{10^{-7}} \right) \text{ arcsec per century}$$

If we choose  $J_2 = 2E - 7$

$$\omega_{prec} \approx 0.024 \text{ arcsec per century}$$

Note General Relativity contributes  $\approx 43$  arcsec per century. See next section.

#### 4.11 Mercury Precession due to Relativity

The formula for Mercury precession due to Relativity is (see [Mercury: Planet and Orbit])

$$\omega_{prec} = \frac{3GM_{sun}n}{a(1 - e^2)c^2}$$

$GM_{sun} \left( \frac{km^3}{s^2} \right)$	132,712E6
Mercury $e$	0.2056
Mercury semi-major axis (km) $a$	57.91E6
Orbital Period (days) $T_d$	87.969
Orbital Period (sec) $T_s$	7,600,522
Mean angular velocity (per sec) $n$	8.27E-07
Speed of light $c \frac{km}{s}$	299,792

$$\omega_{prec} = 6.6 (10^{-14}) \text{ radians per second}$$

$$\omega_{prec} = 2.08 (10^{-4}) \text{ radians per century}$$

$$\omega_{prec} = 0.01193 \text{ degrees per century}$$

$$\omega_{prec} = 42.95 \text{ arcsec per century}$$

## 4.12 Newton's Theorem of Revolving Orbits

We could also account for Mercury's precession by making a small amendment  $\delta$  to the inverse square law [Newton Apsidal]. Let

$$F(r) = -\frac{GMm}{r^{(2+\delta)}}$$

Let  $u = \frac{1}{r}$

$$F(u) = -GMmu^{(2+\delta)} = -GMmu^2u^\delta$$

Using 38

$$\frac{d^2u}{d\lambda^2} + u = -\frac{m}{L^2u^2}F(u) = \left(-\frac{m}{L^2u^2}\right)(-GMmu^2u^\delta) = \frac{GMm^2u^\delta}{L^2}$$

So we have the following (where if  $\delta = 0$  we end up with the standard inverse square law equation).

$$\frac{d^2u}{d\lambda^2} + u = \frac{GMm^2u^\delta}{L^2}$$

$$\frac{d^2u}{d\lambda^2} + u = \eta u^\delta$$

$u^\delta = \exp(\ln u^\delta)$ . Since  $\ln u^\delta = \delta \ln u$  then  $u^\delta = \exp(\delta \ln u)$ . Expanding this to the first order in  $\delta$  gives

$$u^\delta = 1 + \delta \ln u$$

As previously, let us assume that the solution  $u$  is in the region of  $\eta$  (so this derivation is only working for small  $e$ ). Let

$$g(u) = u^\delta = 1 + \delta \ln u$$

Expand around  $\eta$

$$g(u) = g_0(\eta) + g_1(\eta) \Delta u$$

$$g_0 = g(\eta) = 1 + \delta \ln \eta$$

$$g_1 = \left. \frac{dg}{du} \right|_{u=\eta} = \frac{\delta}{\eta}$$

$$\Delta u = u - \eta$$

$$g(u) = g_0 + g_1 \Delta u = (1 + \delta \ln \eta) + \frac{\delta}{\eta} (u - \eta)$$

$$\frac{d^2u}{d\lambda^2} + u = \eta g(u) = \eta(1 + \delta \ln \eta) + \delta u - \delta \eta$$

$$\frac{d^2u}{d\lambda^2} + u = \eta(1 - \delta + \delta \ln \eta) + \delta u$$

$$\frac{d^2u}{d\lambda^2} + (1 - \delta)u = \eta(1 - \delta + \delta \ln \eta) \quad (43)$$

This is of the form  $\frac{d^2u}{d\lambda^2} + k^2u = \text{const}$  so is a periodic function  $\cos k\lambda$ .  $k = \sqrt{1 - \delta}$ . The maximum is at  $\lambda = \frac{2\pi}{\sqrt{1 - \delta}} = 2\pi(1 - \delta)^{-\frac{1}{2}} \approx 2\pi(1 + \frac{\delta}{2}) = 2\pi + \delta\pi$

So the increase is

$$\delta\pi \text{ per orbit}$$

For Mercury, letting  $\delta = 0.00000016$

$$0.00000016\pi \text{ radians per } 87.969 \text{ days}$$

$$6.6387023\pi (10^{-5}) \text{ radians per century}$$

$$0.003803696\pi \text{ degrees per century}$$

$$\approx 43 \text{ arcsec per century}$$

Aside 1: Newton's derivation (Proposition 45 in Book I of the Principia) relates the angle between apocentre and pericentre to be  $\frac{\pi}{\sqrt{n}}$  where the centripetal force is of magnitude  $\mu r^{n-3}$ . Relating this to the above we have  $n - 3 = -(2 + \delta)$  or  $n = (1 - \delta)$  so the angle is  $\frac{\pi}{\sqrt{1-\delta}}$ . Therefore the angle from apocentre to apocentre is twice this i.e.  $\frac{2\pi}{\sqrt{1-\delta}}$  (as above).

#### 4.12.1 Relationship to $c$ and $v$

For Mercury, it's orbital velocity is  $\sim na$  so from 4.11

$$v = 57.91E6 * 8.27E - 07$$

$$v \approx 47.89\text{km/s}$$

Divide by the speed of light is

$$\frac{v}{c} \approx \frac{47.89}{299,792} = 0.0001597441$$

We have a number of interesting relationships given that  $\delta = 0.00000016$  from the above section e.g.

$$2\pi \left(\frac{v}{c}\right)^2 \approx 0.00000016$$

and

$$\frac{6}{(1 - e^2)} \left(\frac{v}{c}\right)^2 \approx 0.00000016$$

Using the second one

$$v = na$$

$$v^2 = n^2 a^2 = \frac{n^2 a^3}{a}$$

From Keplers law

$$v^2 = n^2 a^2 = \frac{GM}{a}$$

so

$$\frac{v^2}{c^2} = \frac{GM}{ac^2}$$

and

$$\delta = \frac{6}{(1 - e^2)} \left(\frac{v}{c}\right)^2 = \frac{6GM}{a(1 - e^2)c^2}$$

so we get the General Relativity correction

$$\pi\delta = \frac{6\pi GM}{a(1 - e^2)c^2}$$

#### 4.12.2 Semi-Latus Rectum Change

Refer to K.

The above 43 means that the ellipse, besides precessing, has the following particular solution

$$u_p = \eta \frac{(1 - \delta + \delta \ln \eta)}{(1 - \delta)}$$

So it also has a increased semi-latus rectum  $l_{new} = \frac{1}{\eta_{new}}$  i.e.

$$\eta_{new} = \eta \left( \frac{(1 - \delta + \delta \ln \eta)}{(1 - \delta)} \right) = \left( 1 + \frac{\delta \ln \eta}{1 - \delta} \right) \eta$$

I haven't found any literature on this consequence of changes to the inverse-square force and how significant/observable it is.

In the case of Mercury

$$\eta_{new} = \left( 1 + \frac{(0.00000016) \ln(1.803(10^{-8}))}{(1 - 0.00000016)} \right) \eta = 0.9999971467\eta$$

And the semi-latus rectum is

$$l_{new} = \frac{1}{\eta_{new}} = \frac{1}{0.9999971467\eta}$$

semi-latus rectum goes from 55,462,066 to 55,462,224 km. So an increase of ~150km.

## 5 Mercury Spin-Orbit Coupling.

Mercury has a 3:2 spin orbit coupling i.e. it rotates on it's axis 3 times in the time it takes to orbit twice around the sun. The following references explain it well [Spin Orbit coupling], [Mercury: Planet and Orbit], [Tidal Torques].

The 3:2 spin orbit coupling involves the effects of 1) tidal torques and 2) triaxial torques due to permanent asymmetry in Mercury's equatorial plane i.e.  $a > b > c$ . Note - the tidal torque does not require a permanent asymmetry in the axis i.e. we could have tidal torque if Mercury was spherical. The tidal torque on it's own would act to slow down Mercury's rotation until it reaches a 1:1 coupling i.e. Mercury would take the same time to rotate on it's axis as it does to orbit the sun. Note the moon is in a 1:1 spin orbit coupling which is why it always presents the same face to the earth. However Mercury hasn't reached the 1:1 state - it spins faster than it orbits and is captured in a 3:2 state.

Lets consider the triaxial torque due to the *permanent* asymmetry of Mercury where the moments of inertia around the 3 principal axis are  $C > B > A$ . [Spin Orbit coupling] gives a good account of the torques in play and the derivation of subsequent equations(see Fig 7).

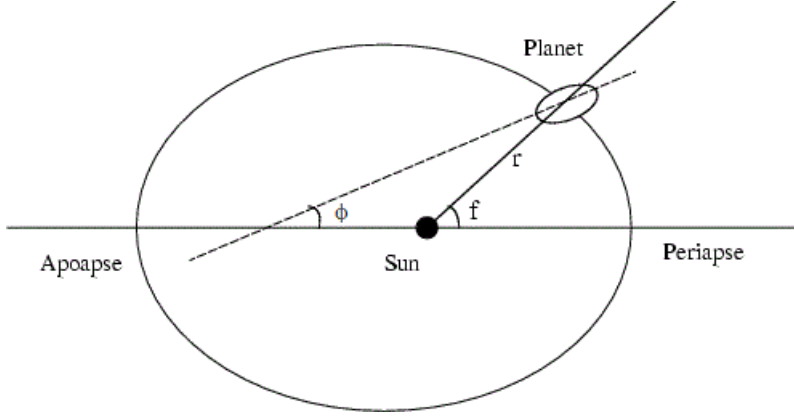


Figure 7: Geometry of spin-orbit coupling (ref [Mercury Main librations]).

Using MacCullagh's formula for the gravitational potential due to Mercury leads to the following formula that describes  $\phi$ . Note  $\dot{\phi}$  describes Mercury's spin.

$$\ddot{\phi} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left( \frac{a}{r} \right)^3 \sin[2(\phi - f)] = 0 \quad (44)$$

Now 44 is not straightforward to solve. Lets consider the situation where Mercury has been spun down by tidal torques until it is approaching the 3:2 resonance. Let us define

$$\gamma = \phi - \frac{3}{2}M$$

where  $M$  is the mean anomaly. So

$$\phi = \gamma + \frac{3}{2}M$$

$$\dot{\phi} = \dot{\gamma} + \frac{3}{2}n$$

where  $n$  is the average angular velocity i.e.  $n = \frac{2\pi}{T} = \sqrt{\frac{GM}{a^3}}$

$$\ddot{\phi} = \ddot{\gamma}$$

So 44 becomes

$$\ddot{\gamma} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left( \frac{a}{r} \right)^3 \sin \left[ 2 \left( \gamma + \frac{3}{2}M - f \right) \right] = 0$$

$$\ddot{\gamma} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left( \frac{a}{r} \right)^3 \sin[2\gamma + 3M - 2f] = 0$$

The following term is similar to what we solved in 3.3.

$$\left( \frac{a}{r} \right)^3 \sin[2\gamma + 3M - 2f]$$

## 5.1 Prerequisites

Revisiting the complex Fourier expansion of a function we have

$$f = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

If  $f$  is real then  $c_k = \bar{c}_{-k}$  i.e. the complex conjugate.

If  $f$  is even,  $c_k$  is real, so  $c_k = c_{-k}$ .

If  $f$  is odd,  $c_k$  is imaginary.

The relation between cosine and sin coefficients to the complex coefficients are

$$a_0 = c_0$$

$$a_k = c_k + c_{-k}$$

$$b_k = i(c_k - c_{-k})$$

## 5.2 Expansion of $\frac{a^3}{r^3} \sin(2\gamma + 3M - 2f)$

$$\sin(2\gamma + 3M - 2f) = \frac{\exp(i(2\gamma + 3M - 2f)) - \exp(-i(2\gamma + 3M - 2f))}{2i}$$

From 30

$$\exp(i(2\gamma + 3M - 2f)) = \exp(i(2\gamma + 3M)) \exp(-i2f) = \exp(i(2\gamma + 3M)) \frac{\exp(-i2E)(1 - \beta \exp(-iE))^{-2}}{(1 - \beta \exp(iE))^{-2}}$$

$$\begin{aligned} 2i \sin(2\gamma + 3M - 2f) &= \exp(i(2\gamma + 3M)) \frac{\exp(-i2E)(1 - \beta \exp(-iE))^{-2}}{(1 - \beta \exp(iE))^{-2}} \\ &\quad - \exp(-i(2\gamma + 3M)) \frac{\exp(i2E)(1 - \beta \exp(-iE))^2}{(1 - \beta \exp(iE))^2} \end{aligned}$$

$$\begin{aligned} &= \exp(i(2\gamma + 3M)) \exp(-i2E)(1 - \beta \exp(-iE))^{-2}(1 - \beta \exp(iE))^2 \\ &\quad - \exp(-i(2\gamma + 3M)) \exp(i2E)(1 - \beta \exp(-iE))^2(1 - \beta \exp(iE))^{-2} \end{aligned}$$

Let's expand the r, f term in a Fourier series as before

$$function = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

$$\frac{a^3}{r^3} \sin(2\gamma + 3M - 2f) = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

$$c_k = \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} [\sin(2\gamma + 3M - 2f)] \exp -ikM dM$$

Let's look at the first term first

$$c_{k_1} = \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} \left[ \frac{\exp(i(2\gamma + 3M)) \exp(-i2E)(1 - \beta \exp(-iE))^{-2}(1 - \beta \exp(iE))^2}{2i} \right] \exp -ikM dM$$

From previously, we can substitute  $\frac{a^3}{r^3}$  with  $\frac{a^2}{r^2} \frac{a}{r} dM$  or  $\frac{a^2}{r^2} dE$  and take constant terms out of the integral ( $\gamma = \phi - \frac{3}{2}M$  so  $\gamma$  is approximately constant near the 3:2 resonance.)

$$c_{k_1} = \frac{1}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} \frac{a^2}{r^2} \left[ \exp(i3M) \exp(-i2E)(1 - \beta \exp(-iE))^{-2}(1 - \beta \exp(iE))^2 \right] \exp -ikM dE$$

substitute  $\frac{a^2}{r^2}$

$$= \frac{1}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} \frac{(1 + \beta^2)^2}{[(1 - \beta \exp(iE))(1 - \beta \exp(-iE))]^2} \left[ \exp(i3M) \exp(-i2E) (1 - \beta \exp(-iE))^{-2} (1 - \beta \exp(iE))^2 \right] \exp -ikM dE$$

Rearrange terms

$$= \frac{(1 + \beta^2)^2}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \left[ \exp(-i2E) (1 - \beta \exp(-iE))^{-2} (1 - \beta \exp(iE))^2 \right] \exp -i(k-3)M dE$$

substitute  $M$  and combine  $iE$  terms

$$= \frac{(1 + \beta^2)^2}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} (1 - \beta \exp(-iE))^{-4} \exp(-i2E) \exp(i[(k-3)e \sin E - (k-3)E]) dE$$

so the first term is

$$c_{k_1} = \frac{(1 + \beta^2)^2}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} (1 - \beta \exp(-iE))^{-4} \exp(i[(k-3)e \sin E - (k-1)E]) dE$$

$$c_{k_1} = \frac{(1 + \beta^2)^2}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} \sum_{b=0}^{\infty} \binom{-4}{b} (-1)^b \beta^b \exp(-iEb) \exp(i[(k-3)e \sin E - (k-1)E]) dE$$

$$c_{k_1} = \frac{(1 + \beta^2)^2}{4\pi i} \exp(i2\gamma) \int_0^{2\pi} \sum_{b=0}^{\infty} \binom{-4}{b} (-1)^b \beta^b \exp(i[(k-3)e \sin E - (k-1+b)E]) dE$$

$$c_{k_1} = \frac{\exp(i2\gamma)}{2i} \left[ (1 + \beta^2)^2 \sum_{b=0}^{\infty} \binom{-4}{b} (-1)^b \beta^b J_{k-1+b}((k-3)e) \right]$$

For the second term, and omitting some steps

$$c_{k_2} = \frac{1}{2\pi} \int_0^{2\pi} \frac{a^3}{r^3} \left[ \frac{\exp(-i(2\gamma + 3M)) \exp(i2E) (1 - \beta \exp(-iE))^2 (1 - \beta \exp(iE))^{-2}}{2i} \right] \exp -ikM dM$$

$$= \frac{1}{4\pi i} \exp(-i2\gamma) \int_0^{2\pi} (1 + \beta^2)^2 (1 - \beta \exp(iE))^{-2} (1 - \beta \exp(-iE))^{-2} \left[ \exp(-i3M) \exp(i2E) (1 - \beta \exp(-iE))^2 (1 - \beta \exp(iE))^{-2} \right] \exp -ikM dE$$

$$= \frac{(1 + \beta^2)^2}{4\pi i} \exp(-i2\gamma) \int_0^{2\pi} (1 - \beta \exp(iE))^{-4} \exp(i((k+3)e \sin E - (k+1)E)) dE$$

$$c_{k_2} = \frac{\exp(-i2\gamma)}{2i} \left[ (1 + \beta^2)^2 \sum_{b=0}^{\infty} \binom{-4}{b} (-1)^b \beta^b J_{k+1-b}((k+3)e) \right]$$

$$c_k = c_{k_1} - c_{k_2}$$

Using a program, we can calculate the bit in the bracket for both  $c_{k_1}$  and  $c_{k_2}$  which will be a function of  $k$  and  $e$ . This is basically the same way we did manually in section 3.2.3).

Here are the results.



```
file:///C:/dev/SpheroidCode/spheroid/bin/Debug/spheroid.EXE
k=0 1st:7/2e^1 + -123/16e^3, 2nd:7/2e^1 + -123/16e^3
k=1 1st:1/1e^0 + -5/2e^2, 2nd:17/2e^2
k=-1 1st:17/2e^2, 2nd:1/1e^0 + -5/2e^2
k=2 1st:-1/2e^1 + 1/16e^3, 2nd:845/48e^3
k=-2 1st:845/48e^3, 2nd:-1/2e^1 + 1/16e^3
```

Figure 8: Calculation of  $e$  dependency

Calculate the  $k = 0$  term -  $c_0$  - keeping only as high as  $O(e)$ .

$$c_0 \exp i0M = c_{0_1} \cdot 1 - c_{0_2} \cdot 1 = \frac{7e \exp(i2\gamma)}{2} \frac{1}{2i} - \frac{7e \exp(-i2\gamma)}{2} \frac{1}{2i}$$

$$c_0 = \frac{7e}{2} \left[ \frac{\exp(i2\gamma) - \exp(-i2\gamma)}{2i} \right]$$

$$c_0 = \frac{7e}{2} \sin(2\gamma)$$

Calculate the  $k = 1$  and  $k = -1$  terms,  $c_1$  and  $c_{-1}$  keeping only as high as  $O(e)$ .

$$c_1 \exp iM = c_{1_1} \exp iM - c_{1_2} \exp iM = 1 \cdot \frac{\exp(i2\gamma) \exp iM}{2i} - O(e^2) = \frac{\exp(i(2\gamma + M))}{2i}$$

$$c_{-1} \exp -iM = c_{-1_1} \exp -iM - c_{-1_2} \exp -iM = O(e^2) - 1 \cdot \frac{\exp(-i2\gamma) \exp -iM}{2i} = -\frac{\exp(-i(2\gamma + M))}{2i}$$

$$c_1 \exp iM + c_{-1} \exp -iM = \sin(2\gamma + M)$$

Calculate the  $k = 2$  and  $k = -2$  terms,  $c_2$  and  $c_{-2}$  keeping only as high as  $O(e)$ .

$$c_2 \exp i2M = c_{2_1} \exp i2M - c_{2_2} \exp i2M = -\frac{e \exp(i2\gamma) \exp i2M}{2} \frac{1}{2i} + O(e^3) = -\frac{e \exp(i(2\gamma + 2M))}{2} \frac{1}{2i}$$

$$c_{-2} \exp -i2M = c_{-2_1} \exp -i2M - c_{-2_2} \exp -i2M = O(e^3) + \frac{e \exp(-i2\gamma) \exp -i2M}{2} \frac{1}{2i} = +\frac{e \exp(-i(2\gamma + 2M))}{2} \frac{1}{2i}$$

$$c_2 \exp i2M + c_{-2} \exp -i2M = -\frac{e}{2} \sin(2\gamma + 2M)$$

Now we can go back to the original expansion

$$\frac{a^3}{r^3} \sin(2\gamma + 3M - 2f) = \sum_{k=-\infty}^{\infty} c_k \exp ikM$$

and using the values we have calculated for  $c_k \exp ikM$  for  $k = 0, 1, 2$  we have

$$\frac{a^3}{r^3} \sin(2\gamma + 3M - 2f) = \frac{7e}{2} \sin(2\gamma) + \sin(2\gamma + M) - \frac{e}{2} \sin(2\gamma + 2M) + \dots$$

$$\ddot{\gamma} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left( \frac{a}{r} \right)^3 \sin \left[ 2 \left( \gamma + \frac{3}{2}M - f \right) \right] = 0$$

$$\ddot{\gamma} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left[ \frac{7e}{2} \sin(2\gamma) + \sin(2\gamma + M) - \frac{e}{2} \sin(2\gamma + 2M) \right] = 0$$

$$\ddot{\gamma} = -\frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left[ \left( \frac{7e}{2} + \cos M - \frac{e}{2} \cos 2M \right) \sin(2\gamma) + \left( \sin M - \frac{e}{2} \sin 2M \right) \cos(2\gamma) \right]$$

$$\ddot{\gamma} = -\frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \left[ \left( \frac{7e}{2} + \cos nt - \frac{e}{2} \cos 2nt \right) \sin(2\gamma) + \left( \sin nt - \frac{e}{2} \sin 2nt \right) \cos(2\gamma) \right] \quad (45)$$

Over an full orbit, the sin and cos terms with a dependency on  $t$  on the RHS in 45 average to zero i.e. the change in  $\gamma$  is driven by the  $\frac{7e}{2}$  term  
e.g. if we look at the  $\cos nt$  term

$$\begin{aligned} \int \ddot{\gamma} dt &= \dot{\gamma} = \int -\frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \cos(nt) \sin(2\gamma) \\ \dot{\gamma} &= \left[ -\frac{3}{2}n^2 \sin(2\gamma) \left( \frac{B-A}{C} \right) \right] \int \cos(nt) \\ \dot{\gamma} &= \left[ -\frac{3}{2}n^2 \sin(2\gamma) \left( \frac{B-A}{C} \right) \left( \frac{1}{n} \right) \right] \sin(nt) \\ \Delta\gamma &= \int_0^{2\pi} \dot{\gamma} dt = 0 \end{aligned}$$

so we can write

$$\begin{aligned} \ddot{\gamma} + \frac{3}{2}n^2 \left( \frac{B-A}{C} \right) \frac{7e}{2} \sin(2\gamma) &= 0 \\ \ddot{\gamma} + \frac{21}{4}en^2 \left( \frac{B-A}{C} \right) \sin(2\gamma) &= 0 \end{aligned} \quad (46)$$

Equation 46 is a pendulum equation. For the 3:2 resonance,  $\gamma$  as defined is small so  $\sin(2\gamma) \approx 2\gamma$

$$\ddot{\gamma} + \frac{21}{4}en^2 \left( \frac{B-A}{C} \right) 2\gamma = 0 \quad (47)$$

This is of the form  $\ddot{\gamma} + k^2\gamma = 0$  so the orientation of Mercury's longest axis points towards the Sun at the perihelion and librates with an angular frequency

$$k = \sqrt{\frac{21}{2}en^2 \left( \frac{B-A}{C} \right)} = n\sqrt{\frac{21}{2}e \left( \frac{B-A}{C} \right)}$$

To calculate, use  $e = 0.2056317$ . For  $\frac{B-A}{C}$  we have from [Mercury Main Librations Messenger] 0.0002206 (whereas from an earlier paper [Mercury Main librations] we have 0.00012)

$$k \approx n\sqrt{10.5 * 0.2056317 * 0.0002206} = n\sqrt{2.159 * 0.0002206} = 0.0218244n$$

So with  $T = \frac{2\pi}{n}$  the period of the librations compared to the orbital period  $T_M$  is

$$\frac{\frac{2\pi}{0.0218244n}}{\frac{2\pi}{n}} = \frac{1}{0.0218244} \approx 45.8202615T_M$$

Using  $T_M = 88$ , the libration period is

$$T_L (\text{days}) = 4032$$

$$T_L (\text{years}) = 11.04$$

If we were to take terms to  $O(e^3)$  in the calculation of  $c_{k=0}$  we would have  $\frac{7e}{2} - \frac{123e^3}{16} \approx 0.65286$  giving

$$k \approx n\sqrt{3 * 0.65286 * 0.0002206} = 0.020786n$$

$$T_L (\text{days}) = \frac{1}{0.020786}T_M = 48.1087T_M = 4233$$

$$T_L (\text{years}) = 11.59$$

### 5.3 Interpretation

$$\gamma = \phi - \frac{3}{2}M = A \sin kt$$

where

$$k \approx 0.0218244n$$

Note we assume  $A$  is small (i.e.  $\gamma$  is small) in order to go from  $\sin(2\gamma) \approx 2\gamma$  in the derivation in the above section.

At  $t = 0$ , if we stand at the pericentre of Mercury's orbit, i.e.  $M = 0$ , with our back to the Sun and look at a point on the equator of Mercury then  $\gamma = \phi = 0$  i.e. orientation of Mercury's longest axis points towards the Sun.

The next time Mercury reaches the pericentre is  $t = 1T_M = 88$  days. With  $T_M = \frac{2\pi}{n}$

$$\phi = A \sin kt = A \sin \left( 0.0218244n \left( 1 \frac{2\pi}{n} \right) \right) = 0.136697404A$$

Next occasion is  $t = 2T_M = 176$  days

$$\phi = A \sin kt = A \sin \left( 0.0218244n \left( 2 \frac{2\pi}{n} \right) \right) = 0.27082841A$$

When  $t = 11T_M = 968$  days it is starting to reach it's maximum displacement.

$$\phi = A \sin kt = A \sin \left( 0.0218244n \left( 11 \frac{2\pi}{n} \right) \right) = A \sin (1.508394244) \approx A \sin \frac{\pi}{2} = A$$

## A Asaph Hall Apsidal Precession derivation

Precession due to a force law differing slightly from Inverse-square (this was the hypothesis made by Asaph Hall in 1894). Derivation from [Newton Apsidal]

$$\frac{d^2 u}{d\lambda^2} + u = \eta u^\delta \quad (48)$$

Let the solution of the above be

$$u = c_h (1 + e \cos k_h \lambda) + \delta u' \quad (49)$$

where  $c_h$  is a constant and  $k_h$  represents a rotating ellipse. From [Newton Apsidal]

. Where  $e$  is larger, we cannot simply identify a rotating ellipse with the orbit of interest. Instead, we shall employ a rotating ellipse *plus* additional terms; this will allow for deformation of the shape as well as motion of the apse. The additional terms will be given by the perturbation  $\delta u'$ . We shall restrict this perturbation so as not to contain terms proportional to  $\cos \lambda \theta$ ; thus it will not be implicated in the determination of the constants of the rotating ellipse.

Substituting this into  $u^\delta$  and keeping  $O(\delta)$  only

$$u^\delta = c_h^\delta (1 + e \cos k_h \lambda)^\delta$$

$$\ln u^\delta = \ln c_h^\delta + \delta \ln (1 + e \cos k_h \lambda)$$

Taking exponential

$$u^\delta = c_h^\delta \exp(\delta \ln (1 + e \cos k_h \lambda))$$

Expanding exponential to  $O(\delta)$

$$u^\delta = c_h^\delta (1 + \delta \ln (1 + e \cos k_h \lambda))$$

Expanding the  $\ln$

$$u^\delta = c_h^\delta \left( 1 + \delta e \left( \cos k_h \lambda - \frac{e}{2} \cos^2 k_h \lambda + \frac{e^2}{3} \cos^3 k_h \lambda \right) \right)$$

Using the identities

$$\cos 2\theta = 2 \cos^2 \theta - 1 \implies \cos^2 k_h \lambda = \frac{1}{2} + \frac{1}{2} \cos 2k_h \lambda$$

$$\cos 3\theta = 4 \cos^3 \theta - 3 \cos \theta \implies \cos^3 k_h \lambda = \frac{3}{4} \cos k_h \lambda + \frac{1}{4} \cos 3k_h \lambda$$

We get

$$\begin{aligned} u^\delta &= c_h^\delta \left( 1 + \delta e \left( \cos k_h \lambda - \frac{e}{2} \left( \frac{1}{2} + \frac{1}{2} \cos 2k_h \lambda \right) + \frac{e^2}{3} \left( \frac{3}{4} \cos k_h \lambda + \frac{1}{4} \cos 3k_h \lambda \right) \right) \right) \\ u^\delta &= c_h^\delta \left( 1 + \delta e \left( -\frac{e}{4} + \cos k_h \lambda - \frac{e}{4} \cos 2k_h \lambda + \frac{e^2}{4} \cos k_h \lambda + \frac{e^2}{12} \cos 3k_h \lambda \right) \right) \\ u^\delta &= c_h^\delta \left( 1 + \delta e \left( -\frac{e}{4} + \left( 1 + \frac{e^2}{4} \right) \cos k_h \lambda - \frac{e}{4} \cos 2k_h \lambda + \frac{e^2}{12} \cos 3k_h \lambda \right) \right) \end{aligned} \quad (50)$$

Now insert 49 into the left side of 48

$$\begin{aligned} \delta \left( \frac{d^2 u'}{d\lambda^2} + u' \right) - c_h e k_h^2 \cos k_h \lambda + c_h + c_h e \cos k_h \lambda \\ \delta \left( \frac{d^2 u'}{d\lambda^2} + u' \right) + c_h + c_h e (1 - k_h^2) \cos k_h \lambda \end{aligned} \quad (51)$$

From 48 and using 51 and 50

$$\delta \left( \frac{d^2 u'}{d\lambda^2} + u' \right) + c_h + c_h e (1 - k_h^2) \cos k_h \lambda = \eta c_h^\delta \left( 1 + \delta e \left( -\frac{e}{4} + \left( 1 + \frac{e^2}{4} \right) \cos k_h \lambda - \frac{e}{4} \cos 2k_h \lambda + \frac{e^2}{12} \cos 3k_h \lambda \right) \right)$$

Equating constant terms

$$c_h = \eta c_h^\delta \left(1 - \frac{\delta e^2}{4}\right)$$

$$\eta c_h^{\delta-1} = \left(1 - \frac{\delta e^2}{4}\right)^{-1} \approx \left(1 + \frac{\delta e^2}{4}\right)$$

The coefficients of  $\cos k_h \lambda$  must also be equal so

$$c_h e (1 - k_h^2) = \eta c_h^\delta \delta e \left(1 + \frac{e^2}{4}\right)$$

$$1 - k_h^2 = \delta \eta c_h^{\delta-1} \left(1 + \frac{e^2}{4}\right)$$

$$1 - k_h^2 = \delta \left(1 + \frac{\delta e^2}{4}\right) \left(1 + \frac{e^2}{4}\right) \approx \delta \left(1 + \frac{e^2}{4}\right)$$

$$k_h = \left(1 - \delta \left(1 + \frac{e^2}{4}\right)\right)^{\frac{1}{2}}$$

$$k_h \approx 1 - \frac{\delta}{2} \left(1 + \frac{e^2}{4}\right)$$

The precession per orbit is

$$\Delta\lambda = \frac{2\pi}{k_h} = 2\pi \left(1 - \frac{\delta}{2} \left(1 + \frac{e^2}{4}\right)\right)^{-1} - 2\pi$$

$$\Delta\lambda \approx 2\pi \left(1 + \frac{\delta}{2} \left(1 + \frac{e^2}{4}\right)\right) - 2\pi$$

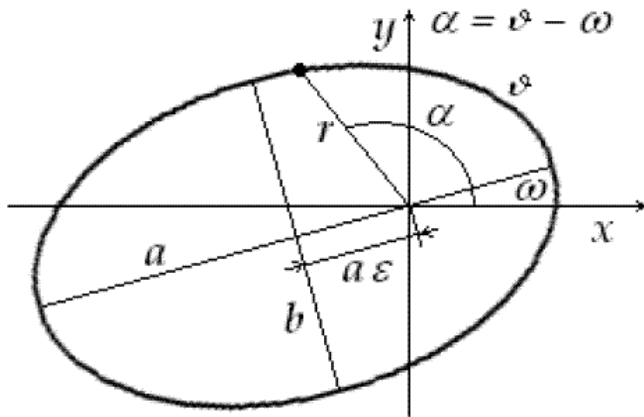
$$\Delta\lambda = \frac{2\pi}{k_h} = \delta\pi \left(1 + \frac{e^2}{4}\right)$$

so the precession increases as the eccentricity increases. The difference is small though in the case of Mercury.

## B Gerber's Theory

From [Gerber Theory]. (Still working through this)

The co-ordinate system is as below so we are initially dealing with  $\vartheta$  where  $\vartheta = \omega + \alpha$  (from [Gerber Coords]). To keep it consistent with this document I'll use  $f$  for the true anomaly rather than  $\alpha$ . So  $\vartheta = \omega + f$



Note the below refers to *radial* velocity  $v_r$ . I'm also using  $\mu = GM$  in the below. Gerber's gravitational Lagrangian potential is

$$S = \frac{\mu}{r \left(1 - \frac{v_r}{c}\right)^2}$$

binomially expand

$$S = \frac{\mu}{r} \left[ 1 + 2\frac{v_r}{c} + 3\left(\frac{v_r}{c}\right)^2 \right]$$

using Lagrangian formula for calculating acceleration

$$a = \frac{\partial S}{\partial r} - \frac{d}{dt} \frac{\partial S}{\partial v_r}$$

$$a = -\frac{\mu}{r^2} \left[ 1 + 2\frac{v_r}{c} + 3\left(\frac{v_r}{c}\right)^2 \right] - \mu \frac{d}{dt} \frac{1}{r} \left[ \frac{2}{c} + \frac{6v_r}{c^2} \right]$$

using  $\frac{d}{dt} = \frac{dr}{dt} \frac{d}{dr} + \frac{dv_r}{dt} \frac{d}{dv_r} = v_r \frac{d}{dr} + \dot{v}_r \frac{d}{dv_r}$  and

$$a = -\frac{\mu}{r^2} \left[ 1 + 2\frac{v_r}{c} + 3\left(\frac{v_r}{c}\right)^2 \right] - \mu \left( -\frac{v_r}{r^2} \right) \left[ \frac{2}{c} + \frac{6v_r}{c^2} \right] - \frac{\mu}{r} \dot{v}_r \left[ \frac{6}{c^2} \right]$$

$$a = -\frac{\mu}{r^2} \left[ 1 + 2\frac{v_r}{c} + 3\frac{v_r^2}{c^2} \right] + \frac{\mu}{r^2} \left[ \frac{2v_r}{c} + 6\frac{v_r^2}{c^2} - 6\frac{rv_r}{c^2} \right]$$

$$a = -\frac{\mu}{r^2} \left[ 1 - 3\frac{v_r^2}{c^2} + 6\frac{rv_r}{c^2} \right]$$

Aside: In deriving the above, the  $2\frac{v_r}{c}$  term in the binomial expansion (or more generally any  $O(v_r)$  term) doesn't contribute to the acceleration  $a$  as the terms cancel as in the above. So we could write Gerber Lagrangian potential as

$$S = \frac{\mu}{r} \left[ 1 + 3\left(\frac{v_r}{c}\right)^2 \right]$$

or Gerber potential energy

$$V = \frac{\mu}{r} \left[ 1 - 3\left(\frac{v_r}{c}\right)^2 \right]$$

This is similar in form the the Weber potential in electrodynamics 68.

Let

$$\Lambda(r, v_r, \dot{v}_r) = 3\frac{v_r^2}{c^2} - 6\frac{rv_r}{c^2} \quad (52)$$

$$a = \frac{d^2 r}{dt^2} = -\frac{\mu}{r^2} [1 - \Lambda] \quad (53)$$

$$\mathbf{a} = [-\mu(1 - \Lambda)] \frac{\mathbf{r}}{r^3} = [-\mu(1 - \Lambda)] \frac{(x\mathbf{i} + y\mathbf{j} + z\mathbf{k})}{r^3}$$

$$\frac{d^2 x}{dt^2} = -\frac{x\mu}{r^3} [1 - \Lambda]$$

$$\frac{d^2 y}{dt^2} = -\frac{y\mu}{r^3} [1 - \Lambda]$$

it follows (and this really is just conservation of angular momentum  $\frac{dL}{dt} = 0$  see below)

$$x \frac{d^2 y}{dt^2} - y \frac{d^2 x}{dt^2} = 0$$

using  $r^2 \frac{d\vartheta}{dt} = \frac{L}{m} \implies \frac{1}{r^2} = \frac{m}{L} \frac{d\vartheta}{dt}$  and  $\frac{x}{r} = \cos \vartheta$  and  $\frac{y}{r} = \sin \vartheta$ , we have

$$\frac{d^2 x}{dt^2} = -\frac{\mu m}{L} [1 - \Lambda] \cos \vartheta \frac{d\vartheta}{dt}$$

$$\frac{d^2 y}{dt^2} = -\frac{\mu m}{L} [1 - \Lambda] \sin \vartheta \frac{d\vartheta}{dt}$$

integrating, where  $M$  and  $N$  are constants, gives

$$\frac{dx}{dt} = -\frac{\mu m}{L} \sin \vartheta + \left( M + \int \frac{\mu m}{L} \Lambda \cos \vartheta d\vartheta \right)$$

$$\begin{aligned}\frac{dy}{dt} &= \frac{\mu m}{L} \cos \vartheta + \left( N + \int \frac{\mu m}{L} \Lambda \sin \vartheta d\vartheta \right) \\ y \frac{dx}{dt} &= -\frac{\mu m}{L} (r \sin \vartheta) \sin \vartheta + (r \sin \vartheta) \left( M + \int \frac{\mu m}{L} \Lambda \cos \vartheta d\vartheta \right) \\ x \frac{dy}{dt} &= \frac{\mu m}{L} (r \cos \vartheta) \cos \vartheta + (r \cos \vartheta) \left( N + \int \frac{\mu m}{L} \Lambda \sin \vartheta d\vartheta \right)\end{aligned}$$

from the angular momentum definition,  $\hat{L} = \hat{r} \times \hat{p}$ , we have  $L = m \left( x \frac{dy}{dt} - y \frac{dx}{dt} \right)$

$$\begin{aligned}L &= \frac{\mu m^2 r}{L} + (r \cos \vartheta) \left( N + \int \frac{\mu m^2}{L} \Lambda \sin \vartheta d\vartheta \right) - (r \sin \vartheta) \left( M + \int \frac{\mu m^2}{L} \Lambda \cos \vartheta d\vartheta \right) \\ L &= r \left[ \frac{\mu m^2}{L} + \left( N + \int \frac{\mu m^2}{L} \Lambda \sin \vartheta d\vartheta \right) \cos \vartheta - \left( M + \int \frac{\mu m^2}{L} \Lambda \cos \vartheta d\vartheta \right) \sin \vartheta \right] \\ r &= \frac{L}{\frac{\mu m^2}{L} + \left( N + \int \frac{\mu m^2}{L} \Lambda \sin \vartheta d\vartheta \right) \cos \vartheta - \left( M + \int \frac{\mu m^2}{L} \Lambda \cos \vartheta d\vartheta \right) \sin \vartheta}\end{aligned}\tag{54}$$

Assuming  $r$  is an ellipse, then at the pericentre  $\vartheta = \omega$  and  $r = a(1 - e)$ , at the apocentre  $\vartheta = \omega + \pi$  and  $r = a(1 + e)$  and when  $\vartheta = \omega + \frac{\pi}{2}$ ,  $r = a(1 - e^2) = \frac{b^2}{a}$ .

Abbreviating with  $(\int_{\sin \vartheta})$  and  $(\int_{\cos \vartheta})$  and using trigonometric identities we have

$$\begin{aligned}a(1 - e) &= \frac{L}{\frac{\mu m^2}{L} + (N + \int_{\sin \vartheta}) \cos \omega - (M + \int_{\cos \vartheta}) \sin \omega} \\ a(1 + e) &= \frac{L}{\frac{\mu m^2}{L} - (N + \int_{\sin \vartheta}) \cos \omega + (M + \int_{\cos \vartheta}) \sin \omega} \\ \frac{b^2}{a} &= \frac{L}{\frac{\mu m^2}{L} - (N + \int_{\sin \vartheta}) \sin \omega - (M + \int_{\cos \vartheta}) \cos \omega}\end{aligned}$$

giving

$$\frac{\mu m^2}{L} + \left( N + \int_{\sin \vartheta} \right) \cos \omega - \left( M + \int_{\cos \vartheta} \right) \sin \omega = \frac{L}{a(1 - e)}\tag{55}$$

$$\frac{\mu m^2}{L} - \left( N + \int_{\sin \vartheta} \right) \cos \omega + \left( M + \int_{\cos \vartheta} \right) \sin \omega = \frac{L}{a(1 + e)}\tag{56}$$

using  $\frac{1}{a(1 - e^2)} = \frac{a}{b^2} = \frac{\mu m^2}{L^2} \implies \frac{a}{b^2} L = \frac{\mu m^2}{L}$

$$\begin{aligned}\frac{\mu m^2}{L} - \left( N + \int_{\sin \vartheta} \right) \sin \omega - \left( M + \int_{\cos \vartheta} \right) \cos \omega &= \frac{a}{b^2} L \\ \left( N + \int_{\sin \vartheta} \right) \sin \omega &= - \left( M + \int_{\cos \vartheta} \right) \cos \omega\end{aligned}\tag{57}$$

To find  $L$  add 55 and 56

$$\frac{L}{a(1 - e)} + \frac{L}{a(1 + e)} = 2 \frac{\mu m^2}{L}$$

$$\frac{L(1 + e)}{a(1 - e^2)} + \frac{L(1 - e)}{a(1 - e^2)} = 2 \frac{\mu m^2}{L}$$

$$\frac{2L}{a(1 - e^2)} = 2 \frac{\mu m^2}{L}$$

$$L^2 = \mu m^2 a (1 - e^2)$$

$$L^2 = \mu m^2 \frac{b^2}{a}$$

$$\boxed{L = mb\sqrt{\frac{\mu}{a}}} \quad (58)$$

To find (...), multiply 55 by  $\sin \omega$

$$\frac{\mu m^2}{L} \sin \omega + \left( N + \int_{\sin \vartheta} \right) \cos \omega \sin \omega - \left( M + \int_{\cos \vartheta} \right) \sin^2 \omega = \frac{L}{a(1-e)} \sin \omega$$

using 57

$$\frac{\mu m^2}{L} \sin \omega - \left( M + \int_{\cos \vartheta} \right) \cos^2 \omega - \left( M + \int_{\cos \vartheta} \right) \sin^2 \omega = \frac{L}{a(1-e)} \sin \omega$$

$$\frac{\mu m^2}{L} \sin \omega - \left( M + \int_{\cos \vartheta} \right) = \frac{L}{a(1-e)} \sin \omega = \frac{L(1+e)}{a(1-e)(1+e)} \sin \omega = \frac{L(1+e)}{a(1-e^2)} \sin \omega = \frac{\mu m^2}{L} (1+e) \sin \omega$$

$$\left( M + \int_{\cos \vartheta} \right) = \frac{\mu m^2}{L} (1 - (1+e)) \sin \omega$$

$$\left( M + \int_{\cos \vartheta} \right) = -\frac{\mu m^2}{L} e \sin \omega$$

$$\boxed{M + \int \frac{\mu m^2}{L} \Lambda \cos \vartheta d\vartheta = -\frac{\mu m^2}{L} e \sin \omega}$$

using 57

$$\boxed{N + \int \frac{\mu m^2}{L} \Lambda \sin \vartheta d\vartheta = \frac{\mu m^2}{L} e \cos \omega}$$

From  $\frac{\mu m^2}{L^2} = \frac{a}{b^2} \implies L = mb\sqrt{\frac{\mu}{a}}$ . So  $\frac{\mu m^2}{L} = \frac{\mu m^2}{mb} \sqrt{\frac{a}{\mu}} = \frac{m}{b} \sqrt{a\mu}$

$$M + \int \frac{\mu m^2}{L} \Lambda \cos \vartheta d\vartheta = -\frac{me}{b} \sqrt{a\mu} \sin \omega$$

$$N + \int \frac{\mu m^2}{L} \Lambda \sin \vartheta d\vartheta = \frac{me}{b} \sqrt{a\mu} \cos \omega$$

In the case of  $\omega = 0$  as expected

$$r = \frac{L}{\frac{\mu m^2}{L} + \frac{\mu m^2}{L} e \cos f} = \frac{\frac{L^2}{\mu m^2}}{1 + e \cos f} = \frac{a(1-e^2)}{1 + e \cos f}$$

Taking the derivative wrt  $\vartheta$  in the above 2 equations and assuming both  $e$  and  $\omega$  have a dependency on  $\vartheta$  we have

$$\Lambda \cos \vartheta = \frac{dt}{d\vartheta} \frac{de}{dt} \frac{d}{de} (-e \sin \omega) + \frac{dt}{d\vartheta} \frac{d\omega}{dt} \frac{d}{d\omega} (-e \sin \omega)$$

$$\Lambda = -\frac{\sin \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{de}{dt} - \frac{e \cos \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt}$$

and

$$\Lambda \sin \vartheta = \frac{dt}{d\vartheta} \frac{de}{dt} \frac{d}{de} (e \cos \omega) + \frac{dt}{d\vartheta} \frac{d\omega}{dt} \frac{d}{d\omega} (e \cos \omega)$$

$$\Lambda = \frac{\cos \omega}{\sin \vartheta} \frac{dt}{d\vartheta} \frac{de}{dt} - \frac{e \sin \omega}{\sin \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt}$$

Setting the 2 sides equal

$$-\frac{\sin \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{de}{dt} - \frac{e \cos \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt} = \frac{\cos \omega}{\sin \vartheta} \frac{dt}{d\vartheta} \frac{de}{dt} - \frac{e \sin \omega}{\sin \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt}$$

$$-\frac{\sin \omega}{\cos \vartheta} \frac{de}{dt} - \frac{e \cos \omega}{\cos \vartheta} \frac{d\omega}{dt} = \frac{\cos \omega}{\sin \vartheta} \frac{de}{dt} - \frac{e \sin \omega}{\sin \vartheta} \frac{d\omega}{dt}$$



$$\left(-\frac{\sin \omega}{\cos \vartheta} - \frac{\cos \omega}{\sin \vartheta}\right) \frac{de}{dt} = -e \frac{d\omega}{dt} \left(\frac{\sin \omega}{\sin \vartheta} - \frac{\cos \omega}{\cos \vartheta}\right)$$

$$\begin{aligned} \frac{de}{dt} &= e \frac{d\omega}{dt} \left(\frac{\frac{\sin \omega}{\sin \vartheta} - \frac{\cos \omega}{\cos \vartheta}}{\left(\frac{\sin \omega}{\cos \vartheta} + \frac{\cos \omega}{\sin \vartheta}\right)}\right) \\ &= e \frac{d\omega}{dt} \frac{(\sin \omega \cos \vartheta - \cos \omega \sin \vartheta)}{(\sin \omega \sin \vartheta + \cos \omega \cos \vartheta)} \\ &= e \frac{d\omega}{dt} \frac{\sin(\omega - \vartheta)}{\cos(\omega - \vartheta)} \end{aligned}$$

$$\frac{de}{dt} = e \frac{d\omega}{dt} \tan(\omega - \vartheta)$$

$$\boxed{\frac{de}{dt} = -e \tan f \frac{d\omega}{dt}}$$

(The  $\tan f$  term looks problematic but in the calculation below we end up with  $\frac{d\omega}{dt}$  having cos terms which gets rid of the infinities - but I need to review this whole section)

Plugging this back into the formula for  $\Lambda$

$$\begin{aligned} \Lambda &= -\frac{\sin \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{de}{dt} - \frac{e \cos \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt} \\ \frac{de}{dt} &= -e \tan f \frac{d\omega}{dt} = -e \frac{d\omega}{dt} \tan(\vartheta - \omega) \\ \Lambda &= \frac{\sin \omega}{\cos \vartheta} \frac{dt}{d\vartheta} e \frac{1}{\cos f} \sin(\vartheta - \omega) \frac{d\omega}{dt} - e \frac{\cos \omega}{\cos \vartheta} \frac{dt}{d\vartheta} \frac{d\omega}{dt} \\ &= e \frac{dt}{d\vartheta} \frac{d\omega}{dt} \left(\frac{\sin \omega}{\cos \vartheta} \frac{1}{\cos f} \sin(\vartheta - \omega) - \frac{\cos \omega}{\cos \vartheta}\right) \\ &= e \frac{dt}{d\vartheta} \frac{d\omega}{dt} \left(\frac{\sin \omega}{\cos \vartheta} \frac{1}{\cos f} \sin(\vartheta - \omega) - \frac{\cos(\vartheta - \omega) \cos \omega}{\cos f \cos \vartheta}\right) \\ &= e \frac{dt}{d\vartheta} \frac{d\omega}{dt} \frac{1}{\cos f \cos \vartheta} (\sin \omega \sin(\vartheta - \omega) - \cos(\vartheta - \omega) \cos \omega) \\ &= e \frac{dt}{d\vartheta} \frac{d\omega}{dt} \frac{1}{\cos f \cos \vartheta} (-\cos \vartheta) \\ &\quad \boxed{\Lambda = -\frac{e}{\cos f} \frac{dt}{d\vartheta} \frac{d\omega}{dt}} \tag{59} \end{aligned}$$

From

$$r = \frac{b^2}{a(1 + e \cos f)}$$

$$\frac{dr}{dt} = \frac{\partial}{\partial e} \left(\frac{b^2}{a(1 + e \cos f)}\right) \frac{de}{dt} + \frac{\partial}{\partial f} \left(\frac{b^2}{a(1 + e \cos f)}\right) \frac{df}{dt}$$

$$\text{from } \left(\frac{f}{g}\right)' = \frac{f'g - fg'}{g^2} \text{ and } g = a(1 + e \cos f) = \frac{b^2}{r}$$

$$\begin{aligned} &= \left(\frac{-b^2 a \cos f}{\frac{b^4}{r^2}}\right) \frac{de}{dt} + \left(\frac{b^2 a e \sin f}{\frac{b^4}{r^2}}\right) \frac{df}{dt} \\ &= \frac{ar^2}{b^2} \left(-\cos f \frac{de}{dt} + e \sin f \frac{df}{dt}\right) \end{aligned}$$

from  $f = \vartheta - \omega$

$$= \frac{ar^2}{b^2} \left(-\cos f \frac{de}{dt} + e \sin f \frac{d\vartheta}{dt} - e \sin f \frac{d\omega}{dt}\right)$$

$$\begin{aligned}
&= \frac{ar^2}{b^2} \left( -\cos f \left( -e \tan f \frac{d\omega}{dt} \right) + e \sin f \frac{d\vartheta}{dt} - e \sin f \frac{d\omega}{dt} \right) \\
&= \frac{ar^2}{b^2} \left( e \sin f \frac{d\omega}{dt} + e \sin f \frac{d\vartheta}{dt} - e \sin f \frac{d\omega}{dt} \right) \\
&= e \frac{a}{b^2} \sin f \left( r^2 \frac{d\vartheta}{dt} \right) = e \frac{a}{b^2} \sin f (L) = e \frac{a}{b^2} \left( b \frac{\sqrt{\mu}}{\sqrt{a}} \right) \sin f \\
&\quad \boxed{\frac{dr}{dt} = e \frac{\sqrt{\mu a}}{b} \sin f} \tag{60}
\end{aligned}$$

$$\frac{d^2 r}{dt^2} = \left( \frac{\sqrt{\mu a}}{b} \sin f \right) \frac{de}{dt} + \left( e \frac{\sqrt{\mu a}}{b} \cos f \right) \frac{df}{dt}$$

using  $r^2 \frac{d\vartheta}{dt} = L$  and  $L = \frac{b\sqrt{\mu}}{\sqrt{a}}$  gives  $\frac{d\vartheta}{dt} = \frac{b\sqrt{\mu}}{r^2\sqrt{a}}$ .  
Also  $\vartheta = f + \omega$

$$\begin{aligned}
&= \left( \frac{\sqrt{\mu a}}{b} \sin f \right) \left( -e \tan f \frac{d\omega}{dt} \right) + \left( e \frac{\sqrt{\mu a}}{b} \cos f \right) \left( \frac{b\sqrt{\mu}}{r^2\sqrt{a}} - \frac{d\omega}{dt} \right) \\
&= \left( -e \frac{\sqrt{\mu a}}{b} \frac{\sin^2 f}{\cos f} - e \frac{\sqrt{\mu a}}{b} \cos f \right) \frac{d\omega}{dt} + \frac{e\mu}{r^2} \cos f \\
&\quad \boxed{\frac{d^2 r}{dt^2} = -e \frac{\sqrt{\mu a}}{b} \frac{1}{\cos f} \frac{d\omega}{dt} + \frac{e\mu}{r^2} \cos f} \tag{61}
\end{aligned}$$

Substituting 60 and 61 in 52

$$\begin{aligned}
\Lambda &= 3 \frac{v_r^2}{c^2} - 6 \frac{r \dot{v}_r}{c^2} \\
\Lambda &= \frac{3e^2 \mu a}{c^2 b^2} \sin^2 f + \frac{6er\sqrt{\mu a}}{c^2 b \cos f} \frac{d\omega}{dt} - \frac{6e\mu}{c^2 r} \cos f \tag{62}
\end{aligned}$$

Equating 59 and 62

$$\begin{aligned}
\frac{e}{\cos f} \frac{dt}{d\vartheta} \frac{d\omega}{dt} &= -\frac{3e^2 \mu a}{b^2 c^2} \sin^2 f - \frac{6er\sqrt{\mu a}}{bc^2 \cos f} \frac{d\omega}{dt} + \frac{6e\mu}{rc^2} \cos f \\
\frac{d\theta}{dt} = \frac{d(f+\omega)}{dt} &\implies \frac{dt}{d\theta} = \frac{dt}{df+d\omega} = \frac{\frac{dt}{df}}{1+\frac{d\omega}{df}} \approx \frac{dt}{df} \left( 1 - \frac{d\omega}{df} \right) \\
\text{using } \frac{df}{dt} &= \frac{b\sqrt{\mu}}{r^2\sqrt{a}} \text{ and approximating } \frac{dt}{d\vartheta} \text{ with } \frac{dt}{df} \text{ as we have a } \frac{d\omega}{df} \frac{d\omega}{dt} \text{ term.}
\end{aligned}$$

$$\frac{er^2\sqrt{a}}{b\sqrt{\mu}\cos f} \frac{d\omega}{dt} = -\frac{3e^2\mu a}{b^2c^2} \sin^2 f - \frac{6er\sqrt{\mu a}}{bc^2 \cos f} \frac{d\omega}{dt} + \frac{6e\mu}{rc^2} \cos f$$

multiply through by  $\frac{b\sqrt{\mu}\cos f}{er^2\sqrt{a}}$

$$\boxed{\frac{d\omega}{dt} = -\frac{3\sqrt{a}\mu^{\frac{3}{2}}}{r^2c^2b} e \sin^2 f \cos f - \frac{6\mu}{rc^2} \frac{d\omega}{dt} + \frac{6\mu^{\frac{3}{2}}b}{r^3c^2\sqrt{a}} \cos^2 f} \tag{63}$$

multiply by  $\frac{c^2}{3\mu}$

$$\frac{c^2}{3\mu} \frac{d\omega}{dt} = -\frac{\sqrt{a}\mu^{\frac{1}{2}}}{r^2b} e \sin^2 f \cos f - \frac{2}{r} \frac{d\omega}{dt} + \frac{2\mu^{\frac{1}{2}}b}{r^3\sqrt{a}} \cos^2 f$$

Check terms with Gerber paper

Check 1st term

$$\begin{aligned}
-\frac{3\sqrt{a}\mu^{\frac{3}{2}}}{r^2c^2b} e \sin^2 f \cos f &= -\frac{3\mu^{\frac{3}{2}}}{c^2} e \sin^2 f \cos f \frac{\sqrt{a}}{r^2b} = -\frac{3\mu^{\frac{3}{2}}}{c^2} e \sin^2 f \cos f \frac{\sqrt{a}}{b} \frac{a^2 (1+e \cos f)^2}{b^4} \\
-\frac{3\mu^{\frac{3}{2}}}{c^2} e \sin^2 f \cos f (1+e \cos f)^2 \frac{\sqrt{a}}{a^3} \frac{a^5}{b^5} &= -\frac{3\mu^{\frac{3}{2}}}{c^2} e \sin^2 f \cos f (1+e \cos f)^2 \frac{1}{a^{\frac{5}{2}} (1-e^2)^{\frac{5}{2}}}
\end{aligned}$$

$$= -\frac{3e\mu^{\frac{3}{2}}}{a^{\frac{5}{2}}(1-e^2)^{\frac{5}{2}}c^2}(1+e\cos f)^2\sin^2 f\cos f$$

Check 2nd term

$$-\frac{6\mu}{rc^2}\frac{d\omega}{dt} = -\frac{6\mu}{c^2}\frac{d\omega}{dt}\frac{a(1+e\cos f)}{b^2} = -\frac{6\mu}{c^2}\frac{d\omega}{dt}\frac{a(1+e\cos f)}{a^2(1-e^2)} = -\frac{6\mu}{a(1-e^2)c^2}(1+e\cos f)\frac{d\omega}{dt}$$

Check 3rd term

$$\begin{aligned} & +\frac{6\mu^{\frac{3}{2}}b}{r^3c^2\sqrt{a}}\cos^2 f = \frac{6\mu^{\frac{3}{2}}}{c^2}\cos^2 f \left[ \frac{a^3(1+e\cos f)^3}{b^6}\frac{b}{\sqrt{a}} \right] \\ & = \frac{6\mu^{\frac{3}{2}}}{c^2}\cos^2 f(1+e\cos f)^3 \left[ \frac{a^5}{b^5}\frac{1}{a^2}\frac{1}{\sqrt{a}} \right] = \frac{6\mu^{\frac{3}{2}}}{c^2}\cos^2 f(1+e\cos f)^3 \left[ \frac{1}{(1-e^2)^{\frac{5}{2}}}\frac{1}{a^{\frac{5}{2}}} \right] \\ & = \frac{6\mu^{\frac{3}{2}}}{a^{\frac{5}{2}}(1-e^2)^{\frac{5}{2}}c^2}(1+e\cos f)^3\cos^2 f \end{aligned}$$

Back to

$$\frac{c^2}{3\mu}\frac{d\omega}{dt} = -\frac{\sqrt{a}\mu^{\frac{1}{2}}}{r^2b}e\sin^2 f\cos f - \frac{2}{r}\frac{d\omega}{dt} + \frac{2\mu^{\frac{1}{2}}b}{r^3\sqrt{a}}\cos^2 f$$

From  $\frac{b^2}{a} = a(1-e^2)$  and  $\frac{1}{r} = \frac{(1+e\cos f)}{a(1-e^2)}$  we have  $\frac{1}{r} = \frac{a(1+e\cos f)}{b^2}$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{dt} = -\left( \frac{a}{b^2} \right)^{\frac{1}{2}} \left( \frac{a}{b^2} \right)^2 (1+e\cos f)^2 \mu^{\frac{1}{2}} e \sin^2 f \cos f + 2\mu^{\frac{1}{2}} \left( \frac{a}{b^2} \right)^{-\frac{1}{2}} \left( \frac{a}{b^2} \right)^3 (1+e\cos f)^3 \cos^2 f$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{dt} = -\left( \frac{a}{b^2} \right)^{\frac{5}{2}} (1+e\cos f)^2 \mu^{\frac{1}{2}} [e \sin^2 f \cos f - 2(1+e\cos f) \cos^2 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{dt} = -\left( \frac{a}{b^2} \right)^{\frac{5}{2}} (1+e\cos f)^2 \mu^{\frac{1}{2}} [e(1-\cos^2 f) \cos f - 2\cos^2 f - 2e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{dt} = -\left( \frac{a}{b^2} \right)^{\frac{5}{2}} (1+e\cos f)^2 \mu^{\frac{1}{2}} [e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

Using  $n = \sqrt{\frac{\mu}{a^3}} \Rightarrow na^{\frac{3}{2}} = \mu^{\frac{1}{2}}$  and  $\frac{df}{dM} = (1-e^2)^{\frac{1}{2}} \left( \frac{a}{r} \right)^2 =$

$$\frac{d\omega}{dt} = \frac{d\omega}{df} \frac{df}{dM} \frac{dM}{dt} = \frac{d\omega}{df} (1-e^2)^{\frac{1}{2}} a^2 \left( \frac{a}{b^2} (1+e\cos f) \right)^2 n$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{df} (1-e^2)^{\frac{1}{2}} \left( \frac{a}{b} \right)^4 (1+e\cos f)^2 n = -\left( \frac{a}{b^2} \right)^{\frac{5}{2}} (1+e\cos f)^2 \mu^{\frac{1}{2}} [e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{df} \frac{b}{a} \frac{1}{b^4} (a)^{\frac{8}{3}} n = -\frac{1}{b^5} (a)^{\frac{5}{2}} \mu^{\frac{1}{2}} [e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{df} \frac{b^2}{a} a^{\frac{3}{2}} n = -\mu^{\frac{1}{2}} [e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{df} \frac{b^2}{a} \mu^{\frac{1}{2}} = -\mu^{\frac{1}{2}} [e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} + \frac{2a(1+e\cos f)}{b^2} \right) \frac{d\omega}{df} \frac{b^2}{a} = -[e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} \frac{b^2}{a} + 2(1+e\cos f) \right) \frac{d\omega}{df} = -[e \cos f - 2\cos^2 f - 3e\cos^3 f]$$

$$\left( \frac{c^2}{3\mu} a (1 - e^2) + 2 (1 + e \cos f) \right) \frac{d\omega}{df} = - [e \cos f - 2 \cos^2 f - 3e \cos^3 f]$$

If  $\Upsilon = \frac{3\mu}{a(1-e^2)}$  then

$$\left( \frac{c^2}{\Upsilon} + 2 (1 + e \cos f) \right) \frac{d\omega}{df} = - [e \cos f - 2 \cos^2 f - 3e \cos^3 f]$$

$$\boxed{\frac{d\omega}{df} = \frac{-e \cos f + 2 \cos^2 f + 3e \cos^3 f}{\frac{c^2}{\Upsilon} + (2 + 2e \cos f)}} \quad (64)$$

This isn't quite what Gerber has in [Gerber Theory] but it's close enough. If we integrate over  $[0, 2\pi]$  and just keep the dominant  $\frac{c^2}{\Upsilon}$  term in the denominator we get

$$\begin{aligned} \Delta\omega &= \frac{\Upsilon}{c^2} \left( \int_0^{2\pi} (-e \cos f + 2 \cos^2 f + 3e \cos^3 f) df \right) \\ &= \frac{\Upsilon}{c^2} 2\pi \end{aligned}$$

$$\boxed{\Psi \approx \frac{6\pi\mu}{c^2 a (1 - e^2)}}$$

## B.1 Mercury Radial Velocity

$$\begin{aligned} \frac{dr}{dt} &= \frac{dr}{du} \frac{du}{d\lambda} \frac{d\lambda}{dt} \\ &= -r^2 \cdot (-\eta e \sin \lambda) \cdot \frac{L}{mr^2} = \frac{\eta e L}{m} \sin \lambda \end{aligned}$$

The maximum radial velocity of Mercury is at  $\lambda = \frac{\pi}{2}$

$$\frac{dr}{dt} = \frac{\eta e L}{m}$$

$$\begin{aligned} \left( \frac{dr}{dt} \right)^2 &= \eta^2 \frac{e^2}{m^2} L^2 = \frac{1}{[a(1-e^2)]^2} \frac{e^2}{m^2} [\mu m^2 a (1-e^2)] \\ \left( \frac{dr}{dt} \right)^2 &= \frac{\mu e^2}{a(1-e^2)} \end{aligned}$$

using 4.11

$$\frac{dr}{dt} = \sqrt{\frac{\mu e^2}{a(1-e^2)}} = 10.05 \text{ km/sec}$$

As a comparison, Mercury's orbital speed is about 50 km/sec.

## B.2 Background

Still working through my thoughts on this. Gerber's potential formula is an interesting historical footnote. I haven't fully understood the reasoning behind it.

### B.2.1 Lagrangian Mechanics Review

To arrive at the equations of motion, the aim is to minimise the action  $L = T - V$  over a time interval. For more detail see [Kibble]. The below can be extended from Cartesian coordinates  $(x, y, z)$  to generalised coordinates  $q_i$  (e.g.  $r, \theta, \phi$ ) but I'll stay with just the  $x$  component of Cartesian coordinates in the below.

$$I = \int_{t_0}^{t_1} L dt$$

The position, velocity and therefore the kinetic energy is a function of time  $T(t) = \frac{1}{2}mv^2$ . The  $x$  component of this is  $T_x = \frac{1}{2}mv_x^2$ . So considering just  $T_x(t)$ , the integral below is basically summing the area under the kinetic energy curve  $T_x$  over a time interval  $[t_0, t_1]$ .

$$I = \int_{t_0}^{t_1} T_x(t) dt$$

If we make a small change  $\delta x(t)$  to  $x(t)$  in the interval  $[t_0, t_1]$  then we are going to change the kinetic energy  $T_x$ . Using  $\dot{x}$  for  $v_x$  we have a new kinetic energy curve  $T_x + \delta T_x = T_x + m\dot{x}\delta\dot{x}$ .

$$\delta I = \int_{t_0}^{t_1} m\dot{x}\delta\dot{x} dt$$

We can integrate by parts  $\int u dv = uv - \int v du$

$$\delta I = \int_{t_0}^{t_1} m\dot{x}\delta\dot{x} dt = m \left[ \dot{x}\delta x \Big|_{t_0}^{t_1} - \int_{t_0}^{t_1} \ddot{x}\delta x \right] dt$$

If we make a condition that  $\delta x(t_0) = \delta x(t_1) = 0$  then the first integrated term vanishes and

$$\delta I = - \int_{t_0}^{t_1} m\ddot{x}\delta x dt$$

So the integrand is the work done  $\delta W$  in the  $x$  direction i.e.  $\delta W = F_x \delta x$

$$\delta I = - \int_{t_0}^{t_1} F_x \delta x dt \tag{65}$$

On the other hand, assuming  $T(x, \dot{x})$ , the calculus of variations gives the change in  $I = \int T dt$  for a small change  $\delta x$

$$\delta I = \int_{t_0}^{t_1} \left[ \frac{\partial T}{\partial x} - \frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) \right] \delta x(t) dt \tag{66}$$

Equating 65 and 66 we have

$$\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) - \frac{\partial T}{\partial x} = F_x$$

If  $F_x$  can be written as  $F_x = \frac{d}{dt} \left( \frac{\partial V}{\partial \dot{x}} \right) - \frac{\partial V}{\partial x}$  then we can say

$$\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) - \frac{\partial T}{\partial x} = \frac{d}{dt} \left( \frac{\partial V}{\partial \dot{x}} \right) - \frac{\partial V}{\partial x}$$

or

$$\frac{\partial (T - V)}{\partial x} - \frac{d}{dt} \left( \frac{\partial (T - V)}{\partial \dot{x}} \right) = 0$$

$$\frac{\partial L}{\partial x} - \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) = 0$$

(In the case  $V$  is conservative and only depends on  $x$  this would become  $\frac{\partial T}{\partial x} - \frac{d}{dt} \frac{\partial T}{\partial \dot{x}} = \frac{\partial V}{\partial x}$ ).

This can be extended from a co-ordinate system  $\{x, y, z\}$  to generalised co-ordinates (i.e. generalised momentum - the bit in brackets  $\frac{d}{dt}(\dots)$  - and generalised forces) i.e.

$$\frac{\partial L}{\partial q_i} - \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) = 0 \quad (67)$$

i.e. instead of using Cartesian co-ordinates  $q_i = \{x, y, z\}$  we can use curvilinear co-ordinates e.g.  $\{r, \theta, \phi\}$  and if we express the Lagrangian in terms of these co-ordinates then 67 still holds. For co-ordinate system  $\{r, \theta, \phi\}$ ,  $q_1 = r, q_2 = \theta, q_3 = \phi$ . For a central force only  $r$  needs be considered i.e.  $q_1 = r, \dot{q}_1 = v_r$ .

In Gerber's theory, the potential has a velocity dependency on  $v_r$ . So he assumes that the force can be expressed as  $F = \frac{d}{dt} \left( \frac{\partial V}{\partial v_r} \right) - \frac{\partial V}{\partial r}$ .

### B.2.2 Velocity Dependent Forces

Other examples of velocity dependent forces are

1. The non-conservative friction force  $F \propto v$ .
2. The Lorentz force  $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$  is an example of a force which is velocity dependent and can be expressed in Lagrangian form i.e.  $F_i = \frac{d}{dt} \left( \frac{\partial V}{\partial \dot{q}_i} \right) - \frac{\partial V}{\partial q_i}$ . The potential  $V$  is  $V = q\phi(r, t) - q\mathbf{v} \cdot \mathbf{A}(r, t)$ .  $\phi$  is the scalar electrostatic potential.  $\mathbf{A}$  is the magnetic vector potential such that  $\mathbf{B} = \nabla \times \mathbf{A}$  and  $\mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}$ . This force is perpendicular to the velocity so does no work.

### B.3 Weber Electrodynamics

There are also velocity and acceleration dependent forces attempts in electromagnetism. Weber's formulation of force between charges can be derived from a potential [Weber's. Electrodynamics]. (See also [Ampere's Force] and [Kirk - Hall Effect]). For generality let's introduce a constant  $k$  which for the Weber case we will later put  $k = 1$ .

$$V = \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}} \left( 1 - k \frac{\dot{r}_{ij}^2}{2c^2} \right) \quad (68)$$

$$V_{k=1} = \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}} \left( 1 - \frac{\dot{r}_{ij}^2}{2c^2} \right) \quad (69)$$

This gives, using  $\frac{d}{dr}(\dot{r}_{ij}^2) = 2\dot{r}_{ij} \frac{dr_{ij}}{dr} = 2\dot{r}_{ij} \frac{dr_{ij}}{dt} \frac{dt}{dr} = 2\ddot{r}_{ij}$

$$\begin{aligned} F &= -\frac{dV}{dr} = -\frac{q_i q_j}{4\pi\epsilon_0} \left[ -\frac{1}{r_{ij}^2} \left( 1 - k \frac{\dot{r}_{ij}^2}{2c^2} \right) + \frac{1}{r_{ij}} k \left( -\frac{2\ddot{r}_{ij}}{2c^2} \right) \right] \\ &= -\frac{q_i q_j}{4\pi\epsilon_0} \left[ -\frac{1}{r_{ij}^2} \left( 1 - k \frac{\dot{r}_{ij}^2}{2c^2} \right) - \frac{1}{r_{ij}^2} k \left( \frac{r_{ij} \ddot{r}_{ij}}{c^2} \right) \right] \\ &= \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}^2} \left[ 1 - k \frac{\dot{r}_{ij}^2}{2c^2} + k \frac{r_{ij} \ddot{r}_{ij}}{c^2} \right] \end{aligned}$$

In the case  $k = 1$

$$F = \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}^2} \left[ 1 - \frac{\dot{r}_{ij}^2}{2c^2} + \frac{r_{ij} \ddot{r}_{ij}}{c^2} \right] \quad (70)$$

Note that this potential conserves energy because if we have

$$\begin{aligned} T &= \frac{1}{2} m_i \dot{r}_i^2 + \frac{1}{2} m_j \dot{r}_j^2 \\ \frac{dT}{dt} &= \dot{r}_i m_i \ddot{r}_i + \dot{r}_j m_j \ddot{r}_j \end{aligned}$$

The force  $m\ddot{r}$  is the same on both charges and in opposite directions

$$\frac{dT}{dt} = F_{ij} (\dot{r}_j - \dot{r}_i) = F_{ij} \dot{r}_{ij}$$

$$\begin{aligned}\frac{dV}{dt} &= \frac{q_i q_j}{4\pi\epsilon_0} \left[ -\frac{1}{r_{ij}^2} \dot{r}_{ij} \left( 1 - k \frac{\dot{r}_{ij}^2}{2c^2} \right) + \frac{1}{r_{ij}} k \left( \frac{\dot{r}_{ij} \ddot{r}_{ij}}{c^2} \right) \right] \\ &= -\frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}^2} \dot{r}_{ij} \left[ 1 - k \frac{\dot{r}_{ij}^2}{2c^2} + k \frac{\dot{r}_{ij} \ddot{r}_{ij}}{c^2} \right]\end{aligned}$$

from 70 ( $k = 1$  but more generally for any  $k$ )

$$\frac{dV}{dt} = -\dot{r}_{ij} F_{ij}$$

so

$$\frac{dT}{dt} - \frac{dV}{dt} = 0$$

Comparing Weber and Gerber potentials we have

$$V = \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}} \left( 1 - \frac{\dot{r}_{ij}^2}{2c^2} \right)$$

and

$$V = \frac{\mu}{r} \left[ 1 - 3 \left( \frac{v_r}{c} \right)^2 \right]$$

Comparing Weber and Gerber forces we have

$$F = \frac{q_i q_j}{4\pi\epsilon_0} \frac{1}{r_{ij}^2} \left[ 1 - \frac{\dot{r}_{ij}^2}{2c^2} + \frac{\dot{r}_{ij} \ddot{r}_{ij}}{c^2} \right]$$

and

$$F = -\frac{\mu m}{r^2} \left[ 1 - 6 \frac{v_r^2}{2c^2} + 6 \frac{r \dot{v}_r}{c^2} \right]$$

## C Energy in an Elliptic Orbit

From [Newtonian Mechanics]. Note for this section, we are switching to Physics notation for potential energy.

The energy in the orbit is constant so let us evaluate it at the apocentre  $r_{max} = a(1+e)$ .

The potential energy is straightforward.

$$U(r_{max}) = -\frac{GMm}{a(1+e)}$$

At the apocentre, the kinetic energy is purely tangential

$$K(r_{max}) = \frac{1}{2} m v_\theta^2 = \frac{1}{2} m r^2 \left( \frac{d\theta}{dt} \right)^2 \quad (71)$$

From Kepler's 2nd law, the satellite sweeps out equal areas in equal time. So we have for an ellipse

$$\frac{dA}{dt} = \frac{\pi ab}{T}$$

$$\left( \frac{dA}{dt} \right)^2 = \frac{\pi^2 a^2 b^2}{T^2}$$

Using Kepler's 3rd law  $T^2 = \frac{4\pi^2 a^3}{GM}$  and the definition of eccentricity  $e = \sqrt{1 - \frac{b^2}{a^2}}$

$$\left( \frac{dA}{dt} \right)^2 = \frac{\pi^2 a^2 b^2}{4\pi^2 a^3} GM = \frac{1}{4} GM \frac{b^2}{a}$$

$$\left( \frac{dA}{dt} \right)^2 = \frac{1}{4} GM a (1 - e^2) \quad (72)$$

However from geometry we have

$$\frac{dA}{dt} = \frac{1}{2}r^2 \frac{d\theta}{dt}$$

$$\left(\frac{dA}{dt}\right)^2 = \frac{1}{4}r^4 \left(\frac{d\theta}{dt}\right)^2$$

therefore

$$r^2 \left(\frac{d\theta}{dt}\right)^2 = \frac{4}{r^2} \left(\frac{dA}{dt}\right)^2$$

Plugging this into 71

$$K(r_{max}) = \frac{1}{2}mr^2 \left(\frac{d\theta}{dt}\right)^2 = \frac{1}{2}m \left(\frac{4}{r^2} \left(\frac{dA}{dt}\right)^2\right) = \frac{2m}{r^2} \left(\frac{dA}{dt}\right)^2$$

and using 72

$$K(r_{max}) = \frac{2m}{r^2} \left(\frac{1}{4}GMa(1-e^2)\right) = \frac{m}{2r^2} (GMa(1-e^2))$$

which at the apocentre gives

$$K(r_{max}) = \frac{GMma(1-e^2)}{2a^2(1+e)^2} = \frac{GMm(1-e)}{2a(1+e)}$$

The total energy is therefore

$$\begin{aligned} E &= K(r_{max}) + U(r_{max}) = \frac{GMm(1-e)}{2a(1+e)} - \frac{GMm}{a(1+e)} \\ &= \frac{GMm(1-e) - 2GMm}{2a(1+e)} = \frac{GMm(-1-e)}{2a(1+e)} = -\frac{GMm}{2a} \\ E &= -\frac{GMm}{2a} \end{aligned} \tag{73}$$

Note I could have got to this much quicker by using  $v_\theta = \frac{L}{mr}$  (e.g. 76).

### C.1 Orbital Velocity

From 73 we can calculate the orbital velocity

$$E = T + V$$

$$\begin{aligned} -\frac{GMm}{2a} &= \frac{1}{2}mv^2 - \frac{GMm}{r} \\ \frac{1}{2}mv^2 &= GMm \left(\frac{1}{r} - \frac{1}{2a}\right) \\ v &= \sqrt{GM \left(\frac{2}{r} - \frac{1}{a}\right)} \end{aligned}$$

## D Centrifugal Force/Radial Acceleration

In polar coordinates we have

$$\mathbf{r} = r\mathbf{e}_r$$

Using  $\frac{d\mathbf{e}_r}{dt} = \frac{d\lambda}{dt}\mathbf{e}_\lambda$  and  $\frac{d\mathbf{e}_\lambda}{dt} = -\frac{d\lambda}{dt}\mathbf{e}_r$

$$\begin{aligned} \mathbf{v} &= \frac{d\mathbf{r}}{dt} = \frac{dr}{dt}\mathbf{e}_r + r\frac{d\mathbf{e}_r}{dt} \\ \mathbf{v} &= \frac{dr}{dt}\mathbf{e}_r + r\frac{d\lambda}{dt}\mathbf{e}_\lambda \end{aligned} \tag{74}$$



To get acceleration

$$\begin{aligned}
\mathbf{a} &= \frac{d\mathbf{v}}{dt} = \frac{d^2r}{dt^2} \mathbf{e}_r + \frac{dr}{dt} \frac{d}{dt} \mathbf{e}_r + \frac{dr}{dt} \frac{d\lambda}{dt} \mathbf{e}_\lambda + r \frac{d^2\lambda}{dt^2} \mathbf{e}_\lambda + r \frac{d\lambda}{dt} \frac{d}{dt} \mathbf{e}_\lambda \\
\mathbf{a} &= \frac{d^2r}{dt^2} \mathbf{e}_r + \frac{dr}{dt} \frac{d\lambda}{dt} \mathbf{e}_\lambda + \frac{dr}{dt} \frac{d\lambda}{dt} \mathbf{e}_\lambda + r \frac{d^2\lambda}{dt^2} \mathbf{e}_\lambda - r \frac{d\lambda}{dt} \frac{d\lambda}{dt} \mathbf{e}_r \\
\mathbf{a} &= \left[ \frac{d^2r}{dt^2} - r \left( \frac{d\lambda}{dt} \right)^2 \right] \mathbf{e}_r + \left[ r \frac{d^2\lambda}{dt^2} + 2 \frac{dr}{dt} \frac{d\lambda}{dt} \right] \mathbf{e}_\lambda
\end{aligned} \tag{75}$$

Note e.g. the extra  $\frac{dr}{dt} \frac{d\lambda}{dt}$  term in 75 than we might have expected from just  $\frac{d}{dt} (r \frac{d\lambda}{dt} \mathbf{e}_\lambda)$  in 74.

All the above is general so far. If we now assume a *central* force is causing the acceleration, then there is no  $\mathbf{e}_\lambda$  acceleration. This means

$$r \frac{d^2\lambda}{dt^2} + 2 \frac{dr}{dt} \frac{d\lambda}{dt} = 0$$

and leads to the following (true for *any* central force)

$$\frac{dA}{dt} = \frac{1}{2} r^2 \frac{d\lambda}{dt} = \frac{L}{2m} = \text{constant} \tag{76}$$

The radial acceleration is given by

$$a_r = \frac{d^2r}{dt^2} - r \left( \frac{d\lambda}{dt} \right)^2$$

Let us now assume that the acceleration is due to the inverse square law.

$$\begin{aligned}
a_r &= \frac{d^2r}{dt^2} - r \left( \frac{d\lambda}{dt} \right)^2 = -\frac{GM}{r^2} \\
\frac{d^2r}{dt^2} &= -\frac{GM}{r^2} + r \left( \frac{d\lambda}{dt} \right)^2
\end{aligned}$$

## D.1 The case where $\lambda$ doesn't change

$\frac{d\lambda}{dt} = 0$ , there is no angular motion and the satellite accelerates straight towards the centre as expected i.e.

$$\frac{d^2r}{dt^2} = -\frac{GM}{r^2}$$

## D.2 The case in the orbit where $r \left( \frac{d\lambda}{dt} \right)^2 = \frac{GM}{r^2}$

In this case we have a situation almost like  $r \left( \frac{d\lambda}{dt} \right)^2$  is an equal and opposite force to  $-\frac{GM}{r^2}$  and there is no acceleration i.e.

$$\frac{d^2r}{dt^2} = 0$$

Note that for a central force we have, from 76,  $\frac{d\lambda}{dt} = \frac{L}{mr^2}$

$$r \frac{L^2}{m^2 r^4} = \frac{GM}{r^2}$$

$$\frac{1}{r} = \frac{GMm^2}{L^2} = \eta = \frac{1}{a(1-e^2)}$$

i.e. at  $r = a(1-e^2)$  (the semi-latus rectum - the radius at  $\lambda = \pm 90^\circ$ ),  $r \left( \frac{d\lambda}{dt} \right)^2 = \frac{GM}{r^2}$ .

$\frac{dr}{dt}$  at the semi-latus rectum is constant (note not zero) so  $\frac{d^2r}{dt^2} = \frac{d}{dt} \frac{dr}{dt} = \frac{dv}{dt} = 0$ . At this  $r$ , the centrifugal force matches the gravitational attraction no matter what the  $e$  is.

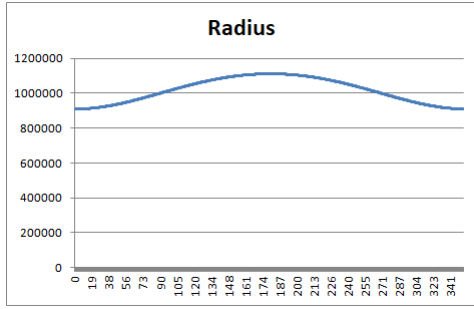
$\frac{d^2r}{dt^2} = 0$  at  $\lambda = \pm 90^\circ$  also follows by just taking the time derivatives of  $\frac{1}{r} = u = \eta(1 + e \cos \lambda)$  and using  $\frac{d\lambda}{dt} = \frac{L}{mr^2}$ .

In the case  $e = 0$ , we have  $r = a$  i.e. circular motion.

The following graphs demonstrate how  $r$  changes.

Aside - In Excel, I've used  $e = 0.1$  and  $\eta = 0.000001$  (i.e.  $\frac{1}{r} = u = 0.000001(1 + 0.1 \cos \lambda)$ ) and used  $\lambda \approx M + (2e - \frac{1}{4}e^3) \sin M + \frac{5}{4}e^2 \sin 2M + \frac{13}{12}e^3 \sin 3M$ . Then at intervals of  $M$  of 0.0048, calculate  $\frac{1}{r}$ . Then just take the step change in  $r$  to approximate  $v$ , and likewise take the step change in  $v$  to approximate  $a$ .

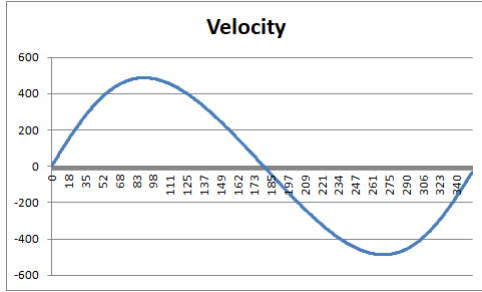
1) Radius - as expected it has it's minimum at  $\lambda = 0$  and it's maximum at  $\lambda = 180^\circ$



2) Velocity - as expected there is no radial velocity at  $\lambda = 0$  and  $\lambda = 180^\circ$  (pericentre and apocentre).

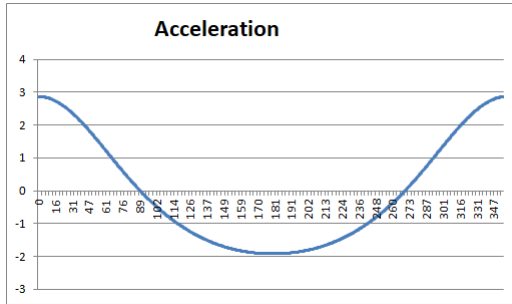
The maximum radial velocity is at  $\lambda = 90^\circ$  i.e. the satellite is moving away from the central body at it's fastest rate.

The minimum radial velocity is at  $\lambda = 270^\circ$  i.e. the satellite is moving towards the central body at it's fastest rate.



3) Acceleration - the maximum radial acceleration is at the pericentre  $\lambda = 0^\circ$  and the minimum acceleration is at the apocentre  $\lambda = 180^\circ$ .

There is zero radial acceleration at  $\lambda = 90^\circ$  and  $\lambda = 270^\circ$ . At this point the gravitational force and the centrifugal force cancel.



## E True to Eccentric Anomaly

For this section, I'll use  $e$  instead of  $\exp$  as there is no confusing  $e$  with eccentricity.

$$e^{i\theta} = \cos \theta + i \sin \theta$$

$$\sin \theta = \frac{e^{i\theta} - e^{-i\theta}}{2i}$$

$$\cos \theta = \frac{e^{i\theta} + e^{-i\theta}}{2}$$

$$\tan \frac{\theta}{2} = \frac{\sin \frac{\theta}{2}}{\cos \frac{\theta}{2}}$$

$$\tan \frac{\theta}{2} = \frac{e^{\frac{i\theta}{2}} - e^{-\frac{i\theta}{2}}}{i(e^{\frac{i\theta}{2}} + e^{-\frac{i\theta}{2}})}$$

times through by  $e^{\frac{i\theta}{2}}$

$$\tan \frac{\theta}{2} = \frac{e^{i\theta} - 1}{i(e^{i\theta} + 1)}$$

The relationship between true and eccentric anomaly is given by [Elliptic Orbits]

$$\tan \left( \frac{f}{2} \right) = \left( \frac{1+e}{1-e} \right)^{\frac{1}{2}} \tan \left( \frac{E}{2} \right)$$

Let  $p = \sqrt{\frac{1+e}{1-e}}$   
Aside

$$\begin{aligned} p^2 - 1 &= \frac{1+e - (1-e)}{1-e} = \frac{2e}{1-e} \\ \frac{1}{(p-1)(p+1)} &= \frac{(1-e)}{2e} \\ \frac{(p+1)}{(p-1)} &= \frac{(1-e)}{2e} \left[ \sqrt{\frac{1+e}{1-e}} - 1 \right]^2 \\ &= \frac{1}{2e} [\sqrt{1+e} - \sqrt{1-e}]^2 \\ &= \frac{1}{2e} [1+e + 1-e - 2\sqrt{1+e}\sqrt{1-e}] \\ &= \frac{1}{2e} [2 - 2\sqrt{1-e^2}] \\ \frac{(p+1)}{(p-1)} &= \left[ \frac{1 - \sqrt{1-e^2}}{e} \right] = \beta \end{aligned}$$

Going back to  $\tan \left( \frac{f}{2} \right) = \left( \frac{1+e}{1-e} \right)^{\frac{1}{2}} \tan \left( \frac{E}{2} \right)$

$$\begin{aligned} \tan \left( \frac{f}{2} \right) &= p \tan \left( \frac{E}{2} \right) \\ \frac{e^{if} - 1}{i(e^{if} + 1)} &= p \frac{(e^{iE} - 1)}{i(e^{iE} + 1)} \\ e^{if} - 1 &= p \frac{(e^{iE} - 1)}{(e^{iE} + 1)} (e^{if} + 1) \\ e^{if} - 1 &= p \frac{(e^{iE}e^{if} + e^{iE} - e^{if} - 1)}{(e^{iE} + 1)} \\ e^{if} - 1 &= \frac{pe^{iE}e^{if} + pe^{iE} - pe^{if} - p}{(e^{iE} + 1)} \\ e^{if} - 1 &= \frac{e^{if}(pe^{iE} - p) + pe^{iE} - p}{(e^{iE} + 1)} \\ (e^{if} - 1)(e^{iE} + 1) &= e^{if}(pe^{iE} - p) + pe^{iE} - p \\ e^{if}e^{iE} + e^{if} - e^{iE} - 1 &= e^{if}(pe^{iE} - p) + pe^{iE} - p \\ e^{if}(e^{iE} + 1) - e^{iE} - 1 &= e^{if}(pe^{iE} - p) + pe^{iE} - p \end{aligned}$$

Bring all  $e^{if}$  terms to the left

$$e^{if}(e^{iE} + 1 + p - pe^{iE}) = pe^{iE} - p + e^{iE} + 1$$

$$e^{if} ((1+p) + (1-p) e^{iE}) = (1-p) + (1+p) e^{iE}$$

$$e^{if} = \frac{(1-p) + (1+p) e^{iE}}{(1+p) + (1-p) e^{iE}}$$

Using  $\beta = \frac{p-1}{p+1}$  from above and divide the above by  $(1+p)$  we get

$$e^{if} = \frac{-\beta + e^{iE}}{1 - \beta e^{iE}}$$

$$e^{if} = \frac{e^{iE} (1 - \beta e^{-iE})}{1 - \beta e^{iE}}$$

## F Program to Calculate Coefficients of cosine term

Series Calculator

## G Radius of a Spheroid (ellipse)

Because we are considering a spheroid which is got by rotating an ellipse around the  $z$  axis, there is no azimuthal  $\lambda$  dependency for  $r$  i.e.  $r(\phi)$ .

The polar form for the radius of the ellipse is given by

$$r = \frac{ab}{\sqrt{a^2 \sin^2 \phi + b^2 \cos^2 \phi}}$$

$$r = \frac{ab}{\sqrt{a^2 \sin^2 \phi + b^2 (1 - \sin^2 \phi)}}$$

$$r = \frac{ab}{\sqrt{(a^2 - b^2) \sin^2 \phi + b^2}}$$

$$r = \frac{ab}{b \sqrt{\frac{(a^2 - b^2)}{b^2} \sin^2 \phi + 1}}$$

$$r = \frac{a}{\sqrt{\frac{(a^2 - b^2)}{b^2} \sin^2 \phi + 1}}$$

$$r = \frac{a}{\sqrt{1 + \frac{(a^2 - b^2)}{b^2} \sin^2 \phi}}$$

$$r = a \left[ 1 + \frac{(a^2 - b^2)}{b^2} \sin^2 \phi \right]^{-\frac{1}{2}}$$

$$r = a \left[ 1 + \frac{(a+b)(a-b)}{b^2} \sin^2 \phi \right]^{-\frac{1}{2}}$$

using  $\epsilon = \frac{a-b}{R_\mu}$

$$r = a \left[ 1 + \frac{(a+b)\epsilon R_\mu}{b^2} \sin^2 \phi \right]^{-\frac{1}{2}}$$

using  $a+b = (a-b) + 2b = \epsilon R_\mu + 2b$

$$r = a \left[ 1 + \frac{(\epsilon R_\mu + 2b)\epsilon R_\mu}{b^2} \sin^2 \phi \right]^{-\frac{1}{2}}$$

$$r = a \left[ 1 + \left( \frac{2b\epsilon R_\mu}{b^2} \sin^2 \phi + \frac{\epsilon^2 R_\mu^2}{b^2} \sin^2 \phi \right) \right]^{-\frac{1}{2}}$$

Binomial expansion of  $(1+x)^{-\frac{1}{2}}$

$$(1+x)^{-\frac{1}{2}} = 1 - \frac{1}{2}x + \frac{3}{8}x^2$$

So binomially expand to  $x$  term

$$r \simeq a \left[ 1 - \frac{2b\epsilon R_\mu}{2b^2} \sin^2 \phi - \frac{\epsilon^2 R_\mu^2}{2b^2} \sin^2 \phi \right]$$

Aside.  $\sin^2 \phi$  can be expressed in terms of Legendre Polynomials i.e.  $P_2 = \frac{3}{2} \sin^2 \phi - \frac{1}{2} = \frac{3}{2} \sin^2 \phi - \frac{1}{2} P_0 \Rightarrow \frac{2}{3} P_2 = \sin^2 \phi - \frac{1}{3} P_0 \Rightarrow \sin^2 \phi = \frac{2}{3} P_2 + \frac{1}{3} P_0$

We will be expressing  $r$  as a Legendre Polynomial expansion, however we are just keeping  $O(\epsilon)$  terms in our calculation of  $r$

$$r \simeq a \left[ 1 - \frac{2\epsilon R_\mu}{2b} \sin^2 \phi \right]$$

$$r \simeq a - \frac{a\epsilon R_\mu}{b} \sin^2 \phi$$

$$r \simeq (2a+b) - \frac{a\epsilon R_\mu}{b} \sin^2 \phi - (a+b)$$

using  $R_\mu = \frac{2a+b}{3}$

$$r \simeq 3R_\mu - \frac{a\epsilon R_\mu}{b} \sin^2 \phi - (a+b)$$

From the definition of flattening  $f$  Appendix L,  $a/b \simeq 1+f \simeq 1+\epsilon$

$$r \simeq 3R_\mu - \epsilon R_\mu \sin^2 \phi - (a+b)$$

$$r \simeq 3R_\mu - \frac{2}{3}\epsilon R_\mu \frac{1}{2} 3 \sin^2 \phi - (a+b)$$

Need  $(a+b)$  in terms of  $2R_\mu$

$$(a+b) = 2R_\mu + ?$$

$$? = (a+b) - 2R_\mu = (a+b) - 2 \frac{(2a+b)}{3} = \frac{3(a+b) - 2(2a+b)}{3} = \frac{-(a-b)}{3} = \frac{-\epsilon R_\mu}{3}$$

so

$$(a+b) = 2R_\mu - \frac{\epsilon R_\mu}{3} \tag{77}$$

$$r \simeq 3R_\mu - \frac{2}{3}\epsilon R_\mu \frac{1}{2} 3 \sin^2 \phi - 2R_\mu + \frac{\epsilon R_\mu}{3}$$

$$r \simeq R_\mu - \frac{2}{3}\epsilon R_\mu \frac{1}{2} 3 \sin^2 \phi + \frac{1}{2} \frac{2}{3} \epsilon R_\mu$$

$$r \simeq R_\mu - \frac{2}{3}\epsilon R_\mu \left[ \frac{1}{2} (3 \sin^2 \phi - 1) \right]$$

$$r \simeq R_\mu \left[ 1 - \frac{2}{3} \epsilon P_2(\sin \phi) \right]$$

## G.1 $J_2$ term

We have an oblate (flattened) spheroid obtained by rotating an ellipse with semi-major axis  $a_e$  and semi-minor axis  $b_e$  around around it's minor axis b.

B=The moment of Inertia around b is  $\frac{2}{5}Ma_e^2$

A=The moment of Inertia around a is  $\frac{1}{5}M(a_e^2 + b_e^2)$

Note also that  $J_2$  in [GeoPotential Model] is  $\frac{(B-A)}{Ma_e^2}$  (see [GRS80]) where A and B are the principal moments of inertia of the ellipsoid. Note also that  $J_2$  is nondimensional.

$$B - A = \frac{2}{5}Ma_e^2 - \frac{1}{5}M(a_e^2 + b_e^2) = \frac{1}{5}M(a_e^2 - b_e^2)$$

The following uses 84 and 77

$$J_2 = \frac{1}{5a_e^2}(a_e^2 - b_e^2) = \frac{1}{5a_e^2}(a_e - b_e)(a_e + b_e) = \frac{1}{5a_e^2}\epsilon R_\mu(a_e + b_e) = \frac{1}{5a_e^2}\epsilon R_\mu\left(2R_\mu - \frac{\epsilon R_\mu}{3}\right) = \frac{2}{5a_e^2}\epsilon R_\mu^2 + O(\epsilon^2) \simeq \frac{2}{5}\epsilon$$

## H Contour Integrals

[Boas] gives a good overview of Contour Integrals and the Residue Theorem.

### H.1 Contour Integral I

From [Boas] and [Contour Integral]. Note  $e$  is the eccentricity, which is  $< 1$ .

$$I = \int_0^{2\pi} \frac{1}{1 - e \cos \theta} d\theta$$

Using  $z = \exp(i\theta)$  and  $dz = izd\theta$

$$= \oint \frac{1}{iz} \left( \frac{1}{1 - e \left( \frac{z + \frac{1}{z}}{2} \right)} \right) dz$$

$$= \frac{1}{i} \oint \left( \frac{1}{z - \frac{e}{2}z^2 - \frac{e}{2}} \right) dz$$

$$I = -\frac{2}{ie} \oint \left( \frac{1}{z^2 - \frac{2}{e}z + 1} \right) dz$$

$$f(z) = \frac{1}{z^2 - \frac{2}{e}z + 1}$$

The roots to the denominator are

$$z = \frac{\frac{2}{e} \pm \sqrt{\frac{4}{e^2} - 4}}{2}$$

$$z_+ = \frac{1}{e} + \sqrt{\frac{1}{e^2} - 1}$$

$$z_- = \frac{1}{e} - \sqrt{\frac{1}{e^2} - 1}$$

i.e.

$$f(z) = \frac{1}{(z - z_+)(z - z_-)}$$

These are 2 simple poles. We want the one that is  $< 1$ .

From

$$z_- = \frac{1}{e} - \sqrt{\frac{1}{e^2} - 1} = \frac{1}{e} [1 - \sqrt{1 - e^2}]$$

we need

$$1 - \sqrt{1 - e^2} < e$$

$$\begin{aligned}
(1-e) - \sqrt{(1-e)(1+e)} &< 0 \\
\sqrt{(1-e)(1-e)} - \sqrt{(1-e)(1+e)} &< 0 \\
\sqrt{(1-e)} \left[ \sqrt{(1-e)} - \sqrt{(1+e)} \right] &< 0
\end{aligned}$$

which is true for  $0 < e < 1$ , so the root that lies within the contour is  $z_-$ .  
The residue is

$$R(f, z_0) = \frac{1}{(z_- - z_+)} = -\frac{1}{2\sqrt{\frac{1}{e^2} - 1}}$$

The Residue theorem is

$$\oint f(z) dz = 2\pi i R(f, z_0)$$

so we have

$$I = -\frac{2}{ie} \oint f(z) dz = -\frac{2}{ie} 2\pi i R(f, z_0) = \frac{2}{ie} 2\pi i \frac{1}{2\sqrt{\frac{1}{e^2} - 1}}$$

$$I = \frac{2\pi}{e} \frac{1}{\sqrt{\frac{1}{e^2} - 1}}$$

$$I = \frac{2\pi}{\sqrt{1 - e^2}}$$

$$\boxed{\int_0^{2\pi} \frac{1}{1 - e \cos \theta} d\theta = \frac{2\pi}{\sqrt{1 - e^2}}} \quad (78)$$

## H.2 Contour Integral II

I haven't spent much time on Complex Analysis so there are doubtless much more elegant derivations but the below gets there eventually.

$$\begin{aligned}
I &= \int_0^{2\pi} \frac{1}{(1 - e \cos \theta)^2} d\theta \\
I &= \oint \frac{1}{iz} \left( \frac{1}{1 - e \left( \frac{z + \frac{1}{z}}{2} \right)} \right)^2 dz \\
I &= \oint \frac{1}{iz} \left( \frac{z}{z - \frac{e}{2}z^2 - \frac{e}{2}} \right)^2 dz \\
I &= \oint \frac{1}{iz} \left( \frac{4}{e^2} \right) \left( \frac{z}{z^2 - \frac{2}{e}z + 1} \right)^2 dz
\end{aligned}$$

From H.1

$$\begin{aligned}
f(z) &= \left( \frac{4}{ie^2 z} \right) \frac{z^2}{(z - z_-)^2 (z - z_+)^2} \\
f(z) &= \left( \frac{4}{ie^2} \right) \frac{z}{(z - z_-)^2 (z - z_+)^2}
\end{aligned}$$

From [Boas] section on multiple poles, "Multiply  $f(z)$  by  $(z - z_0)^m$  where  $m$  is an integer greater or equal to the order  $n$  of the pole. Differentiate  $m - 1$  times, divide by  $(m - 1)!$  and evaluate resulting expression at  $z = z_0$ ".

So choosing  $m = 2$ , multiply through by  $(z - z_-)^2$

$$R(z_-) = \left( \frac{4}{ie^2} \right) \frac{d}{dz} \frac{z}{(z - z_+)^2} \Big|_{z_-}$$

$$\begin{aligned}
d\left(\frac{f}{g}\right) &= \frac{f'g - g'f}{g^2} \text{ and } \frac{1}{z_- - z_+} = -\frac{1}{2\sqrt{\frac{1}{e^2} - 1}} \\
&= \left(\frac{4}{ie^2}\right) \left[ \frac{\left((z - z_+)^2\right) - (2(z - z_+))z}{(z - z_+)^4} \right] \\
&= \left(\frac{4}{ie^2}\right) \left[ \left(-\frac{1}{2\sqrt{\frac{1}{e^2} - 1}}\right)^2 - 2\left(-\frac{1}{2\sqrt{\frac{1}{e^2} - 1}}\right) \left(\frac{1}{e} - \sqrt{\frac{1}{e^2} - 1}\right) \right] \\
&= \left(\frac{4}{ie^2}\right) \left[ \frac{1}{4} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^2 + \frac{1}{4} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^3 \left(\frac{1}{e} - \sqrt{\frac{1}{e^2} - 1}\right) \right] \\
&= \left(\frac{4}{ie^2}\right) \left[ \frac{1}{4} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^2 + \frac{1}{4e} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^3 - \frac{1}{4} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^2 \right] \\
&= \left(\frac{4}{ie^2}\right) \left[ \frac{1}{4e} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^3 \right] \\
&= \frac{1}{i} \left[ \frac{1}{e^3} \left(\frac{1}{\sqrt{\frac{1}{e^2} - 1}}\right)^3 \right] \\
&= \frac{1}{i} \left[ \left(\frac{1}{e\sqrt{\frac{1}{e^2} - 1}}\right)^3 \right] \\
R(z_-) &= \frac{1}{i} \left[ \left(\frac{1}{\sqrt{1 - e^2}}\right)^3 \right] \\
2\pi i R(z_-) &= \frac{2\pi}{(1 - e^2)^{\frac{3}{2}}} \\
\boxed{\int_0^{2\pi} \frac{1}{(1 - e \cos \theta)^2} d\theta} &= \frac{2\pi}{(1 - e^2)^{\frac{3}{2}}} \tag{79}
\end{aligned}$$

## I Bessel Functions

### I.1 Bessel's Equation

In 28 we came across the integral representation of the Bessel Function i.e.

$$J_n(e) = \frac{1}{2\pi} \int_0^{2\pi} \exp(i(e \sin E - nE)) dE$$

This is the solution to the Bessel equation below - using  $y$  for  $J$  and  $x$  for  $e$

$$x^2 y'' + xy' + (x^2 - n^2)y = 0$$

To show that  $J$  is the solution (cf [Bessel Math Stack])

$$J_n(e) = \frac{1}{2\pi} \int_0^{2\pi} \exp(i(e \sin E - nE)) dE = \frac{1}{2\pi} \int_0^{2\pi} \cos(e \sin E - nE) + i \sin(e \sin E - nE) dE$$

Looking at the cos term first

$$J_1 = \frac{1}{2\pi} \int_0^{2\pi} \cos(e \sin E - nE) dE$$



$$\begin{aligned}
J_1' &= -\frac{1}{2\pi} \int_0^{2\pi} \sin E \sin (e \sin E - nE) \\
J_1'' &= \frac{1}{2\pi} \int_0^{2\pi} -\sin^2 E \cos (e \sin E - nE) = \frac{1}{2\pi} \int_0^{2\pi} (-1 + \cos^2 E) \cos (e \sin E - nE) \\
&= -J_1 + \frac{1}{2\pi} \int_0^{2\pi} \cos^2 E \cos (e \sin E - nE) \\
\Rightarrow J_1'' + J_1 &= \frac{1}{2\pi} \int_0^{2\pi} \cos^2 E \cos (e \sin E - nE)
\end{aligned}$$

So

$$\begin{aligned}
&e^2 J_1'' + e J_1' + (e^2 - n^2) J_1 \\
&= [e^2 (J_1'' + J_1) - n^2 J_1] + e J_1' \\
&= \left[ \frac{1}{2\pi} \int_0^{2\pi} (e \cos E + n) (e \cos E - n) \cos (e \sin E - nE) \right] + e J_1'
\end{aligned}$$

Integrating by parts  $\int u dv = uv - \int v du$  with  $u = (e \cos E + n)$  and  $dv = (e \cos E - n) \cos (e \sin E - nE)$

$$\begin{aligned}
v &= \int dv = \sin (e \sin E - nE) \\
du &= -e \sin E \\
&= \frac{1}{2\pi} \left[ [(e \cos E + n) \sin (e \sin E - nE)]_0^{2\pi} + \int_0^{2\pi} e \sin E \sin (e \sin E - nE) \right] + e J_1' \\
&= e \left[ \frac{1}{2\pi} \int_0^{2\pi} \sin E \sin (e \sin E - nE) \right] + e J_1' \\
&= -e J_1' + e J_1' = 0
\end{aligned}$$

For the second sine term

$$J_1 = \frac{1}{2\pi} \int_0^{2\pi} \sin (e \sin E - nE)$$

The integrand is of the form

$$\sin (e \sin x - nx)$$

$f = e \sin x - nx$  is an odd function. And  $g = \sin (x)$  is also an odd function. So  $f(g(x)) = \sin (e \sin x - nx)$  is also an odd function.

Using  $\sin (a + b) = \cos b \sin a + \sin b \cos a$ .

Using  $\sin (\pi - x) = \sin x$

Using  $\sin (\pi + x) = -\sin x$

So for  $\pi - x$ .

$$\begin{aligned}
&\sin [e \sin (\pi - x) + n (\pi - x)] \\
&= \sin [(e \sin (x) - nx) + n\pi] \\
&= \cos n\pi \sin (e \sin (x) - nx) + \cos (e \sin (x) - nx) \sin n\pi \\
&= \cos n\pi \sin (e \sin (x) - nx)
\end{aligned}$$

and for  $\pi + x$

$$\sin [e \sin (\pi + x) + n (\pi + x)]$$

$$\begin{aligned}
&= \sin [-e \sin (x) + n\pi + nx] \\
&= \sin [-(e \sin (x) - nx) + n\pi] \\
&= -\cos n\pi \sin (e \sin (x) - nx) + \cos (e \sin (x) - nx) \sin n\pi \\
&= -\cos n\pi \sin (e \sin (x) - nx)
\end{aligned}$$

so by the symmetry about  $\pi$ , the integral from 0 to  $2\pi$  is 0.

## I.2 Generating Function

As in 29 we can write the Bessel function as a series solution ( $e$  here is the eccentricity of the orbit).

$$J_n(e) = \left(\frac{e}{2}\right)^n \sum_{m=0}^{\infty} \frac{(-1)^m \left(\frac{e}{2}\right)^{2m}}{m!(n+m)!}$$

Let's see how this is related to what is called a generating function below (in the below  $e$  is the exp function).  
cf [Lambers]

$$\begin{aligned}
g(x, z) &= e^{\left(\frac{x}{2}\right)\left(z - \frac{1}{z}\right)} = e^{\left(\frac{xz}{2}\right)} e^{\left(-\frac{x}{2z}\right)} \\
&= \sum_{l=0}^{\infty} \frac{1}{l!} \left(\frac{xz}{2}\right)^l \sum_{m=0}^{\infty} \frac{1}{m!} \left(-\frac{x}{2z}\right)^m \\
&= \sum_{l=0}^{\infty} \frac{1}{l!} \left(\frac{x}{2}\right)^l z^l \sum_{m=0}^{\infty} \frac{1}{m!} (-1)^m \left(\frac{x}{2}\right)^m z^{-m} \\
&= \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \frac{(-1)^m}{l!m!} \left(\frac{x}{2}\right)^{l+m} z^{l-m}
\end{aligned}$$

Let us consider the case where  $l \geq m$ , and let us introduce  $n = l - m$  i.e.  $n \geq 0$ . The first case we have is  $n = 0$  i.e.

$l$	0	1	2	3
$m$	0	1	2	3

Next  $n = 1$

$l$	1	2	3	4
$m$	0	1	2	3

Next  $n = 2$

$l$	2	3	4	5
$m$	0	1	2	3

So from the above we can see that the summation can be expressed as a sum over  $n$  and  $m$ . We can write the summation as

$$\begin{aligned}
&= \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \frac{(-1)^m}{m!(n+m)!} \left(\frac{x}{2}\right)^{n+2m} z^n \\
&= \sum_{n=0}^{\infty} \left[ \left(\frac{x}{2}\right)^n \sum_{m=0}^{\infty} \frac{(-1)^m \left(\frac{x}{2}\right)^{2m}}{m!(n+m)!} \right] z^n
\end{aligned}$$

The bit in the brackets is  $J_n(x)$ .

More generally we have

$$g(x, z) = e^{\left(\frac{x}{2}\right)\left(z - \frac{1}{z}\right)} = \sum_{n=-\infty}^{\infty} J_n(x) z^n$$

### I.3 Derivation of Integral Form

To see how we can derive the integral form of the Bessel function from the generating function (use  $m$  for the summation index)

$$e^{\left(\frac{x}{2}\right)\left(z-\frac{1}{z}\right)} = \sum_{m=-\infty}^{\infty} J_m(x) z^m$$

divide both side by  $z^{n+1}$

$$\frac{e^{\left(\frac{x}{2}\right)\left(z-\frac{1}{z}\right)}}{z^{n+1}} = \sum_{m=-\infty}^{\infty} J_m(x) z^{m-n-1}$$

The RHS is of the form of a Laurent Series i.e.

$$\begin{aligned} f(z) &= a_0 + a_1(z - z_0) + a_2(z - z_0)^2 + a_3(z - z_0)^3 + \dots \\ &+ \frac{b_1}{(z - z_0)} + \frac{b_2}{(z - z_0)^2} + \frac{b_3}{(z - z_0)^3} + \dots \end{aligned}$$

and do a contour integral choosing  $C$  to be the unit circle centred at  $z_0 = 0$

$$\oint_C \frac{e^{\left(\frac{x}{2}\right)\left(z-\frac{1}{z}\right)}}{z^{n+1}} dz = \oint_C \sum_{m=-\infty}^{\infty} J_m(x) z^{m-n-1} dz$$

We can use the residue theorem for the second term as there is a pole if  $n = m$  and the residue is just the coefficient of  $(z - z_0)^{-1}$

$$\oint_C \frac{e^{\left(\frac{x}{2}\right)\left(z-\frac{1}{z}\right)}}{z^{n+1}} dz = 2\pi i J_n(x)$$

In the first integral, substitute  $z = e^{i\theta}$  and  $dz = ie^{i\theta} d\theta$

$$\int_0^{2\pi} \frac{e^{x\left(\frac{e^{i\theta}-e^{-i\theta}}{2}\right)}}{e^{in\theta} e^{i\theta}} ie^{i\theta} d\theta = 2\pi i J_n(x)$$

$$i \int_0^{2\pi} e^{i(x \sin \theta - n\theta)} d\theta = 2\pi i J_n(x)$$

$$J_n(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{i(x \sin \theta - n\theta)} d\theta$$

which is the integral form of the Bessel function.

#### I.3.1 Contour Integration

The reason why  $\oint_C \frac{1}{z} dz = 2\pi i$  is that we are integrating in 2 dimensions along a path in the complex plane. In the case the path is a unit circle, the real component is  $x = \cos \theta$  and the imaginary component is  $y = \sin \theta$  so

$$z = x + iy = \cos \theta + i \sin \theta$$

and

$$dz = (-\sin \theta + i \cos \theta) d\theta = -(\sin \theta - i \cos \theta) d\theta$$

$$\begin{aligned} \frac{1}{z} dz &= -\frac{(\sin \theta - i \cos \theta)}{(\cos \theta + i \sin \theta)} d\theta = -\left(\frac{i}{i}\right) \frac{(\sin \theta - i \cos \theta)}{(\cos \theta + i \sin \theta)} d\theta \\ &= i \frac{(\sin \theta - i \cos \theta)}{(-i \cos \theta + \sin \theta)} d\theta = i d\theta \end{aligned}$$

It's more obvious by making the substitution  $z = e^{i\theta}$  and therefore  $dz = ie^{i\theta} d\theta$  then the complete integral is

$$\oint_C \frac{1}{z} dz = \int_0^{2\pi} e^{-i\theta} ie^{i\theta} d\theta = i \int_0^{2\pi} d\theta = 2\pi i$$

## J Mean Radius

This text uses  $R_\mu$  - the “mean radius” of an ellipsoid (note - not ellipse). It’s not obvious what the definition of “mean radius” is. From [Mean Radius Wikipedia]

“In geophysics, the International Union of Geodesy and Geophysics (IUGG) defines the mean radius to be  $R_\mu = \frac{2a+b}{3}$ ”

This is the arithmetic mean of the radius i.e.  $(a + a + b)/3$ .

## K Semi-latus rectum

Since the solution for the the orbital motion due to the inverse square law is

$$\frac{1}{r} = u = \eta(1 + e \cos \lambda) \quad (80)$$

where  $\eta = \frac{GMm^2}{L^2}$ , then for  $\lambda = 0$  (the periapse),  $u = \eta(1 + e)$ . But we know at the periapse  $r = \frac{1}{u} = a(1 - e)$  i.e.  $u = \frac{1}{a(1-e)}$ . Therefore

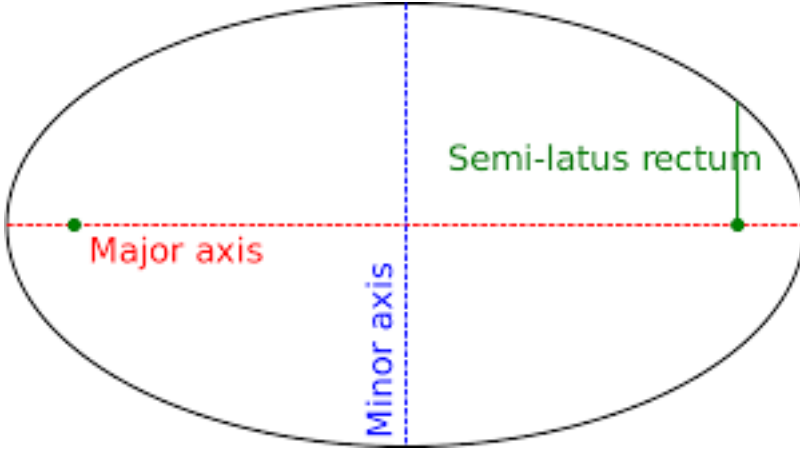
$$\eta(1 + e) = \frac{1}{a(1 - e)}$$

$$\eta = \frac{1}{a(1 + e)(1 - e)} = \frac{1}{a(1 - e^2)}$$

i.e.

$$\eta = \frac{GMm^2}{L^2} = \frac{1}{a(1 - e^2)}$$

Note the semi-latus rectum of the ellipse is given by  $l = \frac{1}{\eta} = a(1 - e^2)$ . We can see that from 80 that this is  $r(\lambda = \frac{\pi}{2})$ .



For Mercury we have

$$\eta = \frac{1}{57,910,000(1 - 0.2056^2)}$$

$$\eta = \frac{1}{55,462,066} = 1.803(10^{-8}) \text{ km}^{-1}$$

## L Notation

The notation used varies across different authors/texts. Below is listed some definitions.

$a_e$  semi-major axis of central body/spheroid.

$b_e$  semi-minor axis of central body/spheroid.

$a$  semi-major axis of satellite’s orbital ellipse.

$b$  semi-minor axis of satellite’s orbital ellipse.

Eccentricity: This is a property of the orbiting satellite.

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} \quad (81)$$

Mean Radius of an ellipsoid (not ellipse): see Appendix J

$$R_\mu = \frac{2a_e + b_e}{3} \quad (82)$$

Flattening: This is a property of the central body i.e. spheroid.

$$f = \frac{(a_e - b_e)}{a_e} \quad (83)$$

Ellipticity: This is a property of the central body i.e. spheroid.

$$\epsilon = \frac{(a_e - b_e)}{R_\mu} \quad (84)$$

Note the previous two (flattening and ellipticity) are very similar and are equivalent to  $O(\epsilon^2)$  or  $O(f^2)$  i.e.

$$\epsilon = \frac{3(a_e - b_e)}{2a_e + b_e}$$

using  $b_e = a_e(1 - f)$

$$\epsilon = \frac{3(a_e - (a_e - a_e f))}{2a_e + (a_e - a_e f)} = \frac{3a_e f}{3a_e - a_e f}$$

Rearrange

$$\frac{f}{\epsilon} = \frac{3a_e - a_e f}{3a_e} = 1 - \frac{f}{3}$$

$$\epsilon = f \left(1 - \frac{f}{3}\right)^{-1} \simeq f + O(f^2)$$

The following  $r_0$  is seen in [Kaula].  $r_0 = a_e \left(1 - \frac{f}{3} + O(f^2)\right)$  which gives the same as  $R_\mu$

The following is used in [Kaula].  $a_e$  mean equatorial radius of the earth.

Gravitational constant  $k$  or  $G$

The following is used in [Kaula].  $\mu = kM$

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