Analysis of RNP Maximum Route Length

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Technical Report

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Analysis of RNP Maximum Route Length

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Technical Report
EXECUTIVE SUMMARY

Maximum Course Length between Required Navigation Performance (RNP) Waypoints

It is the purpose of this analysis to determine a maximum distance between RNP waypoints, which ensure that overall risk to navigation remains at or below an acceptable level.

Ideally, an aircraft flies perfectly centered upon a constructed route. Herein lies two problems: (1) No pilot or autopilot can track an ideal line, and (2) for any route, the geometry of construction may not match the navigation solution and presentation of the route based on the on-board Flight Management System (FMS). The first kind of error is Flight Technical Error (FTE). The second kind of error is Navigation System Error (NSE). The Total System Error (TSE) is a statistical sum of these errors. With the advent of RNP, the TSE must be small enough to ensure that the probability of an aircraft being beyond the protected airspace is not above an acceptable level. One part of the NSE is bias error, due to the difference between the geometrically constructed route and the FMS computed route.

Manufacturers of FMS systems were contacted regarding the computational course solution used in their FMS systems, including satellite navigation. Each indicated that the computations used in each of their respective systems are based upon great circles of the volumetric sphere. The paper cited in the references from Smiths Industries also examines the differences between spherical great circle and geodesic WGS-84 ellipsoid solutions. The results shown are consistent with the analysis contained herein.

For routes with designed primary widths of 8 NM (RNP 2 as an example) constructed using WGS-84 geodetic computations and flown with great circle computations, or vice versa, it is recommended that maximum route length between waypoints be set at 500 NM. If these routes are to be represented on Lambert conformal charts, construction waypoints not more than 100 NM apart should be determined using WGS-84 or volumetric spherical coordinate systems.

Similarly, for routes with designed primary widths of 8 NM constructed using Lambert projections and flown with either great circle or WGS-84 geodetic computations, it is recommended that maximum route length between waypoints be set at 100 NM.

Further, it is recommended that these route lengths or constructions be modified directly by the square root of the ratio of the primary width compared to 8 NM. For example, RNP 3 has a primary width of 12 NM, thus the WGS-84 versus the spherical model maximum route length can be 500 x (12/8)^.5 = 612 NM, and Lambert versus WGS-84 or the sphere can be 100 x (12/8)^.5 = 122 NM. Similarly for RNP 0.3 which has a primary width of 1.2 NM, the recommended maximum route length between waypoints, WGS-84 versus sphere should not exceed 500 x (1.2/8)^.5 = 193 NM, and Lambert versus WGS-84/sphere should not exceed 100 x (1.2/8)^.5 = 38 NM.

Lastly, with an appropriate obstacle assessment, routes constructed and flown using identical computational methods are not limited in their length.
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1.0 Introduction

Briefly, maps are flat, the Earth is not. Errors in navigation do result from these differences. It is important to ensure that navigation errors, due to differences between the route structure and the methods of navigation, do not cause the overall level of risk to be unacceptable. Since the magnitude of error increases with distance, it is the purpose of this analysis to determine a maximum distance between RNP waypoints, which ensures that overall risk to navigation remains at or below an acceptable level.

Several projections and earth models are examined in the following paragraphs to present an overview of these projections and models, and to quantify the magnitude of errors among the ellipsoid and sphere models, and Lambert conformal projections.

2.0 Projections

There are several commonly used two-dimensional (flat) projections of the not so flat earth. These are in no particular order: Tangent plan projection, Mercator Cylindrical Projection, and Lambert Conformal Projection.

a. Tangent Plane. A large area (small scale) tangent plane projection is most commonly used in the Polar Regions, with the tangent point being the North or South Pole. However, local radar displays are often tangent plane projections. Tangent plane projections are very accurate for short distances before radial distances exhibit excessive foreshortening due to earth curvature. As compared to the WGS-84 ellipsoid or to the sphere, radial directions from or to the pole of the projection are accurate, however, other radial directions have some error, and these errors increase with distance from the pole.

b. Mercator Cylindrical. A large area (small scale) Mercator projection is most commonly used to represent the globe, sometimes omitting the extreme Polar Regions. These are the maps where Canada, Alaska, Greenland, Siberia, and Antarctica appear disproportionately large. A Mercator projection centered over a particular point with its equator oriented in the direction of an intended route gives the same results as a spherical model with the same radius. Perpendicular to the equator, a route results in the same errors as the tangent plane projection. Directions other than along the equator or perpendicular to the equator will result in both along-track and cross-track errors, which tend to increase with distance as compared to the WGS-84 ellipsoid or the sphere.

c. Lambert Conformal. A large area (small scale) Lambert projection is often used to represent the contiguous 48 states of the United States. Additionally, Lambert projections of Alaska and Hawaii may also be shown as insets, but each will be based upon a different cone. Here the lines of latitude (east-west lines) show a curvature. The amount of curvature depends on which lines of latitude are used to anchor the cone of projection. Lambert projections are 7.5-minute quadrangle charts.
East-west and north-south errors are minor, but in directions other than the cardinal directions, errors can be much larger. Also errors beyond the bounding latitudes of the projection will exhibit even greater errors. On a small area (large scale) map such as a quadrangle, a Lambert projection does an admirable job of balancing distance, direction, and area errors. Quad charts are the projections upon which TERPS approach and missed approach procedures are hand drawn.

3.0 Three Dimensional Earth Models

Eratosthenes was one of the earliest to calculate the circumference of the earth. He did so by knowing that on a certain date at local noon the sun cast no shadow in a vertical well, which was located a known distance to his south, while at the same time at his location the sun was below the vertical by several degrees. Using this angle difference as the angle subtended from the center of the earth and using the known distance between his location and the well, Eratosthenes was able to calculate the circumference of a spherical earth to within about 15 percent of today’s accepted value.

Isaac Newton was the first to demonstrate that the earth must be an oblate spheroid (an ellipse of revolution with a greater equatorial diameter than polar diameter). Careful measurement over the years, especially with the help of satellite measurement, has refined the three-dimensional model of the earth. The WGS-84 ellipsoid model has a polar flattening of about 14 km and an equatorial bulge of about 7 km as compared to a sphere of the same volume. The WGS-84 is the best second order fit of the geoid, the actual physical body of the earth. Third order fit induces a slight pear shape to the model. The North Pole is about 16 m higher than the ellipsoid. The South Pole is about 16 m lower than the ellipsoid. The northern mid latitudes are, at most, about 7 m below the ellipsoid, and the southern mid latitudes are, at most, about 7 m above the ellipsoid. Local anomalies account for some additional differences, but the combined effect of third and higher order models and local anomalies are not significant with respect to horizontal positioning.

a. Volumetric Sphere Model. The radius of the volumetric sphere is 6,371,000.79 m. Positional distances and directions on the sphere can be found by using spherical trigonometry or by converting to and from a rectangular coordinate system and using plane trigonometry.

b. WGS-84 Ellipsoid Model. The equatorial radius (semi major axis) of the ellipsoid is 6,378,137 m and the polar radius (semi minor axis) is 6,356,752.3141 m. Positional distances and directions on the ellipsoid present a much more complex problem and are computed using iterative numerical methods.
4.0 Route Differentials

Because each projection and earth model portrays the earth’s positional and directional information differently, there are differences in routes constructed between any two known points as well.

**Note:** The WGS-84 model is the same as the 1983 North American Datum (NAD83) model. All longitudes and latitudes were converted from the NAD27 model (equivalent to the Clarke 1863 model) to NAD83 on October 1st of 1993.

Shifts in recorded positions had changes of a few feet in the contiguous 48 states, a little more in Alaska, but as much as 1,600 feet in Hawaii. Old charts and maps published before October of 1993 may well be in error and should not be used to construct routes.

5.0 The Construction and Navigation Problem

Ideally, an aircraft flies perfectly centered upon a constructed route. Herein lies two problems: (1) No pilot or autopilot can track an ideal line and (2) for any route, the geometry of construction may not match the navigation solution and presentation of the route based upon the on board Flight Management System (FMS). The first kind of error is Flight Technical Error (FTE). The second kind of error is Navigation System Error (NSE). The Total System Error (TSE) is a statistical sum of these errors. With the advent of RNP, the TSE must be small enough to ensure that the probability of an aircraft being beyond the protected airspace is not above an acceptable level. One part of the NSE is bias error, due to the difference between the geometrically constructed route and the FMS computed route. Since the beginning and ending waypoints will match, any construction versus navigation error which occurs must happen between these two points, growing from the beginning waypoint to a maximum somewhere near mid course, then reducing to the ending waypoint.

Because of different curvatures based upon the different projections and models, the maximum differential between the constructed and computed routes in not necessarily at the midcourse point, but may occur slightly toward the part of the route which exhibits the greatest curvature. In the case of the spherical model, the route curvature is constant. A Lambert projection in the northern hemisphere has greater east-west curvature (smaller radius) at its northern limit than at its southern limit. The WGS-84 ellipsoid has greatest north-south curvature at the equator. This north-south curvature decreases toward the poles, and along any route the least curvature occurs in the east-west direction. The difference between the course differentials at the point of actual maximum separation and the midcourse separation are not significant and may be ignored for this analysis.

Manufacturers of FMS systems were contacted regarding the computational course solution used in their FMS systems, including satellite navigation. Each indicated that the computations used in each of their respective systems are based upon great circles of the volumetric sphere.
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The paper cited in the references from Smiths Industries also examines the differences between spherical great circle and geodesic WGS-84 ellipsoid solutions. The results shown are consistent with the analysis contained herein.

6.0 Data Analysis

Tables 1 through 3 in Appendix I show computed cross-track and along-track differences at the route midpoints for the WGS-84 ellipsoid versus the volumetric sphere (Table 1), the WGS-84 ellipsoid versus three different Lambert conformal projections (Tables 2a, 2b, and 2c), and the volumetric sphere versus the three different Lambert projections (Tables 3a, 3b, and 3c) for route distances of 100, 200, 300, 400, and 500 NM, all using routes generated from and centered upon the WGS-84 midpoint 35° N 70° W. Table 4 shows the endpoints of the 15 different routes used in the computations. Table 5 shows the effect of latitude on east-west routes.

An inspection of each of the tables suggests that midcourse differences increase with the square of the distance, i.e., doubling the route length approximately quadruples the midcourse differences. East-west and north-south routes show the least midcourse differences and northeast-southwest (and equivalently northwest-southeast) routes show the greatest differences. Latitude also is a factor with WGS-84 ellipsoid versus the sphere exhibiting greatest differences near 45° N or S.

7.0 Recommendations

For routes with designed primary widths of 8 NM (RNP 2 as an example) constructed using WGS-84 geodetic computations and flown with great circle computations, or vice versa, it is recommended that maximum route length between waypoints be set at 500 NM. If these routes are to be represented on Lambert conformal charts, construction waypoints not more than 100 NM apart should be determined using WGS-84 or volumetric spherical coordinate systems.

Similarly, for routes with designed primary widths of 8 NM constructed using Lambert projections and flown with either great circle or WGS-84 geodetic computations, it is recommended that maximum route length between waypoints be set at 100 NM, and that these recommended route lengths or constructions be modified directly by the square root of the ratio of the primary width compared to 8 NM. For example, RNP 3 has a primary width of 12 NM, thus the WGS-84 versus the spherical model maximum route length can be 500 x (12/8)^.5 = 612 NM, and Lambert versus WGS-84 or the sphere can be 100 x (12/8)^.5 = 122 NM. Similarly for RNP 0.3 which has a primary width of 1.2 NM, the recommended maximum route length between waypoints, WGS-84 versus sphere, should not exceed 500 x (1.2/8)^.5 = 193 NM, and Lambert versus WGS-84/sphere should not exceed 100 x (1.2/8)^.5 = 38 NM.

Lastly, with an appropriate obstacle assessment, routes constructed and flown using identical computational methods are not limited in their length.
Appendix A. List of Tables

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Table 4: Route Beginning and Ending Points

Table 5: 500 NM East-West Route Errors, WGS-84 vs. Volumetric Sphere
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<th>WGS-84 vs. Sphere</th>
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<td>WGS-84 mid point 35° N 70° W</td>
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WGS-84 vs. Lambert (30° to 40° N)

WGS-84 mid point 35° N 70° W

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WGS-84 mid point 35° N 70° W

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### Table 2c

**WGS-84 vs. Lambert (35° to 45° N)**

**WGS-84 mid point 35° N 70° W**

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### Table 3a

**Sphere vs. Lambert (30° to 40° N)**  
**WGS-84 mid point 35° N 70° W**

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<tr>
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<td>midpoints</td>
<td>0</td>
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<td>shown in</td>
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<th>Cross Track (NM)</th>
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<td>WGS-84 mid point 35° N 70° W</td>
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<td>Along Track (NM)</td>
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### Table 3c

**Sphere vs. Lambert (35° to 45° N)**

**WGS-84 mid point 35° N 70° W**

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**North-South Route**

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**Northeast-Southwest Route**

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### Table 4

**Route Beginning and Ending Points**

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<td></td>
<td>Lat 1</td>
<td>Lon 1</td>
<td>Lat 2</td>
<td>Lon 2</td>
</tr>
<tr>
<td>100 NM</td>
<td>34° 59.7457' N</td>
<td>68° 59.1399' W</td>
<td>34° 59.7457' N</td>
<td>71° 00.8601' W</td>
</tr>
<tr>
<td>200 NM</td>
<td>34° 58.9831' N</td>
<td>67° 58.2923' W</td>
<td>34° 58.9831' N</td>
<td>72° 01.7077' W</td>
</tr>
<tr>
<td>300 NM</td>
<td>34° 57.7124' N</td>
<td>66° 57.4698' W</td>
<td>34° 57.7124' N</td>
<td>73° 02.5302' W</td>
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<td>34° 55.9344' N</td>
<td>65° 56.6848' W</td>
<td>34° 55.9344' N</td>
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<tr>
<td>500 NM</td>
<td>34° 53.6499' N</td>
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</tbody>
</table>

<table>
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<th></th>
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<tbody>
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<td>Lon 1</td>
<td>Lat 2</td>
<td>Lon 2</td>
</tr>
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<td>70° 00.000' W</td>
</tr>
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<td>33° 19.8246' N</td>
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</tr>
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<td>70° 00.000' W</td>
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<td>Lon 1</td>
<td>Lat 2</td>
<td>Lon 2</td>
</tr>
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<td>34° 24.4601' N</td>
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<td>36° 10.2972' N</td>
<td>68° 32.6676' W</td>
<td>33° 48.6715' N</td>
<td>71° 24.8599' W</td>
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<td>33° 12.6429' N</td>
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</tr>
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</tr>
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**Table 5**

500 NM East-West Routes

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<td>55° N</td>
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<td>85° N</td>
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Appendix B. BASIC Code for Lambert Conformal Projection Midpoints

REM Lambert Conformal Projection Midpoint
CLS

REM Constants
a# = 6378137#
b# = 6356752.4141#
pif# = 4 * ATN(1)

PRINT "Lambert Conformal Projection Midpoint Calculator"
PRINT

REM input upper latitude anchor
PRINT "Input Anchor Latitudes"
PRINT
' INPUT " Upper Anchor Lat degrees ", latupdeg#
' INPUT " Upper Anchor Lat minutes ", latupmin#
' INPUT " Upper Anchor Lat seconds ", latupsec#
' latup# = latupdeg# + latupmin# / 60 + latupsec# / 3600
latup# = 35
PRINT

REM input lower latitude anchor
' INPUT " Lower Anchor Lat degrees ", latdndeg#
' INPUT " Lower Anchor Lat minutes ", latdnmin#
' INPUT " Lower Anchor Lat seconds ", latdnsec#
' latdn# = latdndeg# + latdnmin# / 60 + latdnsec# / 3600
latdn# = 25
PRINT

REM Input Point 1 Latitude and Longitude
PRINT "Input point 1 Latitude and Longitude"
PRINT
INPUT " Lat 1 degrees? ", lat1deg#
INPUT " Lat 1 minutes? ", lat1min#
INPUT " Lat 1 seconds? ", lat1sec#
lat1# = lat1deg# + lat1min# / 60 + lat1sec# / 3600
lat1# = 34
PRINT
INPUT " Lon 1 degrees? ", lon1deg#
INPUT " Lon 1 minutes? ", lon1min#
INPUT " Lon 1 seconds? ", lon1sec#
lon1# = lon1deg# + lon1min# / 60 + lon1sec# / 3600
lon1# = 69
PRINT
REM Input Point 2 Latitude and Longitude
PRINT "Input Point 2 Latitude and Longitude"
PRINT
INPUT " Lat 2 degrees? ", lat2deg#
INPUT " Lat 2 minutes? ", lat2min#
INPUT " Lat 2 seconds? ", lat2sec#
lat2# = lat2deg# + lat2min# / 60 + lat2sec# / 3600
' lat2# = 36
PRINT
INPUT " Lon 2 degrees? ", lon2deg#
INPUT " Lon 2 minutes? ", lon2min#
INPUT " Lon 2 seconds? ", lon2sec#
lon2# = lon2deg# + lon2min# / 60 + lon2sec# / 3600
' lon2# = 71
PRINT
REM Convert to Radians
latupr# = latup# * pi# / 180
latdnr# = latdn# * pi# / 180
lat1r# = lat1# * pi# / 180
lon1r# = lon1# * pi# / 180
lat2r# = lat2# * pi# / 180
lon2r# = lon2# * pi# / 180

REM Find upper and lower anchor radii
rup# = a# ^ 2 / (a# ^ 2 + b# ^ 2 * (TAN(latupr#)) ^ 2) ^ .5
rdn# = a# ^ 2 / (a# ^ 2 + b# ^ 2 * (TAN(latdnr#)) ^ 2) ^ .5

REM Find upper and lower z-values
zup# = b# * (1 - (rup# / a#) ^ 2) ^ .5
zdn# = b# * (1 - (rdn# / a#) ^ 2) ^ .5

REM Find height, upper slant height, and lower slant height
h# = rup# * (zup# - zdn#) / (rdn# - rup#)
sup# = (h# ^ 2 + rup# ^ 2) ^ .5
sdn# = ((h# + zup# - zdn#) ^ 2 + rdn# ^ 2) ^ .5

REM Find difference in longitudes adjusted to cone
alpha# = ABS(lon1# - lon2#) * rup# / sup#

REM Find r1, z1, r2 and z2 for ellipsoid
r1# = a# ^ 2 / (a# ^ 2 + b# ^ 2 * (TAN(lat1r#)) ^ 2) ^ .5
r2# = a# ^ 2 / (a# ^ 2 + b# ^ 2 * (TAN(lat2r#)) ^ 2) ^ .5
z1# = b# * (1 - (r1# / a#) ^ 2) ^ .5
z2# = b# * (1 - (r2# / a#) ^ 2) ^ .5
REM Determine the adjusted r and z's
Det#/ = (-h# / rup# - rup# / h#)
Dr1#/ = -(h# + zup#) - (rup# / h# * r1# - z1#)
Dz1#/ = (h# / rup# * (rup# / h# * r1# - z1#)) - (rup# / h# * (h# + zup#))
r1ad# = Dr1#/ / Det#
z1ad# = Dz1#/ / Det#

Dr2#/ = -(h# + zup#) - (rup# / h# * r2# - z2#)
Dz2#/ = (h# / rup# * (rup# / h# * r2# - z2#)) - (rup# / h# * (h# + zup#))
r2ad# = Dr2#/ / Det#
z2ad# = Dz2#/ / Det#

REM Determine slant heights
s1# = sup# / rup# * r1ad#
s2# = sup# / rup# * r2ad#

REM Law of Cosines to find distance between points
d# = (s1# * 2 + s2# * 2 - 2 * s1# * s2# * COS(alpha# * pi# / 180)) .5

REM Find cosine beta
cbeta# = (s2# * 2 + d# * 2 - s1# * 2) / (2 * s2# * d#)

REM Find slant height and radius and height of midpoint
sm# = (s2# * 2 + d# * 2 / 4 - s2# * d# * cbeta#) .5
rm# = rup# / sup# * sm#
zm# = -h# / rup# * rm# + h# + zup#

REM Find gamma
cgamma# = (sm# * 2 + s2# * 2 - d# * 2 / 4) / (2 * sm# * s2#)
gamma# = ATN((1 - cgamma# * 2) .5 / cgamma#)
IF gamma# < 0 THEN gamma# = gamma# + pi#
gamma# = gamma# * 180 / pi#

REM find output longitude
gambaradj# = gamma# * sup# / rup#
IF lon2# > lon1# THEN lonm# = lon2# - gammaradj# ELSE lonm# = lon2# + gammaradj#

REM Find rajd# by quadratic equation
aq# = (b# / a#) * 2 + (rup# / h#) * 2
bq# = 2 * (rup# / h# * zm# - (rup# / h#) * 2 * rm#)
cq# = zm# * 2 + (rm# * rup# / h#) * 2 - 2 * rup# * rm# * zm# / h# - b# * 2
rmadj# = (-bq# + (bq# * 2 - 4 * aq# * cq#) .5) / (2 * aq#)

REM Find midpoint latitude
tlatm# = (a# * 2 * (a# * 2 - rmadj# * 2) / (b# * rmadj#) * 2) .5
latm# = ATN(tlatm#) * 180 / pi#
'PRINT rup#, rdn#, zup#, zdn#, h#, sup#, sdn#, alpha#, r1#
'PRINT r2#, z1#, z2#, r1adj#, r2adj#, z1adj#, z2adj#, s1#, s2#
'PRINT d#, cbeta#, sm#, rm#, zm#, rmadj#, aq#, bq#, cq#
'PRINT rmadj#
PRINT
PRINT latm#, lonm#
Appendix C. Spherical Midpoint Equations

Given

Lat 1, Lon 1
Lat 2, Lon 2

Convert to Radian Measure

\[
\text{Lat } 1r = \text{Lat } 1 \times \pi/180, \quad \text{Lon } 1r = \text{Lon } 1 \times \pi/180 \]
\[
\text{Lat } 2r = \text{Lat } 2 \times \pi/180, \quad \text{Lon } 2r = \text{Lon } 2 \times \pi/180
\]

Convert to \((x, y, z)\) coordinate system

\[
x_1 = \cos(\text{lat } 1r) \times \cos(\text{lon } 1r)
\]
\[
y_1 = \cos(\text{lat } 1r) \times \sin(\text{lon } 1r)
\]
\[
z_1 = \sin(\text{lat } 1r)
\]
\[
x_2 = \cos(\text{lat } 2r) \times \cos(\text{lon } 2r)
\]
\[
y_2 = \cos(\text{lat } 2r) \times \sin(\text{lon } 2r)
\]
\[
z_2 = \sin(\text{lat } 2r)
\]

Find straight line midpoint

\[
x = (x_1 + x_2)/2
\]
\[
y = (y_1 + y_2)/2
\]
\[
z = (z_1 + z_2)/2
\]

Unitize lengths for midpoint

\[
xm = x/(x^2 + y^2 + z^2)^{.5}
\]
\[
ym = y/(x^2 + y^2 + z^2)^{.5}
\]
\[
zm = z/(x^2 + y^2 + z^2)^{.5}
\]

Convert to latitude and longitude in radians

\[
\text{lat } \text{mid} = \arccos(xm^2 + ym^2)^{.5}
\]
\[
\text{lon } \text{mid} = \arctan(ym/xm)
\]

Convert to degrees

\[
\text{lat } \text{mid} = \text{lat } \text{mid} \times 180/\pi
\]
\[
\text{lon } \text{mid} = \text{lon } \text{mid} \times 180/\pi
\]
References:

Smiths Industries: FMCS Earth Model Accuracy Analysis – November 13, 1995

Williams, Ed: Great Circle Calculator – http://williams.best.vwh.net/gecalc.htm,