James Ferguson's Mechanical Paradox Orrery 2

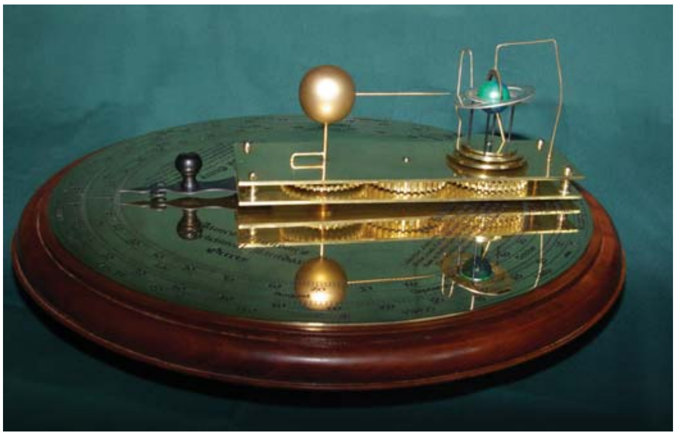
by Ian Coote and James Donnelly

Design and Construction

Both makers worked from the same original drawing, **Figure 1**. JD treated it as an exercise in CNC machining, with many parts drawn in CAD and machined on modern equipment. The model is roughly half the size of JF's original, **Figure 6.**

6. JD's finished models. Photo courtesy of Tina Buescher.

IC made the machine the same size as the original (15 inches diameter) and approached it mostly in the old-fashioned way, using two old lathes and a lot of elbow-grease. The final version of the dial was computer generated (Figure 7).



7. IC's finished model.

Gear Ratios

The design of any mechanism illustrating orbits is dependent upon the correct selection of gearing components which give a close approximation of the observed movements of the objects being represented. The gear ratios in the orrery described here match the observed behaviours remarkably well. The error for the precession of the nodes is about 41 days out of 6793 (18½ years), and the error of the period of the apogee is about 20 days out of 3233 (8 years and 290 days).

The ratio for the regression of the nodes can be approximated as 1-(365.25/6793) = 0.946231. The ratio for the period of the apogee can be approximated as 1-(365.25/3233) = .887024.

The table below illustrates possible gear pairings for the nodes and the apogee sorted by ascending absolute error.

Driving both the nodes and apogee from a 39 tooth gear represents great insight by Ferguson. The choice of 37x39 tooth gears for the nodes is actually the 4th best possible result numerically combined with the 2nd best possible choice for the apogee. A choice of 35x37 for the nodes and 31x35 for the apogee would have been an alternative.

JD's Model

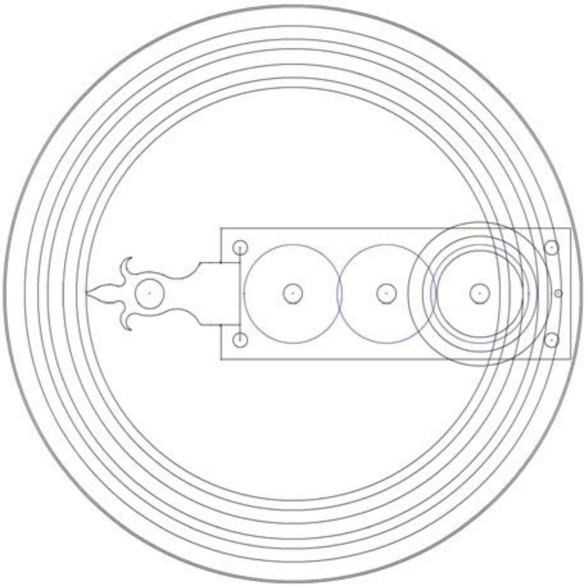
Several factors contributed to my interpretation of Ferguson's original design. First, I wanted to use involute gear cutters that were already in hand, because the involute shape is more forgiving of depthing errors than the cycloidal shape and this project wasn't going to be a monument to pitch diameter precision. Second, I wanted to do an all-brass model for aesthetic appeal. Third, the desire to make two orreries led me to adopt a more rigorous approach to planning and fixturing so that the parts would be interchangeable.

The size of the gears I could make with my 32 pitch cutters led to the derivation of the size of the top and bottom plates. A 32 pitch gear with 39 teeth has an outer diameter of 1.219". To maintain proportions the base plate couldn't be much wider. I settled on a width of 1.700" and length of 4.562". **Figure 8** is one of the master drawings used to plan the project. One of Ferguson's sons had an original reported to have a base 15" in diameter with wooden gears and a paper dial, so this turned out to be considerably smaller than the original.

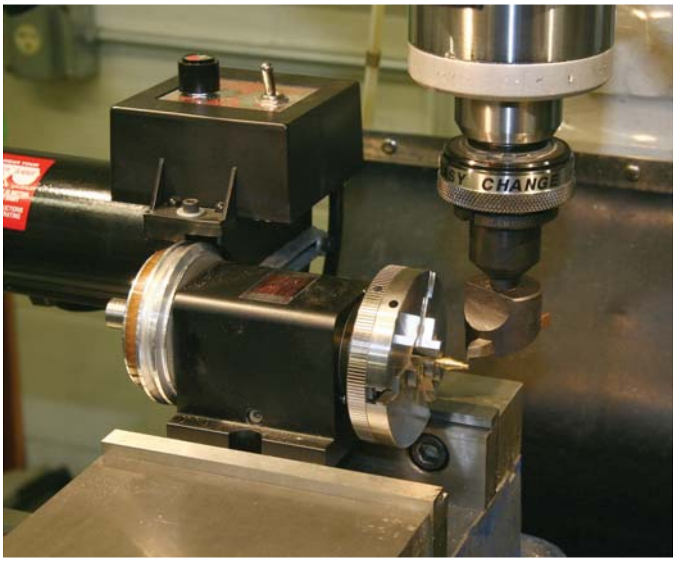
The plates were made from 3/16" rass stock rescued from the scrap yard. These are thicker than would be suggested by scaling the model from Ferguson's engraving. The mechanism is slightly heavier than I'd like as a result, but the plates were able to accommodate decent depth for the blind axes holes and a recess for the pointer with ample rigidity. To accommodate the weight, the mechanism rotates on a wheel under the bottom plate having the same diameter as the Sun gear.

The last major choice in the departure from the clock making tradition was the decision to solder the posts separating the top and bottom plates to the top plate and use screws to hold the bottom plate. A post protruding through the top plate held with a pin would be very reasonable on a larger model, but it didn't look very attractive in my prototype drawings. Since I needed 8 posts for the two orreries and Ferguson's drawing shows a curved post shape, I decided to fashion a CNC lathe out of a

Nodes Gears	Rat Figure 7. IC's finished modelio	Ratio Error	Apogee Gears	Ratio	Ratio Error
35x37	.945945946	-.000285464	47x53	.886792453	-.000231547
18x19, 36x38	.947368421	.001137011	**39x44**	.886363636	-.000660364
34x36, 17x18, 51x54	.944444444	-.001786966	31x35	.885714286	-.001309714
37x39	.948717949	.002486539	24x27, 40x45, 48x54, 32x36	.888888889	.00186489
50x53	.943396226	-.002835184	46x52, 23x26	.884615385	-.002408615
33x35	.942857143	-.003374267	38x43	.88372093	-.00330307



8. Layout.



9. Machining the posts.

10. The finished post.

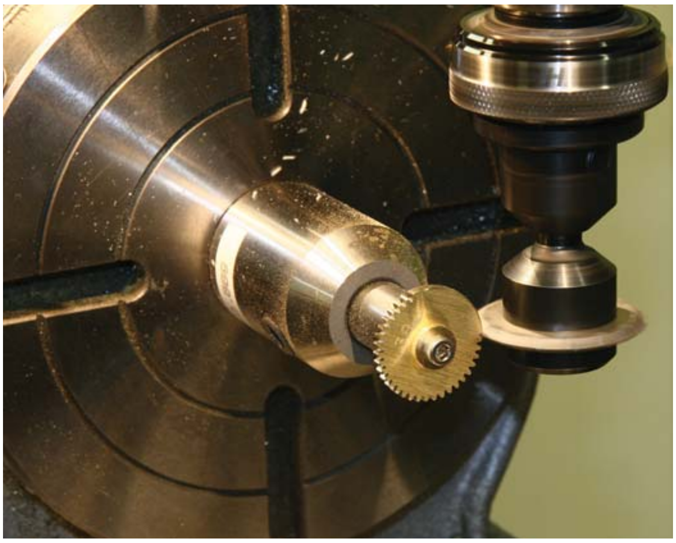
Sherline headstock and my mill. I do not have a picture of the original operation, but the essence of the setup is shown in the photo, **Figure 9.** The result was a post with a shape that is somewhat faithful to the original engraving, **Figure 10**.

Since I intended to build two identical orreries, some parts were cut using CNC programs. The weakness of this approach is exposed in the shape of the pointer, which was cut with a 1/16" 2-flute end mill, **Figure 11.** My intent was to capture as much of the traditional fleur-de-lys shape suggested by Ferguson's engraving. In retrospect, these could have been cut with a fretsaw to provide tighter inside corners.

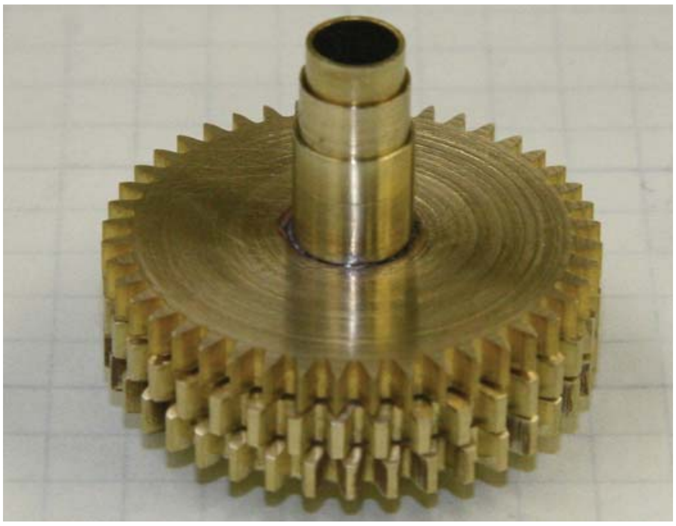
Fabrication of the round plates for the Earth, Nodes, and Apogee and the gears was facilitated by an arbor made from ¾" steel, shown in **Figure 12**. The arbor permitted parts to move between the lathe and mill as needed.

11. Pointer.

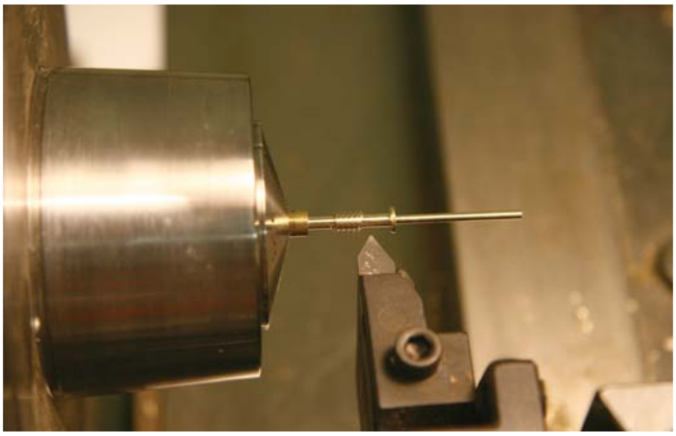
12. Arbor for gear cutting.



13. Cutting a gear.

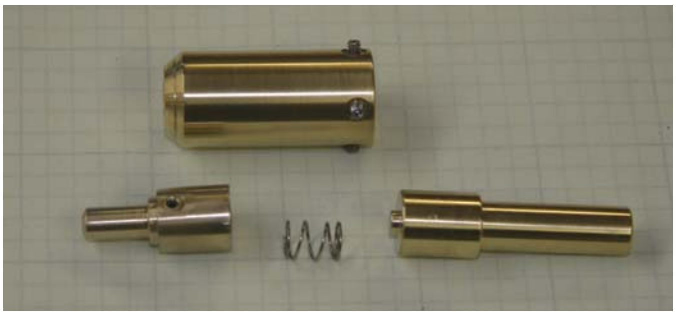


14. Gear assembly.

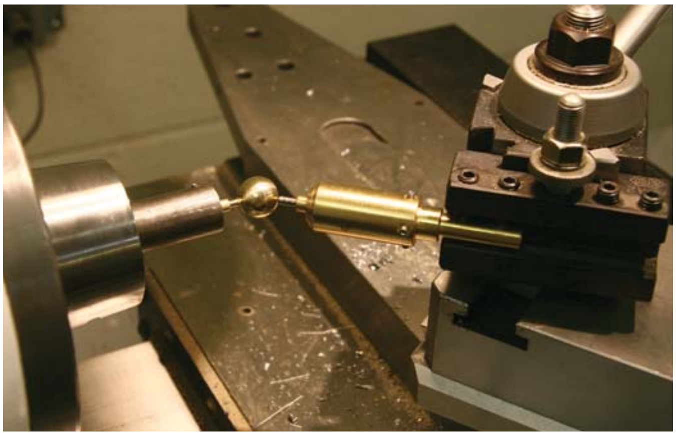


15. Axis for spheres.

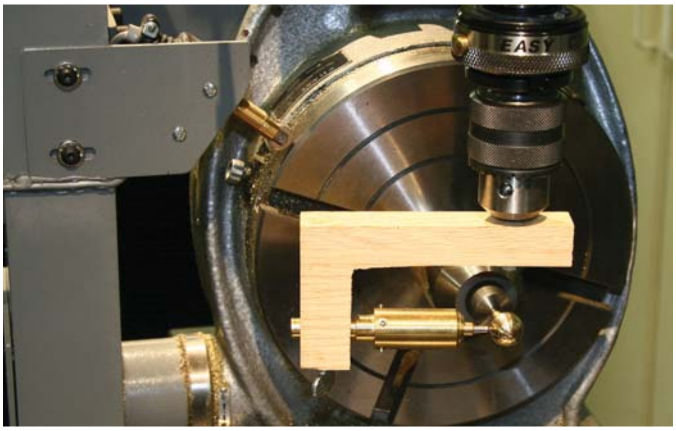
16. Engraver holder.



17. Parts of the engraving holder.



18. Engraving the latitudes.



19. Engraving the longitudes.

Figure 13 shows the gear cutting process. The rotary table has a Morse taper #3 centre that accommodates a ¾" end mill holder perfectly. Being a software engineer at heart, I wrote a Windows program several years ago that generates the G-code sequence for any gear given the pitch and tooth count, which facilitated the gear making process significantly. I used a #3 cutter for all the gears except the 44 tooth gear for the apogee, which required a #2 cutter to achieve a thinner tooth profile. The tubes that connect gears to plates were cut to length and a very tiny shoulder was turned for fitting the top plates. This shoulder is only a couple of thousands of an inch, but it keeps the plates from descending to meet the part below and facilitates a gentle press-fit assembly. Once the tubes and gears were completed, I soldered them together, **Figure 14.**

The Earth and Sun assemblies began as brass spheres purchased from a lamp repair supplier. These have a threaded mounting hole, so I turned custom axes that matched the internal threads, **Figure 15**. This was done by turning the axis diameter first, extruding the part out of the collet about a half inch at a time. The threads were cut after the reliefs were cut on either side. After soldering each sphere onto its axis, lacquer was applied and left to cure for a few days.

All of the engraving in this project was done with a home made spring loaded holder for a 120° diamond bit, **Figure 16.** This is a drag-engraving process – not a rotary application. The holder was fairly simple to make, and has found many uses in the shop. **Figure 17 s**hows parts before assembly. It's useful to have an assortment of springs to match the engraving force to the material.

The setup for engraving the lines on the Earth ball was tricky, but patience was rewarded with lines that matched up quite well. The latitude lines were done on the lathe, **Figure 18**. A temporary wood holder facilitated the longitude lines using the rotary table to index the ball, **Figure 19.** After the lines were engraved they were treated with Blacken-it agent to improve contrast.

Two techniques were used to improve the strength of the solder joints holding the node rings and the alignment peg for the Sun assembly. A 0.020" deep pocket was milled in the underside of the nodes ring to keep the post in place and improve the surface area for the joint, **Figure 20**. **Figure 21** shows the setup for soldering the posts. (Note that the angle is exaggerated in keeping with tradition – the actual angle would be difficult to perceive.) The alignment peg for the Sun has a 0.025" pin

20. Engraving the nodes ring.

21. Soldering the ring supports.

22. Drilling the Sun shaft.

23. Milling the base.

turned onto the end to fit into the Sun axis. **Figure 22** shows the operation for putting the hole in the axis for the alignment peg. This joint turned out to be quite strong for one of the orreries, but less satisfactory for the other, requiring a bit of rework.

The dial symbols were engraved with characters from TruType fonts. There's a significant difference between the outline characters used in my project and the fully formed characters found in original engraved dials. Some day I hope to be able to produce dials that look closer to the 18th century originals.

The base was first turned from Mahogany and treated with a mild calcium carbonate solution to rapidly 'age' the wood. The base was then waxed with Myland's Antique Mahogany wax. Once that was complete, a shallow pocket was milled to accept the calendar ring **Figure 23**. The calendar ring was glued into place as the last step before final assembly.

Part 2 in November's HJ.