OrbitFormer: A Transformer Foundation Model for Multi-Body Asteroid Orbit Forecasting

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1. Motivation

- **Planetary Defense:** Small trajectory errors can alter close-approach estimates and collision-risk assessment.
- **Space Situational Awareness:** Reliable orbit forecasting supports tracking & mission planning.
- **Need for Scalable Forecasting:** Classical propagators are accurate but expensive, while ML models can accumulate long-horizon error.

2. Core Gap

- **Currently used ML models are not truly foundation models:** Many orbit predictors rely on hand-crafted features & exogenous physical variables.
- **Long-horizon forecasting remains unstable:** Classical propagation scales poorly as $O(K^2)$ for K bodies, while autoregressive ML models can compound error:

$$\epsilon_{t+1} \approx (1+\alpha)\epsilon_t, \quad \alpha = \text{error growth rate}$$

3. Experimental Design

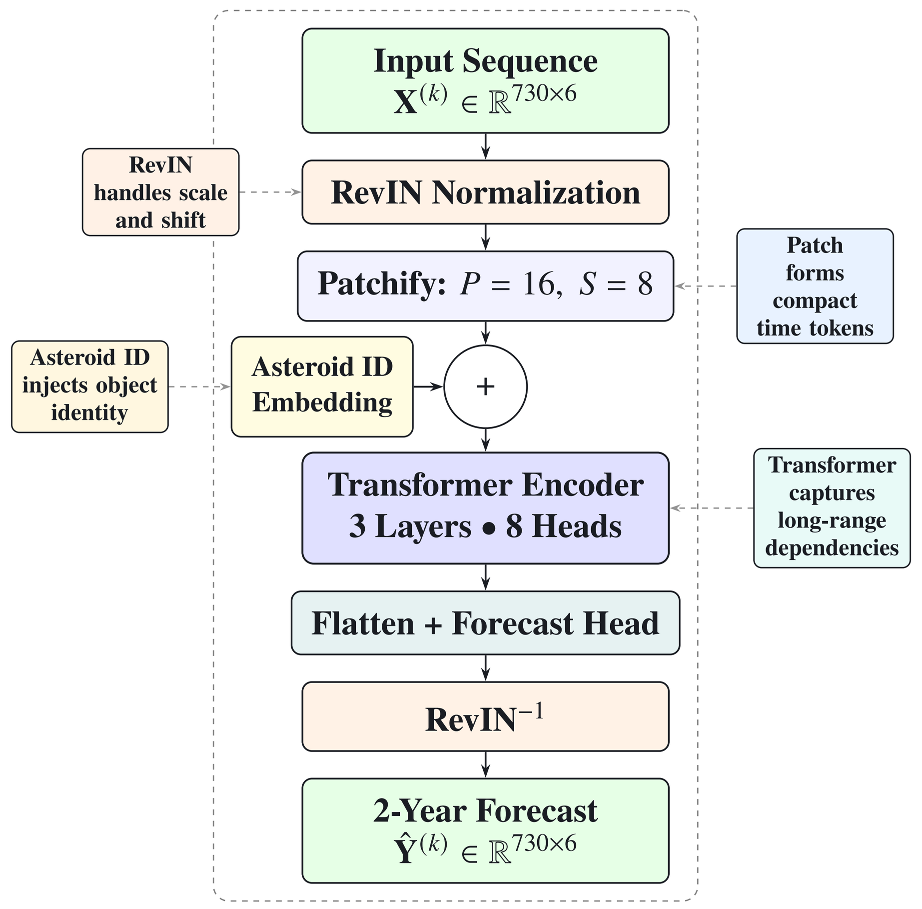
- **Task:** For each asteroid k, OrbitFormer learns directly from a 4-year history of 6D orbital state vectors and predicts the next 2 years.

$$s_t = (x_t, y_t, z_t, v_{x,t}, v_{y,t}, v_{z,t})^\top$$

Input: 4-year history **Output: 2-year forecast**

- **Data:** Trained on **400 NASA JPL asteroids** spanning **Jan. 1, 2020 – Jan. 1, 2024**.
- **Evaluation:** Forecasts are evaluated using MSE in the original physical coordinate space.

4. OrbitFormer Architecture



5. Result 1: Efficiency (12-Month Forecast)

Model	Number of Training Asteroids			
	50	100	200	400
OrbitFormer	**7.4**	**11.9**	**17.3**	**49.6**
TimeAutoDiff	16.9	22.2	44.9	92.7
FNN + Exogenous	31.4	46.6	58.9	115.7
LSTM	20.4	22.8	68.1	227.3
ARIMA	44.9	89.1	192.7	497.1
cDDPM	92.7	493.1	$O(10^3)$	$O(10^7)$

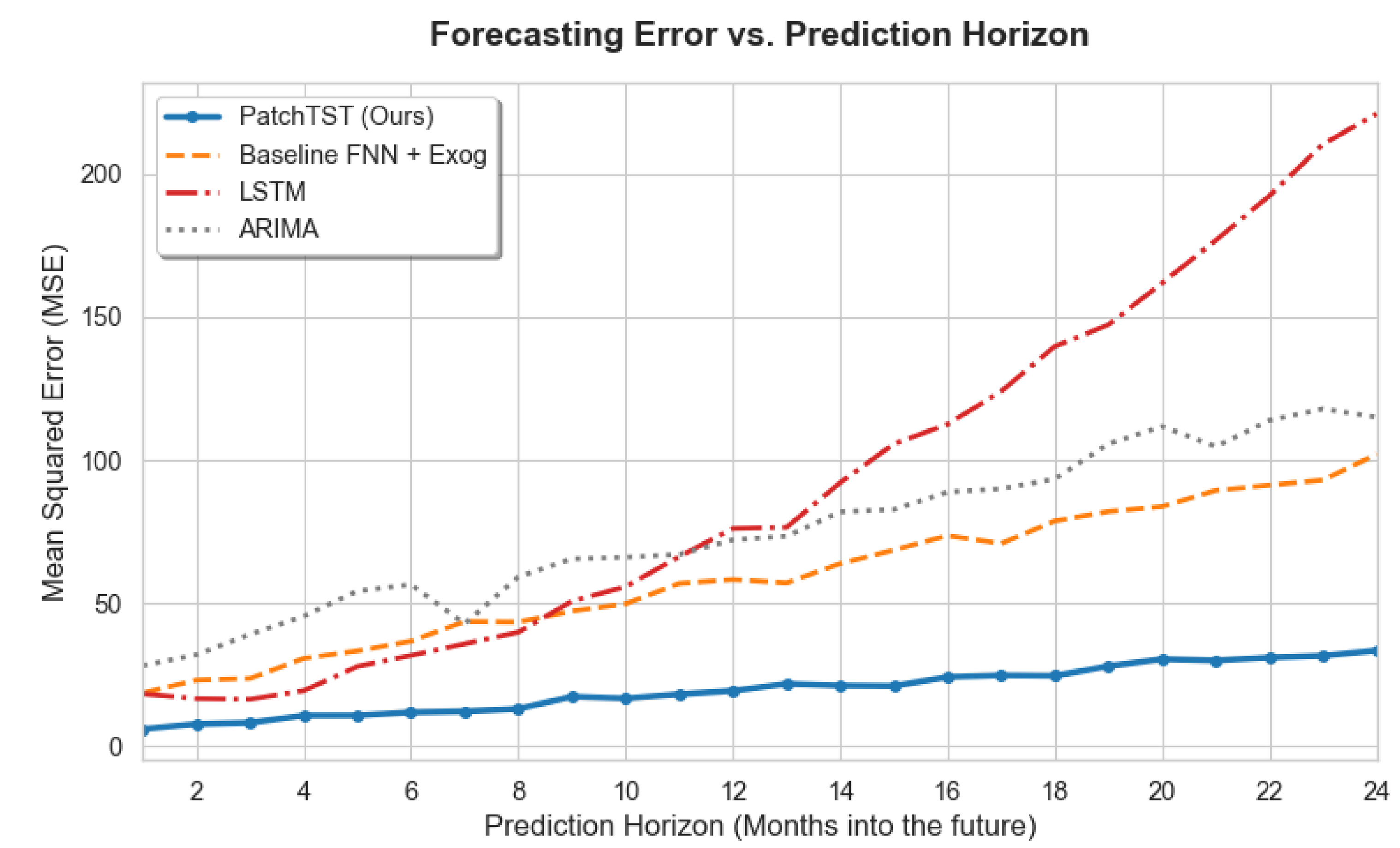
Lower MSE is better. Rows are sorted from best to worst by overall performance across training-set sizes.

6. Result 2: Generalization Across Asteroid Types

Model	Ast. 1	Ast. 2	Ast. 3
	Nearest	Mid-Distance	Farther
OrbitFormer	**1.1**	**7.4**	98.1
TimeAutoDiff	4.8	47.1	**76.2**
LSTM	7.2	11.9	115.2
FNN + Exogenous	12.4	49.2	119.3
ARIMA	18.7	27.3	Collapse
cDDPM	118.1	Collapse	Collapse

Lower MSE is better. Rows are ordered by overall generalization performance across asteroid regimes.

7. Result 3: Long-Horizon Stability (24-Month)



8. Future Work & Applications

- **Medical Trajectory Intelligence:** Forecast cancer progression, dementia decline, and ICU deterioration from longitudinal patient signals.
- **Autonomous Driving:** Predict long-horizon vehicle interactions and collision risk in dense traffic.
- **Earth and Climate Systems:** Extend trajectory forecasting to long-term weather, climate risk, and rare-event prediction.

9. Acknowledgements

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- I really appreciate the support of Department of Computer Science, Trinity College.
- **Data source:** NASA Jet Propulsion Laboratory (JPL) asteroid ephemeris data.

Selected References: Vallado, *Fundamentals of Astrodynamics and Applications*; Montenbruck & Gill, *Satellite Orbits*; Nie et al., PatchTST, ICLR 2023; Kim et al., RevIN, ICLR 2022; Vaswani et al., Attention Is All You Need, NeurIPS 2017; Peng & Bai, *Advances in Space Research*, 2018.