THE JÖRMUNGANDR DARK FLIGHT MODEL FOR METEORITE AND ORBITAL DEBRIS RECOVERY. M. D. Fries[1], [1]NASA Astromaterials Acquisition and Curation Office, Johnson Space Center, Houston TX 77058. Email: marc.d.fries@nasa.gov

Introduction: Jörmungandr is a model that replicates the flight paths of falling meteorites to facilitate rapid meteorite collection [e.g. 1-3]. By iteratively entering a range of meteorite masses, a polygonal landing field (or "strewn field") is generated to simplify any search for meteorites. Jörmungandr uses winds-aloft data collected by weather balloons to accurately replicate lateral movement of falling meteorites. Jörmungandr is recently upgraded to v.2 with slightly more accurate fall modelling than v.1, and the math and operations of the model are described here. Jörmungandr data show that strewn field shapes are dominated by local wind conditions which can produce banana-shaped strewn fields in the event of strong crosswinds.

Description: Jörmungandr calculates the flight paths of falling meteorites using winds-aloft data from NOAA and other meteorological sources, combined with location, fireball declination, and direction of travel azimuth from eyewitness accounts and other sources. Those sources include the eyewitness reporting website of the American Meteor Society (amsmeteors.org), social media and data sharing groups therein, allsky cameras, and other sources. Jörmungandr is a "dark flight" model, meaning that it is optimized for the period of meteor dynamics between the end of luminous flight and arrival of meteorites on the ground. It was designed for modeling flight of falling meteorites observed in weather radar imagery and is optimized for this use. It does not include consideration of mass loss during luminous flight via fragmentation and evaporation.

Jörmungandr uses radiosonde observations (RAOB), or "weather balloon" data as a foundation for calculating movement of falling meteorites. These data are recorded as wind speed and direction values with respect to altitude above sea level (ASL). This makes a convenient format for calculating meteorite movement, with wind direction and speed divided into "slices" over a known range of vertical altitude.

Initial Conditions and Setup: Initial values (value-sub-*i*) indicate values at the top of a given altitude slice and final values (value-sub-*f*) indicate values at the low end of the altitude slice after movement has been computed. Sub-*f* values for one slice equal sub-*i* values for the next lower slice. Movement in the Z direction and in the X-Y plane are considered independently as winds only affect lateral movement, not fall velocity. Defining the terms, motion is described in *Fig. 1* with initial direction terms for absolute path length through one iteration (*l*), declination from horizontal (θ), and azimuth (direction the meteorite is traveling towards, ϕ) defined in the text box. Movement vectors x, y, and z are vector components of the two triangles in *Fig. 1*. Velocity vectors (V*j*, V*x*, V*y*), aerodynamic force (F*l*, F*j*, F*x*, F*y*) and acceleration (a*x*, a*y*) vectors correspond with the movement vector components. For the initial conditions in the top-most altitude slice, values θ*i*, ϕ*i*, z, and V*l* are given. Values for *z* come from the altitude of a given altitude slice in the RAOB data, or *zi* – *zf* for that slice. Azimuth ϕ*i* is taken from eyewitness reports or other observations of the meteor. In the absence of specific values for a given meteorite fall, typical values are used: declination angle θ*i* = 40°, and absolute velocity V*l* = 3,000 m/s at the end of luminous flight. Setup of trigonometry definitions includes translation from compass azimuth to unit-circle values.

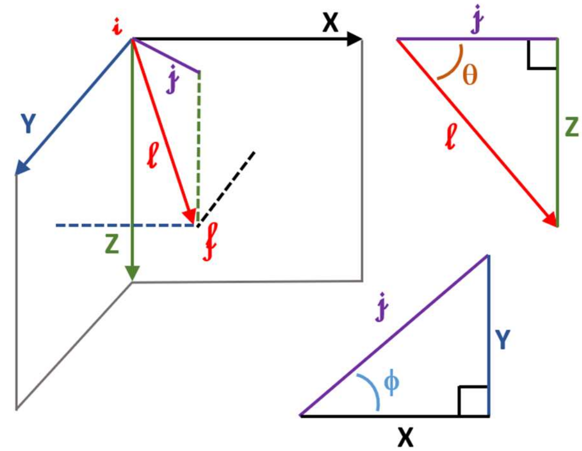

Figure 1: Left: Movement of a meteorite (red arrow) through 3D space along path length *l* with X,Y,Z directions, initial position *i* and final position *f* indicated. Upper Right: Motion of meteorite in the Z direction. Note this is not a projection onto the X-Z plane but follows the azimuth of path length *l* with vector *j* as the X-Y leg of the right triangle. θ is declination from horizontal. Lower Right: Projection onto the X-Y plane with azimuth ϕ. Note that both right triangles share component *j*.

Calculations: Jörmungandr performs sequential calculations to identify unknowns in order to find the path of a meteorite towards the ground (*Fig. 2*).

Step 1: Calculate unknowns in the *j-z* plane (*Fig. 1 upper right*). Known values are *z, l, θ*.

$l = \frac{z}{\sin\theta}$ By trigonometry

$ji = l\cos\theta$ By trigonometry

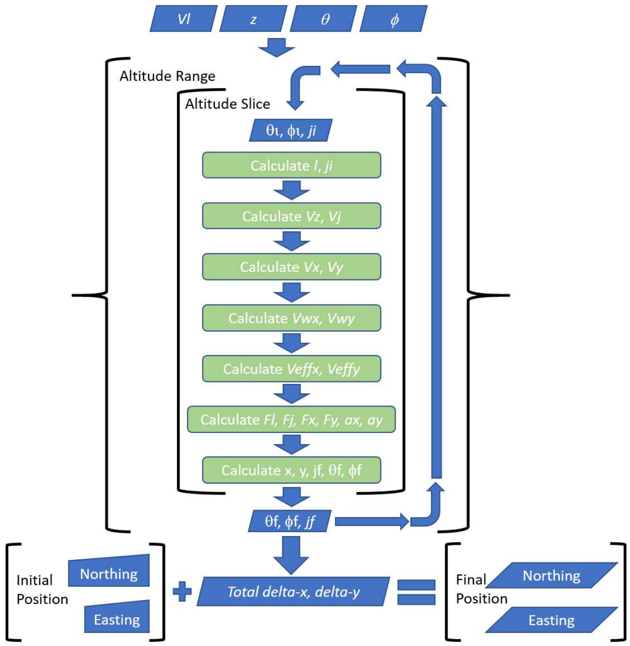

Figure 2: Flow chart for Jörmungandr operations. Given values input at the top. For each altitude "slice" in RAOB data, Jörmungandr performs a sequence of calculations based on trigonometry and formulae for the motion of falling objects. Final output includes a position on the ground for the meteorite expressed in UTM format and others (see text).

Step 2: Calculate unknowns in the *x-y* plane (*Fig. 1 lower right*). Velocity values substitute for motion values as an equivalent triangle to that in *Fig 1 Lower right*. Known values are *Vl, ϕ*. *Vl* is computed for each altitude slice in a separate process.

$Vz = Vl \sin \varphi$ By trigonometry

$Vj = Vl \cos \varphi$ By trigonometry

Step 3: Calculate unknowns for velocity in the *x-y* in the *x-y* plane, which is an equivalent triangle to that in Step 2. Known values are *Vj, ϕ*.

$Vx = Vj \cos \varphi$ By trigonometry

$Vy = Vj \sin \varphi$ By trigonometry

Step 4: Calculate wind vectors in the *x-y* plane, *Vwx* and *Vwy*. Wind direction and speed are given in RAOB data, so knowns are wind velocity (*Vw*) and wind direction (ω).

$Vwx = Vw \cos \omega$ By trigonometry

$Vwy = Vw \sin \omega$ By trigonometry

Step 5: Calculate effective wind experienced by the meteorite in the *x-y* plane. This is the difference between meteorite motion in one direction and the wind speed vector in that direction. Knowns are *Vx,Vy,Vwx,Vwy.*

$Veffx = Vx + Vwx$

$Veffy = Vy + Vwy$

Step 6: Calculate forces and accelerations experienced by the meteorite in the *x,y,* and *z* planes. The *l* direction must be calculated first and then distributed to vector directions, because aerodynamic forces have different drag domains for supersonic and subsonic flight. Division into vectors prior to this calculation will result in errors for movement near the cardinal directions, as small vector values will fall into the subsonic drag regime while the meteorite is actually experiencing supersonic drag.

$Fl = \frac{1}{2}\rho_{atm} A C_d V l^2$ Standard eqn. of atm. drag

$Fj = Fl \cos \theta$ Equiv. triangles with Step 1

$Fx = Fj \cos \varphi = Fj \frac{Vx}{Vj}$ Trig. or equiv. triangles S1

$Fy = Fj \sin \varphi = Fj \frac{Vy}{Vj}$ Trig. or equiv. triangles S1

$ax = \frac{Fx}{m}, ay = \frac{Fy}{m}$ From standard eqn. F=ma

Step 7: Calculate movement in *x* and *y* directions, find iterating values for the next altitude slice.

$x = Veffx * t + \frac{1}{2} ax * t^2$ Standard eqn. of motion

$y = Veffy * t + \frac{1}{2} ay * t^2$ Standard eqn. of motion

$jf = \sqrt{x^2 + y^2}$ Pythagorean equation

$\varphi f = tan^{-1} \frac{y}{x}$ By trigonometry

$\theta f = tan^{-1} \frac{z}{jf}$ By trigonometry

Results: Jörmungandr outputs include landing locations for meteorites across a range of mass values, estimates for masses of meteorites observed in weather radar data, an estimate of the fireball terminus location based on dark flight modeling, millisecond-accurate times of radar detection as well as altitudes, elapsed time for radar detection of falling meteorites, *xyz* movement of meteorites over a prescribed vertical range; and graphs of displacement, wind velocity+direction, force, acceleration, and velocity. Jörmungandr also includes a function for triangulating meteor sonic booms from seismometer data using sonic boom travel times corrected for density, temperature, and winds. Jörmungandr v.2 is currently in validation and will be released on the NASA Github site when complete, and a descriptive paper will be submitted for publication. The current software format is MS Excel.

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References: [1] Fries, M. and Fries, J., 2010. *MAPS*, 45(9), pp.1476-1487. [2] Jenniskens, P., et al 2012. *Science*, 338(6114), pp.1583-1587. [3] Welzenbach L.C., et al, *LPSC* this meeting.