

Atmosphere Reconstruction From Rocket Balloon Instrument Sphere Tracking Data Using a Kalman Filter

*Christopher D. Karlgaard
Analytical Mechanics Associates, Inc., Hampton, Virginia*

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NTRS Registered and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

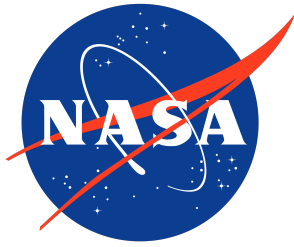
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI Program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- Help desk contact information: <https://www.sti.nasa.gov/sti-contact-form/> and select the "General" help request type.



Atmosphere Reconstruction From Rocket Balloon Instrument Sphere Tracking Data Using a Kalman Filter

*Christopher D. Karlgaard
Analytical Mechanics Associates, Inc., Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

April 2026

Acknowledgments

The author gratefully acknowledges helpful discussion with Clara O'Farrell at the California Institute of Technology's Jet Propulsion Laboratory and Frank Schmidlin at the NASA Wallops Flight Facility.

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Abstract

A new capability for processing Rocket Balloon Instrument (ROBIN) sphere tracking data has been added to the New Statistical Trajectory Estimation Program (NewSTEP). The primary modifications to NewSTEP are to the equations of motion used in the Kalman filter state propagation. The modified process model consists of a set of differential equations describing the translational degrees of freedom under the influence of aerodynamic drag. The motion of the sphere, as measured by ground-based radar tracking stations, can be used to reconstruct the atmospheric properties by processing the data in a Kalman filter. Three types of Kalman filters are implemented in NewSTEP for solving this atmosphere reconstruction problem: an Extended Kalman Filter (EKF), a Divided Difference Filer (DDF), and an Unscented Kalman Filter (UKF). Each filter is tested with a simulated ROBIN sphere trajectory, and real data from a meteorological rocket launch at the Pacific Missile Range Facility (PMRF) recorded in June 2015. The ROBIN sphere reconstruction results generally agree with results from a legacy data processing tool generated by meteorologists at PMRF. The new capability added to NewSTEP for processing ROBIN sphere tracking data is expected to be useful in future flight test projects that require high altitude atmosphere reconstruction.

Contents

1	Introduction	6
2	Kalman Filter Formulation	9
2.1	Equations of Motion	9
2.2	Drag Modeling	11
3	Simulation Test Case	13
4	Application to ROBIN Sphere Data from the Pacific Missile Range Facility	20
5	Conclusions	26
	References	27

List of Tables

1	Drag coefficient uncertainty from [20].	13
2	SFDT-2 Atmospheric data collection launches [32].	20

List of Figures

1	PWN-12A concept of operations [11].	6
2	Loki dart (top) and Super Loki dart (bottom) PWN-12A launchers [12,13].	7
3	PWN-12A dart cross section [11,14].	7
4	PWN-12A payload ejection and inflation [11].	8
5	Inflated PWN-12A ROBIN sphere.	8
6	ECI, ECEF, and GC frame [24].	10
7	ROBIN sphere drag coefficient [19]. The Sandia and Heinrich sources are given in [22] and [23], respectively.	12
8	ROBIN sphere drag coefficient digitized from [19].	12
9	Simulated ROBIN sphere trajectory.	13
10	Simulated ROBIN sphere radar measurements.	14
11	Simulated ROBIN sphere atmosphere reconstruction.	16
12	Simulated ROBIN sphere wind reconstruction.	17
13	Detailed view of reconstructed east wind components over altitudes from 70 to 90 km.	18
14	Simulated ROBIN sphere reconstruction residuals and uncertainties.	19
15	ROBIN sphere radar measurements from sounding rocket 2.	21
16	ROBIN sphere atmosphere reconstruction.	22
17	ROBIN sphere wind reconstruction.	23
18	ROBIN sphere reconstruction residuals and uncertainties.	24
19	ROBIN sphere drag coefficient model inputs and output.	25
20	ROBIN sphere drag coefficient output compared to model data. The DDF and UKF curves are similar to the EKF curve and are not shown for clarity (see Figure 19(c)).	26

Nomenclature

a_{XC}	=	Geocentric north sensed acceleration, m/s ²
a_{YC}	=	Geocentric east sensed acceleration, m/s ²
a_{ZC}	=	Geocentric down sensed acceleration, m/s ²
C_D	=	Drag coefficient
$\vec{e}_{XC}, \vec{e}_{YC}, \vec{e}_{ZC}$	=	Unit vectors of the Geocentric (GC) coordinate system
$\vec{e}_{XF}, \vec{e}_{YF}, \vec{e}_{ZF}$	=	Unit vectors of the Earth Centered Earth Fixed (ECEF) coordinate system
$\vec{e}_{XI}, \vec{e}_{YI}, \vec{e}_{ZI}$	=	Unit vectors of the Earth Centered Inertial (ECI) coordinate system
J_2	=	Zonal harmonic coefficient
M	=	Mach number
Re	=	Reynolds number
r	=	Radius, m
S	=	Reference area, m ²
u	=	Geocentric north velocity, m/s
u_w	=	Geocentric north wind velocity, m/s
$\mathbf{V}_w$	=	Wind-relative velocity vector, m/s
v	=	Geocentric east velocity, m/s
v_w	=	Geocentric east wind velocity, m/s
w	=	Geocentric down velocity, m/s
w_w	=	Geocentric down wind velocity, m/s
θ	=	Longitude, rad
λ	=	Sidereal angle of the Earth's prime meridian, rad
μ	=	Earth's gravitational parameter, m ³ /s ²
ρ	=	Density, kg/m ³
ϕ	=	Declination, rad
Ω	=	Earth angular velocity, rad/s

Abbreviations

DDF	=	Divided Difference Filter
DOF	=	Degrees of freedom
ECEF	=	Earth Centered Earth Fixed
ECI	=	Earth Centered Inertial
EKF	=	Extended Kalman Filter
GC	=	Geocentric
IMU	=	Inertial Measurement Unit
LDSD	=	Low Density Supersonic Decelerator
NewSTEP	=	New Statistical Trajectory Estimation Program
NRLMSISE-00	=	Naval Research Laboratory, Mass Spectrometer and Incoherent Scatter, Exosphere, 2000
PMRF	=	Pacific Missile Range Facility
POST2	=	Program to Optimize Simulated Trajectories II
PWN	=	Soft Pad, Weather, Probe
ROBIN	=	Rocket Balloon Instrument
SFDT	=	Supersonic Flight Dynamics Test
UKF	=	Unscented Kalman Filter

1 Introduction

The Rocket Balloon Instrument (ROBIN) sphere is an inflatable device typically deployed at high altitude from a sounding rocket [1–3]. The sphere is inflated after deployment from the sounding rocket, and is tracked by radar as it descends through the atmosphere. The radar tracks can be processed to obtain estimates of the atmospheric density and winds along the trajectory of the sphere by assuming the drag coefficient of the sphere is known. The spheres, designated as PWN-12A¹, are made of metallic mylar with a 1 meter diameter and 1200 Pa internal pressure when inflated. ROBIN spheres have been extensively employed over the last 60 years to measure the atmosphere from altitude ranges of 30 to 120 km [5–10].

The typical ROBIN sphere concept of operations is shown in Figure 1. The instrument is launched on a sounding rocket where typically a booster burns out and then separates while the dart payload containing the sphere coasts to apogee. Some example launcher configurations corresponding to the Loki and Super Loki rockets are shown in Figure 2.

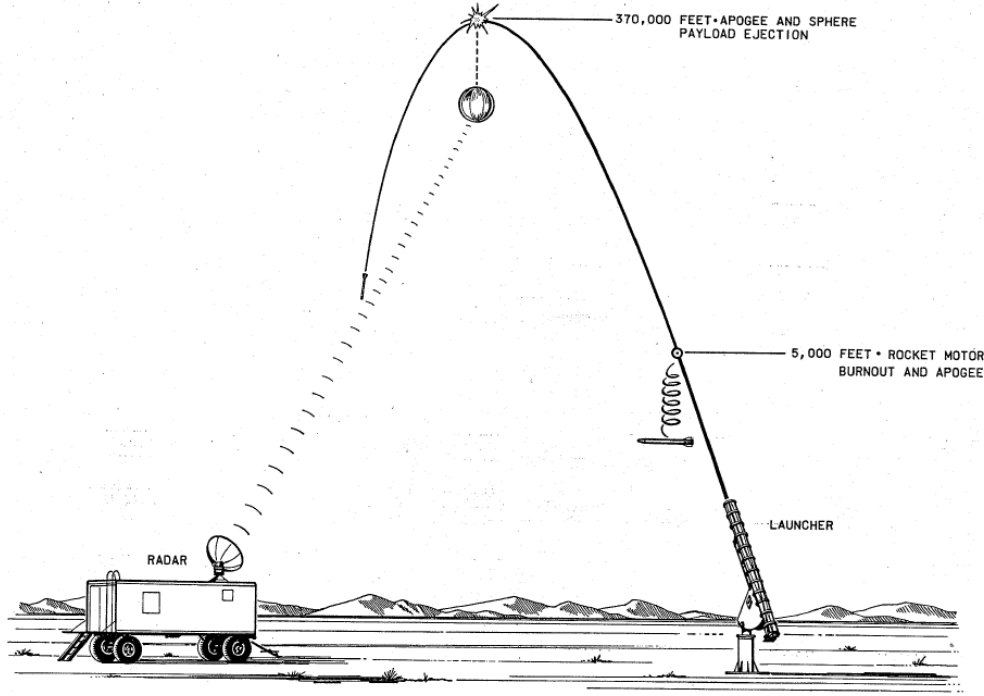


Figure 1: PWN-12A concept of operations [11].

A cross section of the dart upper stage is shown in Figure 3. The dart stage contains the sphere, associated inflation devices, and an ejection piston. The sphere is deployed from the dart at apogee and inflates as the staves break away from the body. The ejection and inflation process is illustrated in Figure 4. A picture of an

¹PWN is a designation in which P = Soft Pad (Launch Environment), W = Weather (Basic Mission), and N = Probe (Vehicle Type) [4]. The 12A designation is an alpha-numeric design number and model identifier.

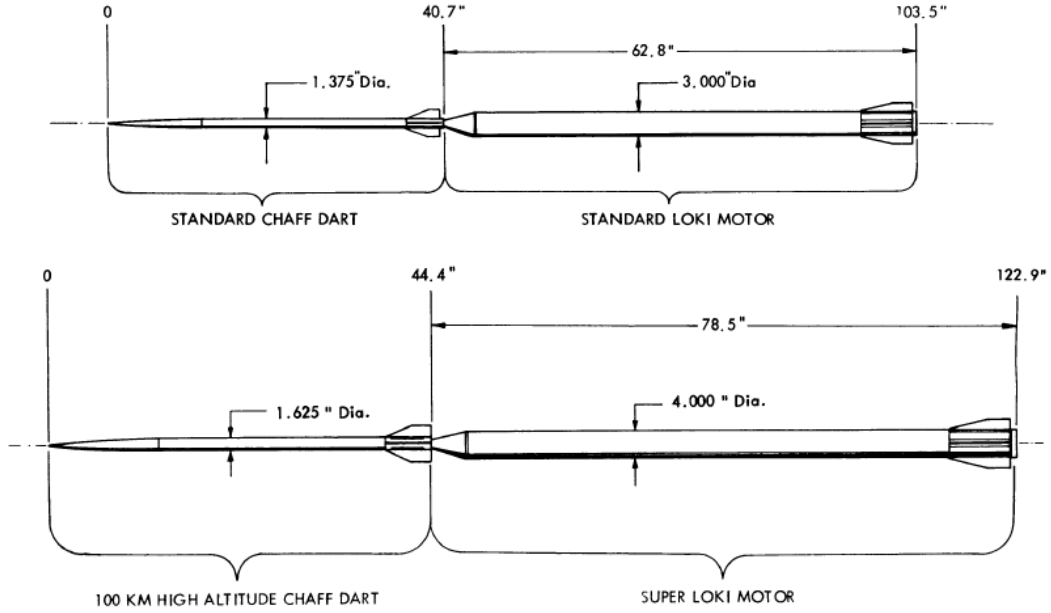


Figure 2: Loki dart (top) and Super Loki dart (bottom) PWN-12A launchers [12,13].

inflated PWN-12A sphere is shown in Figure 5. The inflated sphere then descends through the atmosphere and is tracked by a ground-based radar. The data from the radar track can be used to determine the atmospheric properties based on the ROBIN sphere descent trajectory and estimates of the aerodynamics of the sphere.

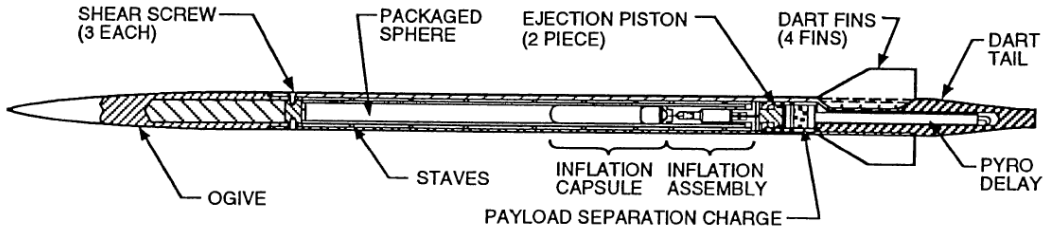


Figure 3: PWN-12A dart cross section [11,14].

Methods for computing estimates of the atmosphere along the trajectory of the sphere have been developed in [15–21]. The methods are generally deterministic in nature, meaning that uncertainties in measurements and parameters are not considered according to a statistical method and thus pose a problem in producing optimal estimates of the atmosphere and the associated uncertainties. The first step in the process is to compute the trajectory of the sphere from the individual radar tracks. The position is then twice differentiated to obtain velocity and accelerations, with various smoothing techniques employed to remove noise from the numerical derivatives. The density is then computed from the vertical velocity and acceleration

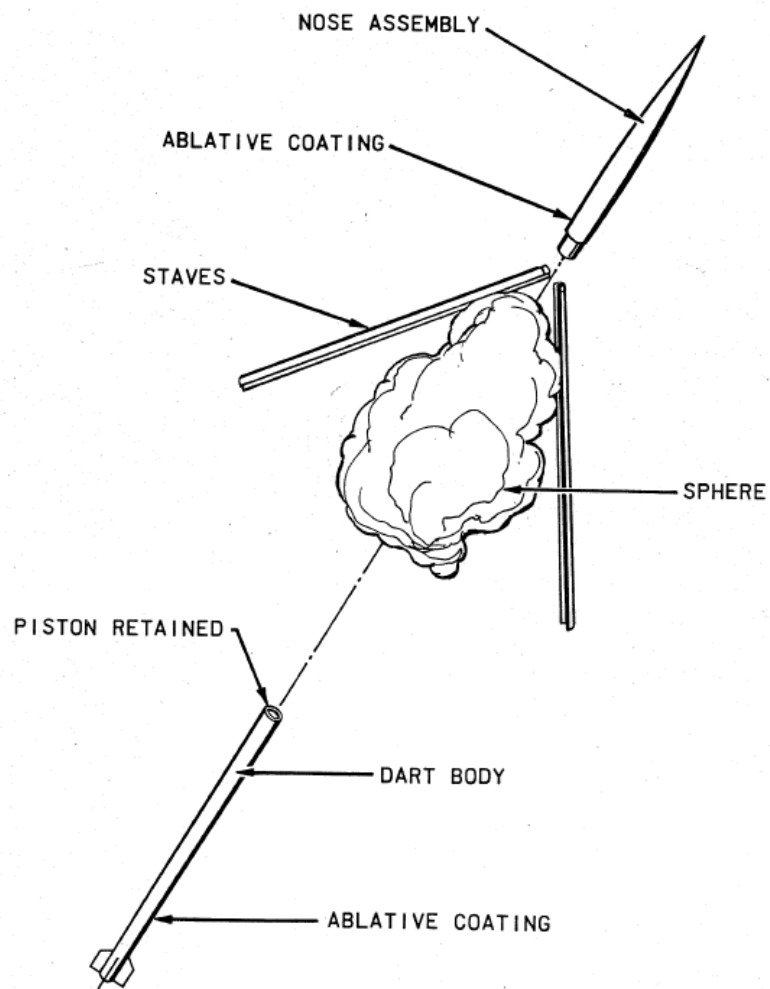


Figure 4: PWN-12A payload ejection and inflation [11].



Figure 5: Inflated PWN-12A ROBIN sphere.

of the sphere, based on an assumed drag coefficient and no vertical component of winds. The horizontal winds are then determined from the kinematics of the sphere's motion in the plane perpendicular to the vertical axis.

The New Statistical Trajectory Estimation Program (NewSTEP) [24–26] is a Kalman filtering tool developed at NASA Langley Research Center for solving post-flight trajectory reconstruction problems. NewSTEP generally operates as a ground-based inertial navigation filter in which accelerations and angular rates measured by an Inertial Measurement Unit (IMU) are integrated in the process model to propagate the filter states in time, and the states are then updated based on various sources of measurement data using a Kalman filter. Three specific types of filters are implemented in NewSTEP: an Extended Kalman Filter (EKF) [24, 25], a Divided Difference Filter (DDF) [26], and an Unscented Kalman Filter (UKF) [26]. A forward and backward pass through the data using the filter is generated to solve a fixed-interval smoothing problem, in which an optimal estimate of the trajectory at each instant in time is computed based on all available measurement data.

In this work, the NewSTEP trajectory reconstruction filter has been modified for solving the ROBIN sphere atmosphere estimation problem. The main modification to the method for this problem is to replace the IMU data integration with an aerodynamic model corresponding to the inflated sphere for the filter's process model. The remainder of this document is organized as follows: Section 2 describes the reformulated equations of motion implemented in the NewSTEP Kalman filter. A simulation case used to test the implementation is described in Section 3. Data from a real ROBIN sphere launch is processed and the results are described in Section 4 and compared with results from legacy ROBIN sphere data processing tools. Concluding remarks are given in Section 5.

2 Kalman Filter Formulation

2.1 Equations of Motion

The main modification of NewSTEP has been made to the equations of motion for modeling drag on the spherical body rather than integration of IMU sensed linear accelerations and angular rates. The sphere is assumed to be uniform in shape such that it can be treated as a point mass with three translational degrees of freedom. The translational equations of motion implemented in NewSTEP are [24, 25]

$$\dot{r} = -w \tag{1}$$

$$\dot{\phi} = \frac{u}{r} \tag{2}$$

$$\dot{\theta} = \frac{v}{r \cos \phi} - \Omega \tag{3}$$

$$\dot{u} = a_{XC} + \frac{1}{r} (uw - v^2 \tan \phi) - \frac{3\mu J_2}{2r^4} \sin 2\phi \tag{4}$$

$$\dot{v} = a_{YC} + \frac{1}{r} (uv \tan \phi + vw) \tag{5}$$

$$\dot{w} = a_{ZC} - \frac{1}{r} (u^2 + v^2) + \frac{\mu}{r^2} - \frac{3\mu J_2}{2r^4} (2 - 3 \cos^2 \phi) \tag{6}$$

Coordinate frames relevant for these equations of motion are illustrated in Figure 6. This figure shows the axis systems for the Earth Centered Inertial (ECI) frame (vectors $\vec{e}_{XI}$, $\vec{e}_{YI}$, and $\vec{e}_{ZI}$), the Earth Centered Earth Fixed (ECEF) frame (vectors $\vec{e}_{XF}$, $\vec{e}_{YF}$, and $\vec{e}_{ZF}$), and the Geocentric (GC) frame (vectors $\vec{e}_{XC}$, $\vec{e}_{YC}$, and $\vec{e}_{ZC}$). The longitude and declination angles (θ and ϕ , respectively) are defined as illustrated in Figure 6. The radius r is the distance from the center of the Earth to the origin of the GC frame, which is carried by the ROBIN sphere body. The inertial velocities u , v , and w , are the components directed along the $\vec{e}_{XC}$, $\vec{e}_{YC}$, and $\vec{e}_{ZC}$ unit vectors, respectively. The sensed acceleration components a_{XC} , a_{YC} , and a_{ZC} are likewise defined as components along the GC frame unit vectors. The sidereal angle λ relates to the motion of the ECEF frame relative to the ECI frame, which are treated as coincident at $t = 0$, thus $\lambda = \Omega t$.

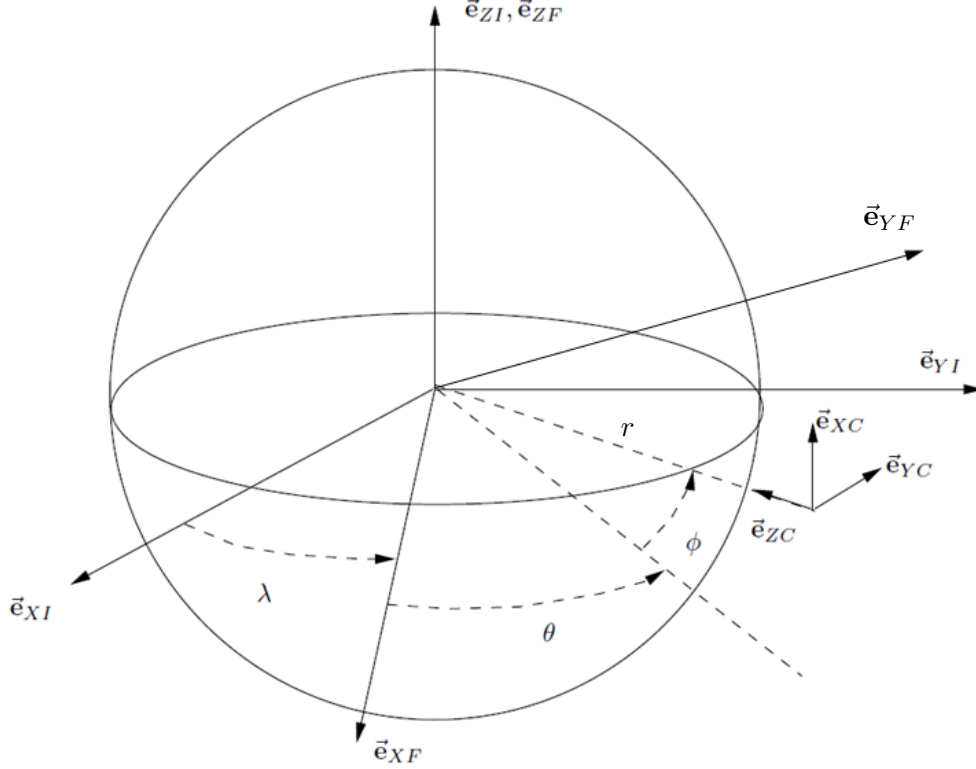


Figure 6: ECI, ECEF, and GC frame [24].

Dynamic equations for the atmospheric states are based on the hydrostatic equation and the ideal gas law for pressure and density states (denoted as p and ρ , respectively), and the winds are modeled as a random walk process. This process treats the winds as constant between measurement updates and the user-specified process noise covariance controls the amount of variability in the random walk process [25]. The winds are modeled as three axis components in the GC frame, which are denoted by u_w , v_w , and w_w , respectively. The resulting dynamic equations for

the atmospheric states are given by

$$\dot{p} = \frac{\mu w \rho}{r^2} \quad (7)$$

$$\dot{\rho} = \frac{\mu w \rho^2}{p r^2} \quad (8)$$

$$\dot{u}_w = 0 \quad (9)$$

$$\dot{v}_w = 0 \quad (10)$$

$$\dot{w}_w = 0 \quad (11)$$

The accelerations in Eqs. (4–6) are modeled for the ROBIN sphere problem as the acceleration due to aerodynamic drag, given by

$$\begin{Bmatrix} a_{XC} \\ a_{YC} \\ a_{ZC} \end{Bmatrix} = -\frac{1}{2} \rho ||\mathbf{V}_w|| \mathbf{V}_w C_D(M, R_e) S \quad (12)$$

where S is the reference area, and the wind-relative velocity is given by

$$\mathbf{V}_w = \begin{Bmatrix} u \\ v - r\Omega \cos \phi \\ w \end{Bmatrix} - \begin{Bmatrix} u_w \\ v_w \\ w_w \end{Bmatrix} \quad (13)$$

The drag coefficient (C_D) is a user-defined table look up based on Mach (M) and Reynolds (R_e) numbers, which is discussed in the next subsection.

2.2 Drag Modeling

The ROBIN sphere atmosphere reconstruction approach is dependent on an assumed drag coefficient of the sphere for integration of the equations of motion described in the previous subsection. ROBIN sphere drag has been studied extensively in various experimental facilities such as those described in [22] and [23]. The ROBIN sphere drag coefficient data were plotted as a function of Mach and Reynolds numbers in [19], as shown in Figure 7.

The data shown in Figure 7 were digitized and implemented as a Matlab table lookup suitable for implementation in the NewSTEP equations of motion. The digitized data are shown in Figure 8 as a function of Mach and Reynolds numbers. Note that the drag coefficient table lookup is set to extrapolate in both Mach and Reynolds numbers by holding the last value.

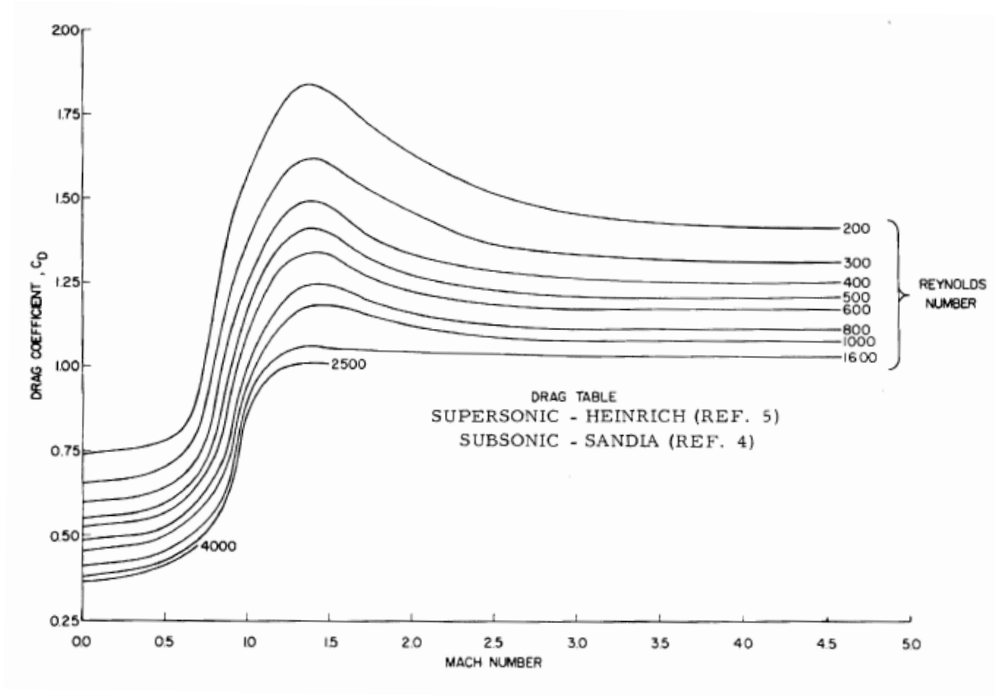


Figure 7: ROBIN sphere drag coefficient [19]. The Sandia and Heinrich sources are given in [22] and [23], respectively.

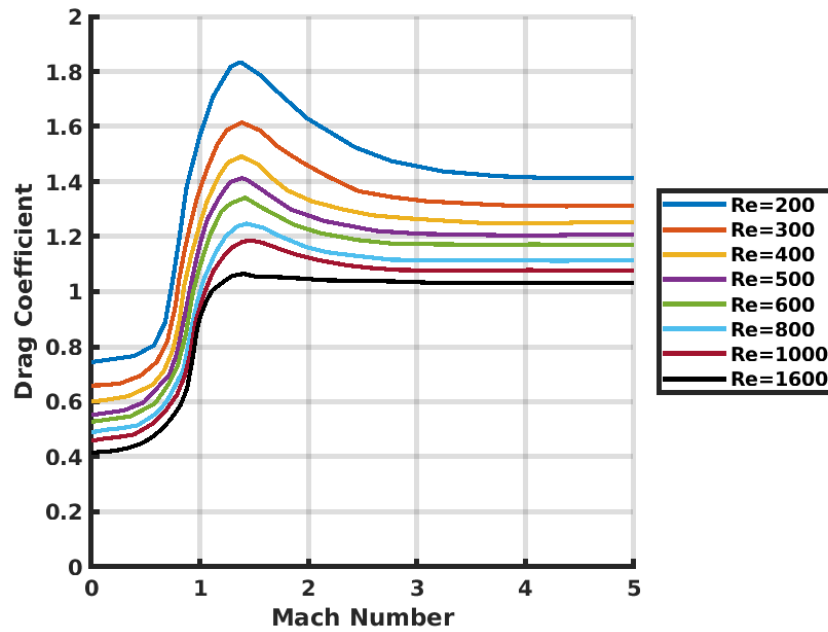


Figure 8: ROBIN sphere drag coefficient digitized from [19].

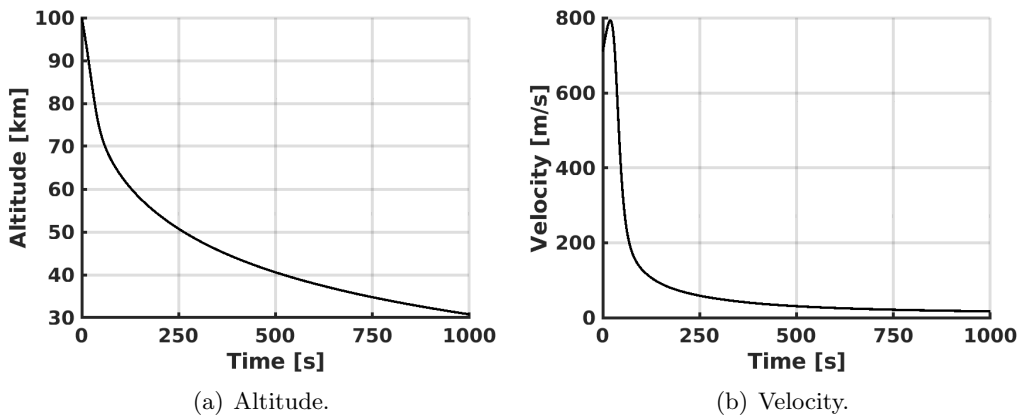
Table 1: Drag coefficient uncertainty from [20].

Altitude km	C_D 3σ uncertainty percent
100 and above	10
95	8
90	6
85	3
80	1
75	2
70	6
65	4
60	3
55 and below	2

The uncertainties in the drag coefficient data as given in [20] are shown in Table 1. The filter accounts for the uncertainties in the modeled drag coefficient using a consider parameter approach [27].

3 Simulation Test Case

A simulated ROBIN sphere trajectory was created in the Program to Optimize Simulated Trajectories II (POST2) [28]. The trajectory begins just after ROBIN sphere inflation at an altitude of 100 km. The simulation was created based on a ROBIN sphere mass of 156.5 grams, a constant drag coefficient of 1.25 with 3σ uncertainty of 1%, and the 1962 US Standard Atmosphere [29] with a constant east wind of 10 m/s. The resulting altitude and velocity of the ROBIN sphere are shown in Figure 9.

**Figure 9: Simulated ROBIN sphere trajectory.**

Range, azimuth, and elevation data were computed based on the trajectory and site coordinates to create simulated radar data. The simulated radar measurements are shown in Figure 10. The simulated radar data set was created at a sample rate of 10 Hz. The radar 3σ measurement uncertainties were assumed to be 30 m in range, 0.45 mrad in azimuth, and 0.6 mrad in elevation [25].

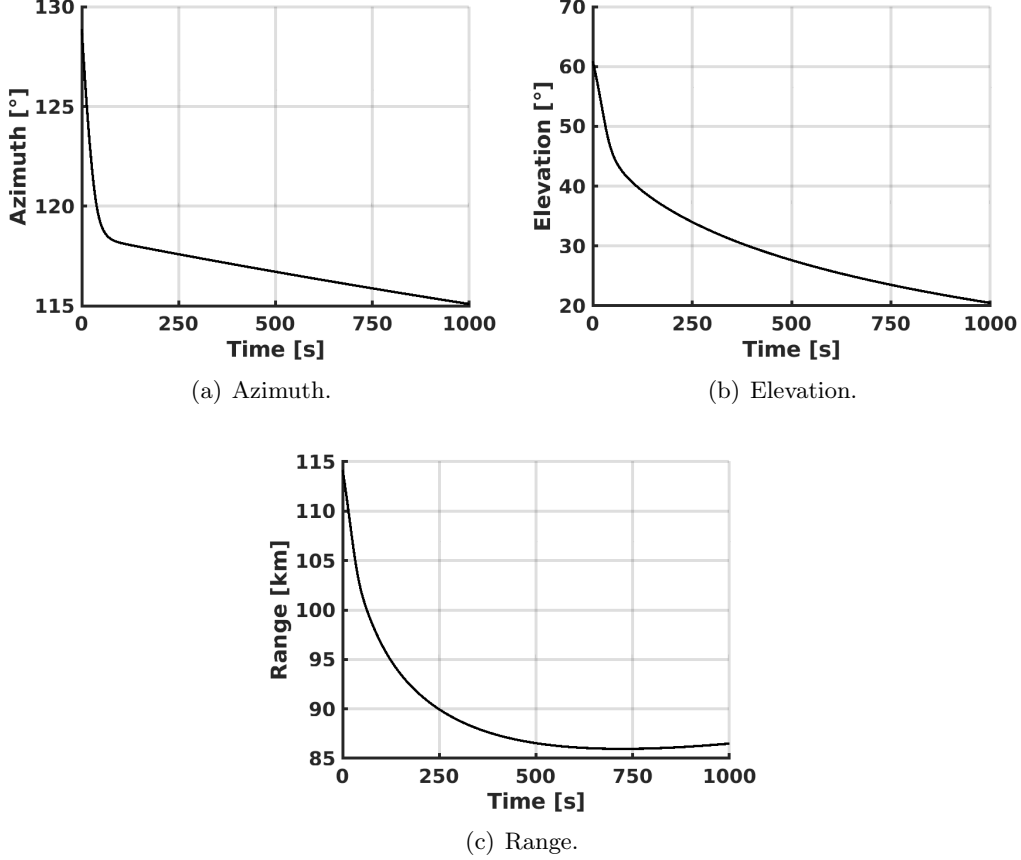
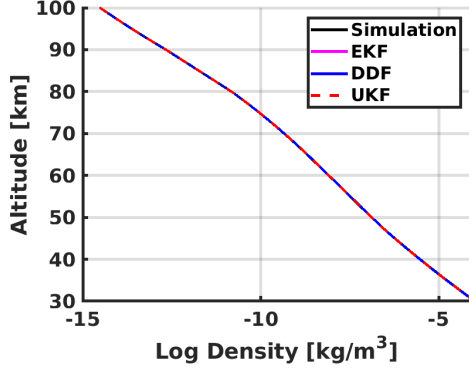


Figure 10: Simulated ROBIN sphere radar measurements.

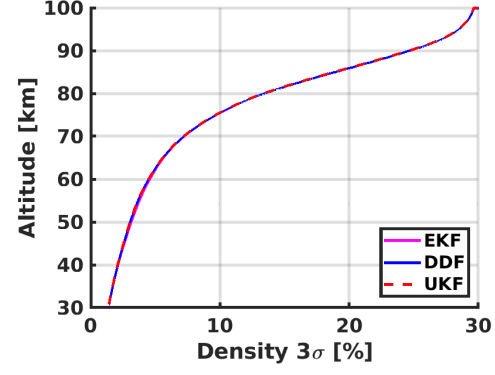
The simulated radar measurements were processed by the EKF, DDF, and UKF using the ROBIN sphere process model to estimate the atmosphere along the trajectory. The filters were initialized assuming zero winds, introducing a 10 m/s initial error in the east wind component. The filters were initialized with 3σ position and velocity uncertainties of 45 m and 3 m/s, respectively, and atmosphere uncertainties of 30% in density and pressure, and 60 m/s in each horizontal wind component and 15 m/s in the vertical wind component. The equations of motion in the process model were integrated numerically using a 4th order fixed-step Runge-Kutta method with time step of 0.01 s.

The results of the atmosphere reconstruction are shown in the following figures. Figures 11 and 12 shows the reconstructed atmosphere and winds from the ROBIN sphere tracking data compared to the 1962 Standard Atmosphere and the assumed winds that were used in the generation of the simulated data. Figure 11 shows the reconstructed density, pressure, and temperature and the associated 3σ uncertainties from the filter covariance. The black curves indicate the 1962 Standard Atmosphere used in generating the trajectory simulation, the magenta curve indicates the solution from the EKF, the blue curve indicates the solution from the DDF, and the red curve is that from the UKF. The reconstructed atmospheric states match with the 1962 Standard Atmosphere, indicating that the filters were able to estimate the truth atmosphere from the simulation. The DDF and UKF results both produce uncertainties smaller than that of the EKF, approximately 0.05 m/s smaller in wind uncertainties, 0.2 K in temperature uncertainty, 0.005% in pressure uncertainty, and 0.1% in density uncertainty. This result is expected since the DDF and UKF are both second-order filters [26]. The reduced uncertainty comes with a cost of nearly 300% of the run time of the EKF for this problem.

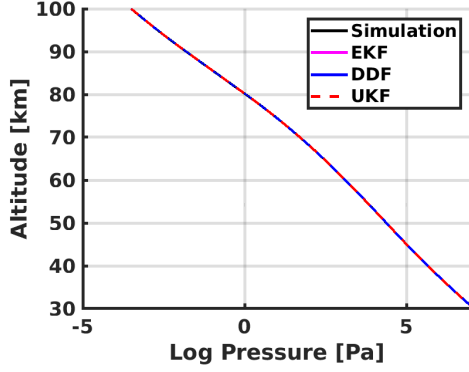
Similarly, the results of the wind state reconstruction are shown in Figure 12. As noted previously, the filters were initialized with a 10 m/s error in the easterly wind component. The estimate of the wind tracks towards the truth value as the filter processes data, converging close to the truth value of 10 m/s at an altitude of roughly 70 km and below. The second-order DDF and UKF results converge slightly faster than the EKF as shown in a detailed view of the east winds over an altitude range of 70 to 90 km in Figure 13. Some small transients are visible in the north and down components of the wind shown in Figure 12.



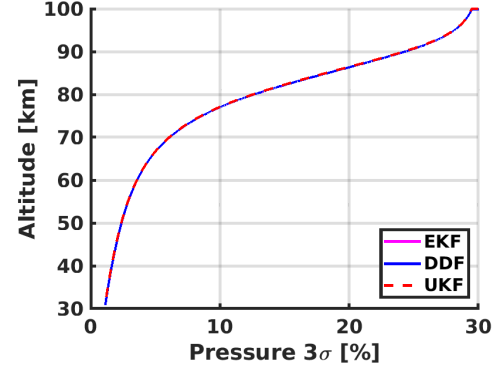
(a) Density.



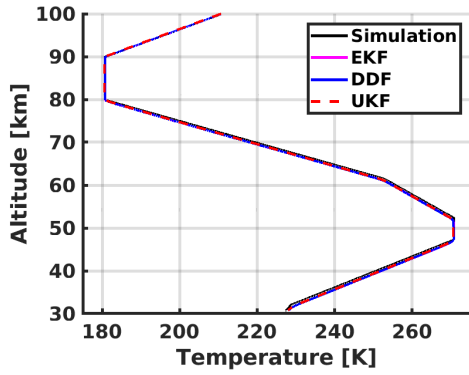
(b) Density uncertainty.



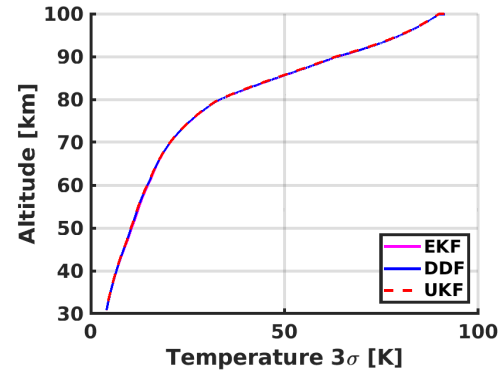
(c) Pressure.



(d) Pressure uncertainty.

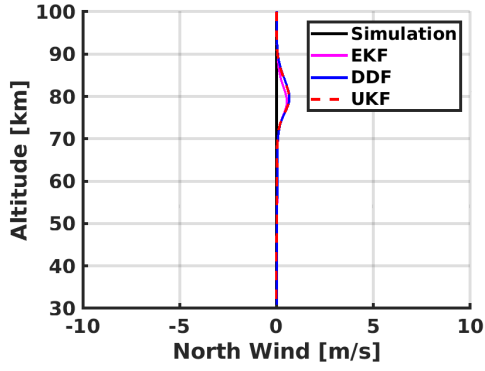


(e) Temperature.

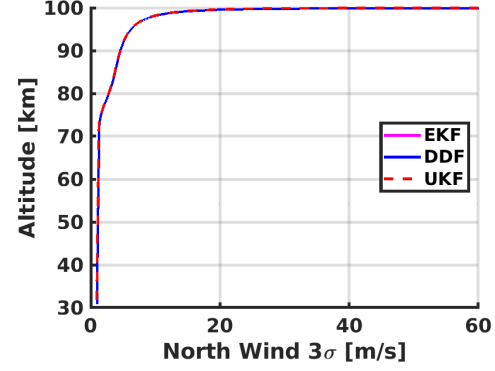


(f) Temperature uncertainty.

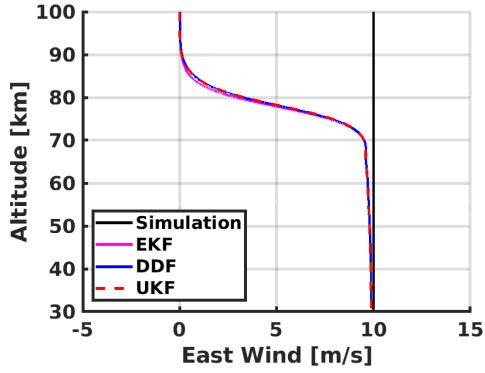
Figure 11: Simulated ROBIN sphere atmosphere reconstruction.



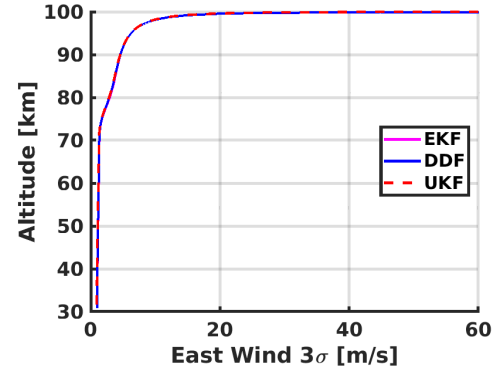
(a) North wind.



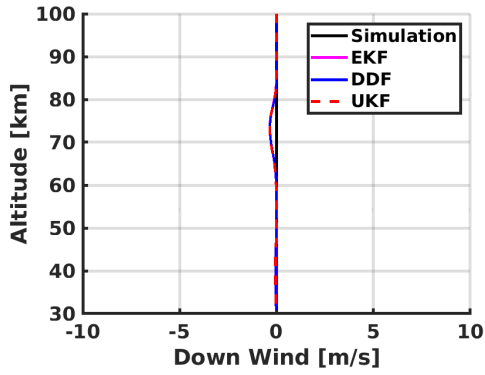
(b) North wind uncertainty.



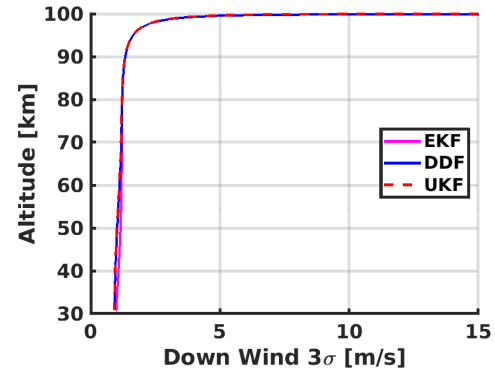
(c) East wind.



(d) East wind uncertainty.



(e) Down wind.



(f) Down wind uncertainty.

Figure 12: Simulated ROBIN sphere wind reconstruction.

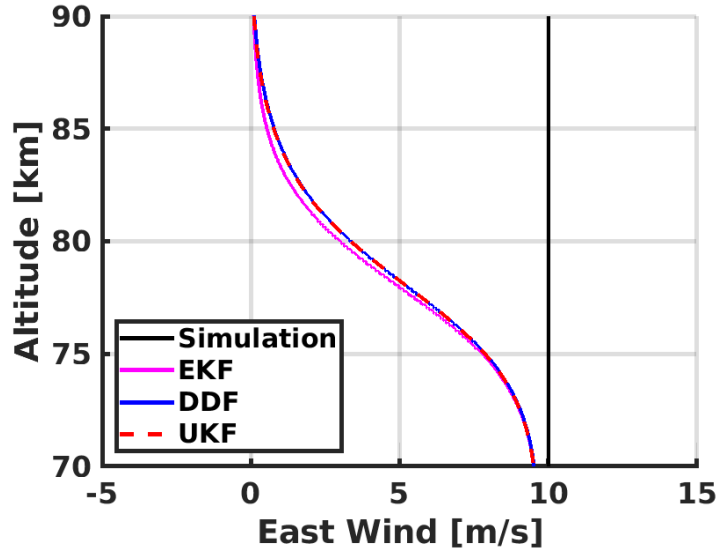
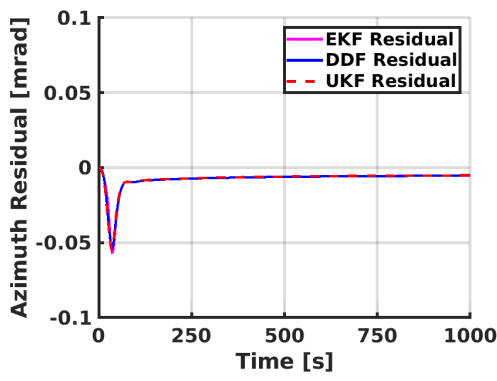
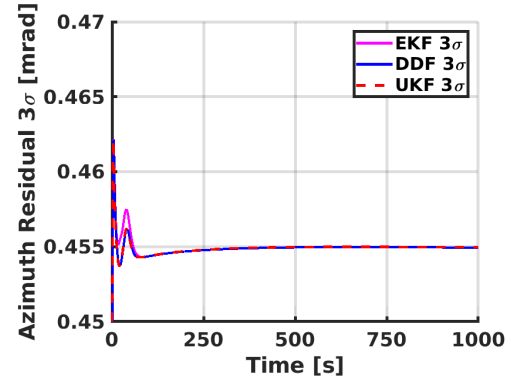


Figure 13: Detailed view of reconstructed east wind components over altitudes from 70 to 90 km.

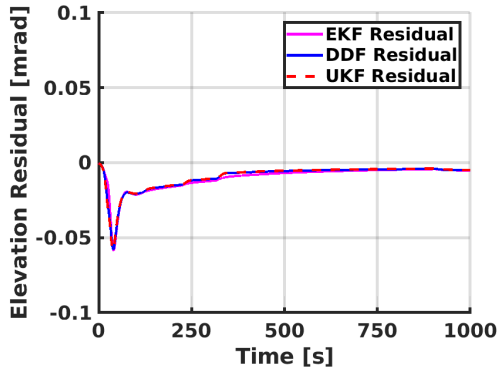
Lastly, the radar measurement residuals are shown in Figure 14(a), (c), and (e) and the corresponding 3σ residual uncertainties are shown in Figure 14(b), (d), and (f). Note the differences in scale between the residual values and the uncertainties. The residuals from the three filters are roughly the same with a small transient after initialization but otherwise are close to zero over the entire reconstruction. The DDF and UKF residual uncertainties are slightly smaller than those of the EKF. These results are indicative of good filter performance for this sample problem.



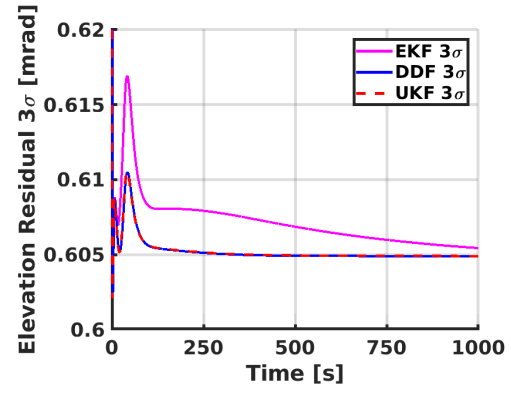
(a) Azimuth.



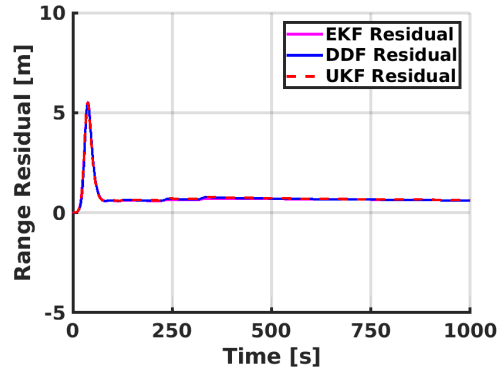
(b) Azimuth 3σ uncertainty.



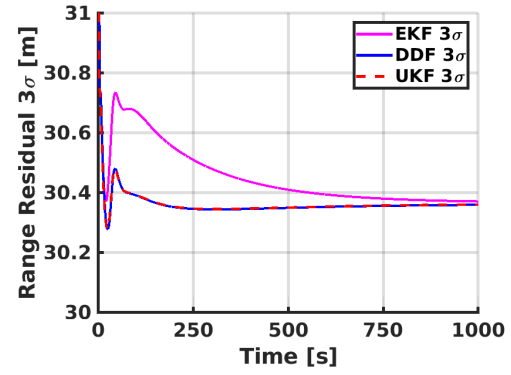
(c) Elevation.



(d) Elevation 3σ uncertainty.



(e) Range.



(f) Range 3σ uncertainty.

Figure 14: Simulated ROBIN sphere reconstruction residuals and uncertainties.

4 Application to ROBIN Sphere Data from the Pacific Missile Range Facility

This section describes the application of the Kalman filter formulation to data acquired from a PWN-12A ROBIN Sphere launch on June 8 2015 at the Pacific Missile Range Facility (PMRF). The ROBIN sphere launch was conducted in support of the second Supersonic Flight Dynamics Test (SFDT) of the Low-Density Supersonic Decelerator (LDSD) project [30–32]. A total of four PWN-12A ROBIN spheres were launched in support of the flight test. In addition, two weather balloons were launched from the ground to provide low altitude atmospheric conditions [32]. A timeline of the ROBIN sphere sounding rocket and weather balloon launches in support of the flight test is given in Table 2, from [32].

Table 2: SFDT-2 Atmospheric data collection launches [32].

Time (HST)	Event
05:59	Weather balloon 1 launch
08:45	Sounding rocket 1 launch
08:59	Weather balloon 2 launch
09:15	Sounding rocket 2 launch
12:35	Sounding rocket 3 launch
13:05	Sounding rocket 4 launch

Each ROBIN sphere was tracked by two radar stations. The ROBIN sphere tracks were processed using legacy tools by meteorologists at PMRF to provide the reconstructed atmosphere to be used in conjunction with other data to evaluate the test vehicle performance, as described in [32]. In this section, the new formulation for NewSTEP to reconstruct the atmosphere from ROBIN sphere tracks is applied to real data from this test. The results are compared to the legacy tool results that were used by the meteorologist to produce atmosphere profiles for the trajectory reconstruction described in [32]. Specifically, data from the second ROBIN sphere sounding rocket launch measured from one radar station are processed as a test case in the NewSTEP reconstruction. The radar track from this ROBIN sphere is shown in Figure 15. The radar track provided data for atmosphere reconstruction from an altitude of approximately 74.75 km to 30.25 km, over a corresponding time interval of 598.85 s. The radar measurements were recorded at a sample rate of 40 Hz.

The Naval Research Laboratory, Mass Spectrometer and Incoherent Scatter, Exosphere, 2000 (NRLMSISE-00) [33] model was used to provide an initial guess of the atmospheric pressure and density for the reconstruction. The winds were initialized as zero in all components. The position states were initialized from the radar measurements, and the velocity states were initialized based on numerical differentiation of the radar measurements. The equations of motion in the process model were integrated using a 4th order fixed-step Runge-Kutta method with step size of 0.0125 s (half the sample rate of the radar measurements). The reconstruction made use of the drag coefficient model shown in Figure 8 and the associated uncertainties

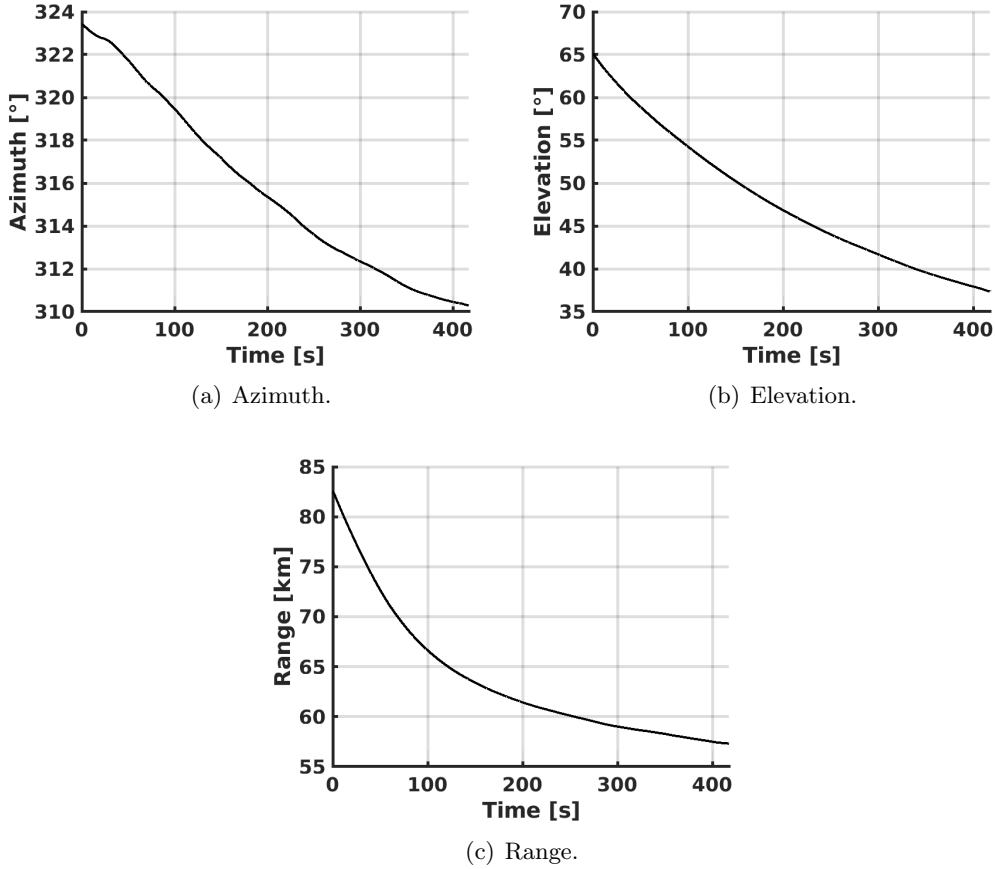
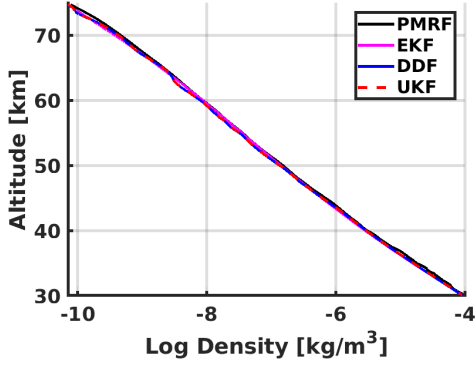


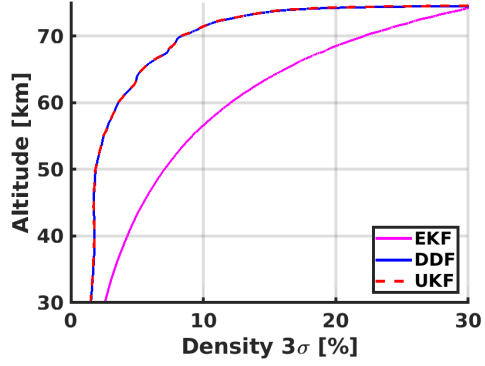
Figure 15: ROBIN sphere radar measurements from sounding rocket 2.

listed in Table 1. The Reynolds number was computed assuming a 1 m reference length and dynamic viscosity for air computed using Sutherland’s law.

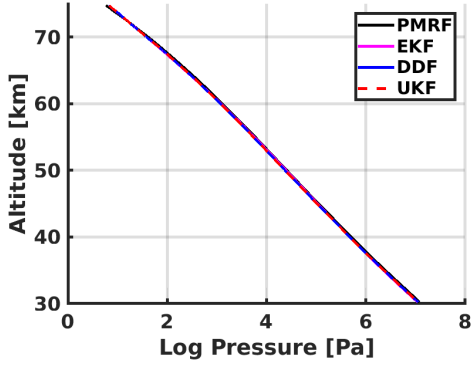
The reconstruction results are shown in the following figures in comparison to a reconstruction generated by meteorologists at PMRF. The reconstructed atmospheric state and uncertainties are shown in Figure 16. The reconstructed density and pressure are in general agreement with each other and with the PMRF reconstruction. The UKF and DDF reconstructions are nearly identical, which is expected as these filters are both second-order and have a similar structure as sigma-point filters [26]. The second-order nature of these filters is reflected in the reduced state uncertainties compared to those of the EKF. Note that the PMRF reconstruction did not include any uncertainties to compare with.



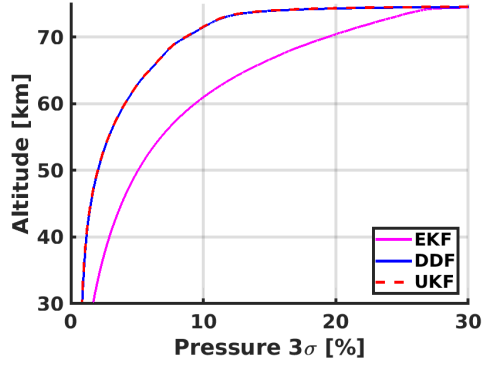
(a) Density.



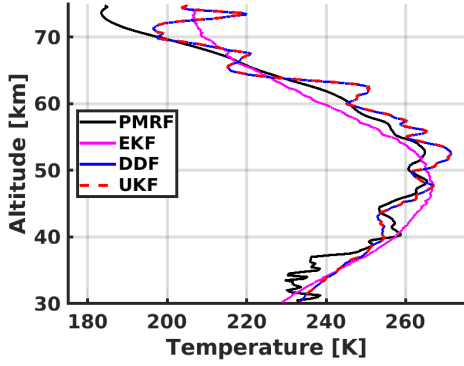
(b) Density uncertainty.



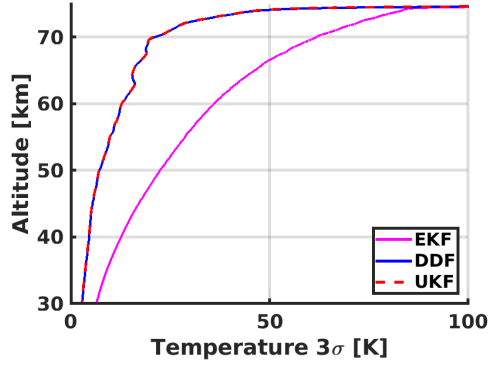
(c) Pressure.



(d) Pressure uncertainty.



(e) Temperature.



(f) Temperature uncertainty.

Figure 16: ROBIN sphere atmosphere reconstruction.

The reconstructed wind states are shown in Figure 17. There is some variability in the reconstructed upper altitude winds but below roughly 55 km the reconstructions agree with each other and with the reconstruction from PMRF. The DDF and UKF both indicate a small downward component of wind in the lower altitude regime. Note again that the PMRF reconstruction did not include uncertainties.

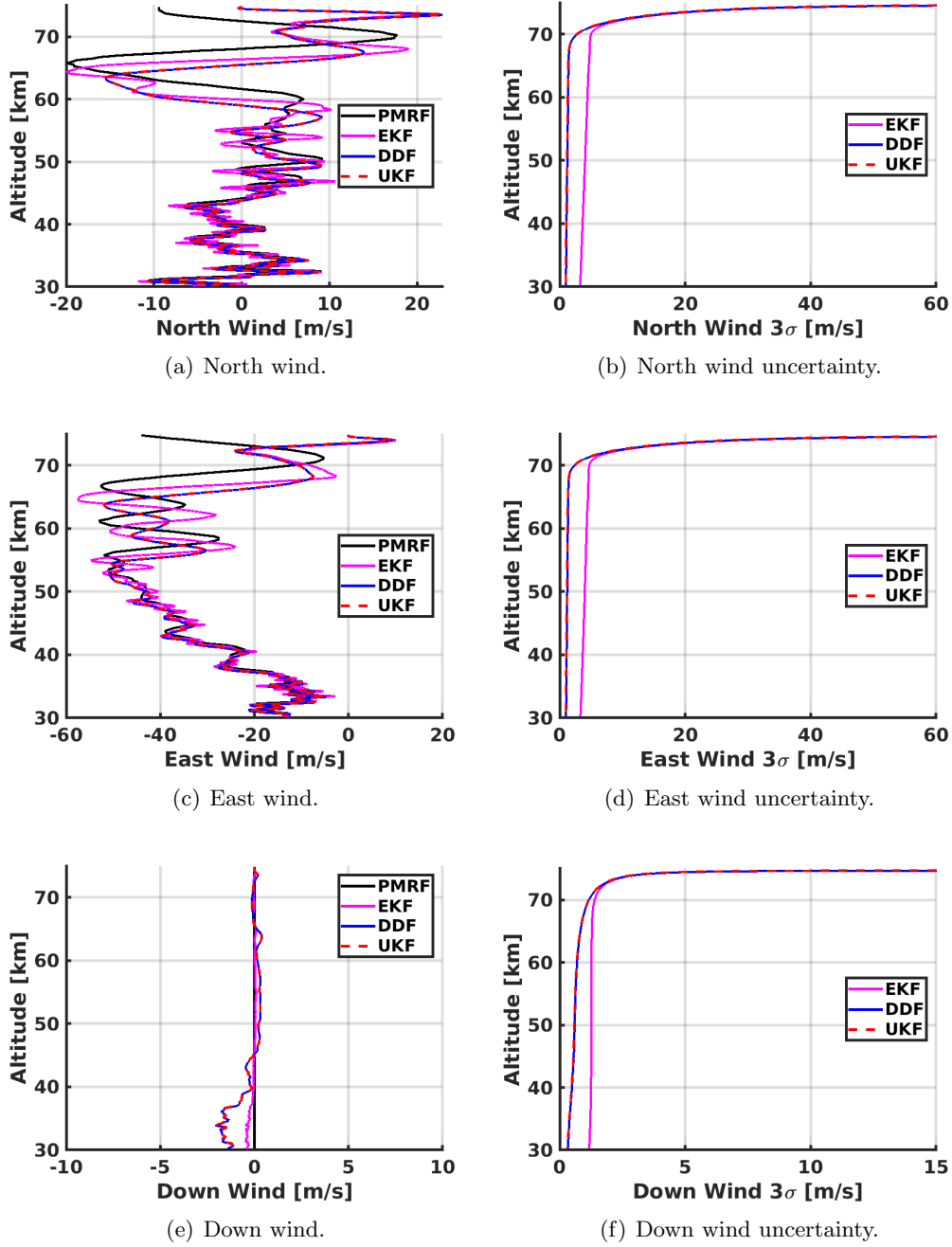


Figure 17: ROBIN sphere wind reconstruction.

The radar measurement residuals are shown in Figure 18(a), (c), and (e) and the corresponding 3σ residual uncertainties are shown in Figure 18(b), (d), and (f). Note the differences in scale between the residual values and the uncertainties. The residuals are roughly zero mean and largely within the $\pm 3\sigma$ bounds, indicating the reconstruction was a fit to the measured radar track without systematic error or

other indicators of problematic filter performance. The DDF and UKF produce slightly smaller residual uncertainties than those of the EKF.

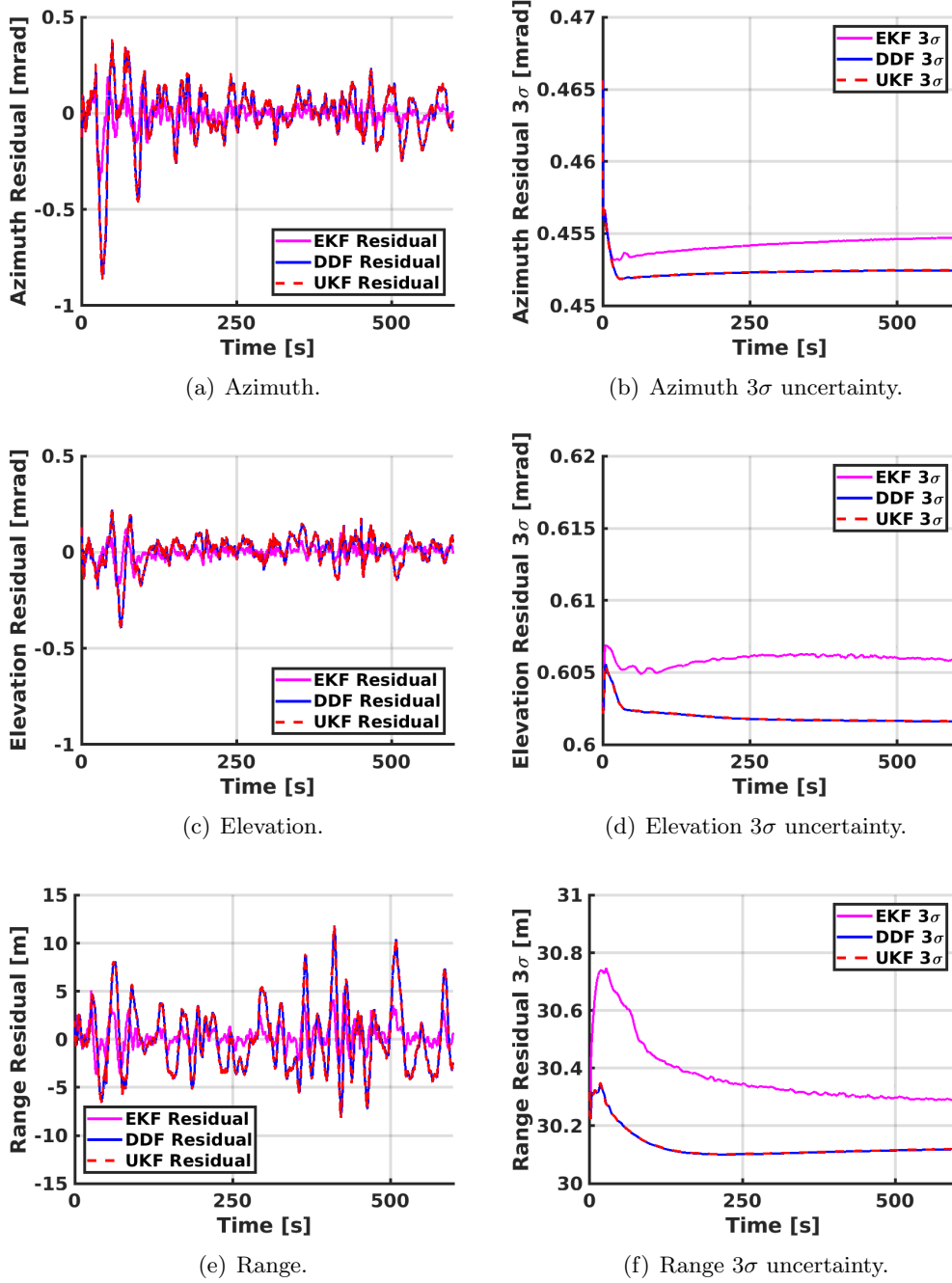


Figure 18: ROBIN sphere reconstruction residuals and uncertainties.

The reconstructed Mach number, Reynolds number, and the ROBIN sphere drag coefficient evaluated along the trajectories are shown in Figure 19. The drag coefficient shown in Figure 19(c) is the result of evaluating the model data shown in Figure 8 along the reconstructed trajectories. The reconstructed drag coefficients from the three filter solutions are shown relative to the model data in Figure 20. The reconstructions are within the data set initially with Mach and Reynolds numbers of approximately 1.1 and 900, respectively. As the ROBIN sphere descends, the Reynolds number shown in Figure 19(b) exceeds the upper range of the model data, and the model is set to hold the last value beyond the limits of the data. Thus, the reconstructed drag coefficients follow the curve corresponding to a Reynolds number of 1600.

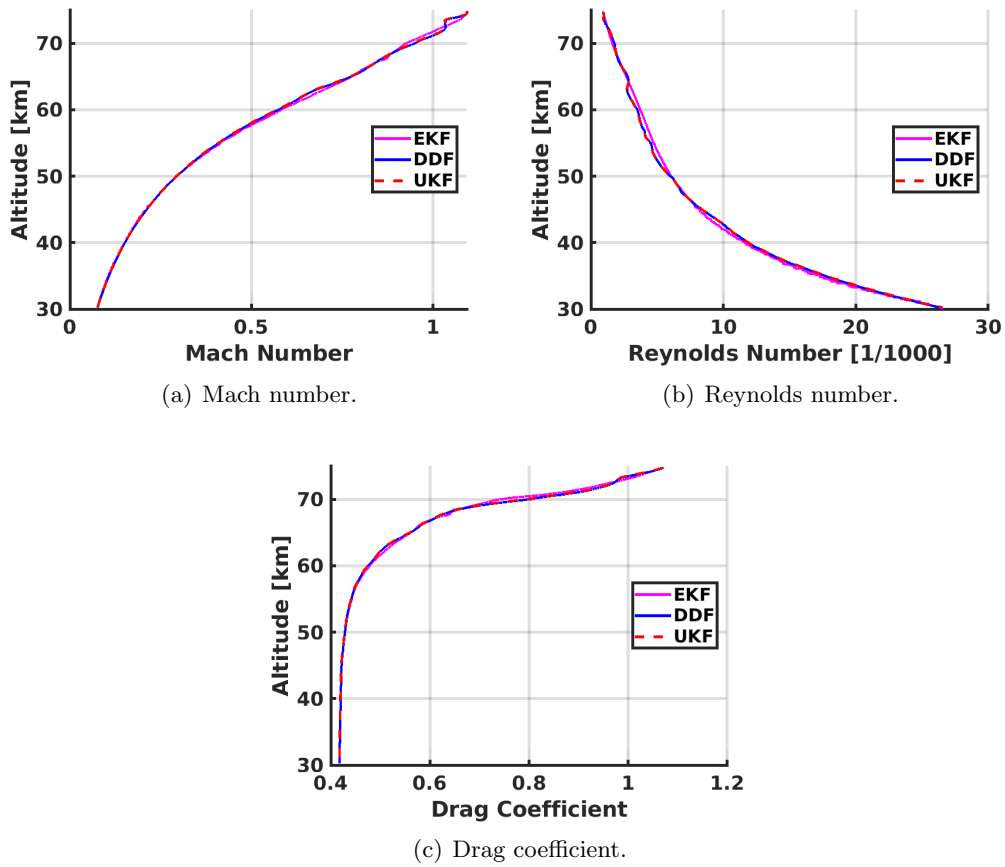


Figure 19: ROBIN sphere drag coefficient model inputs and output.

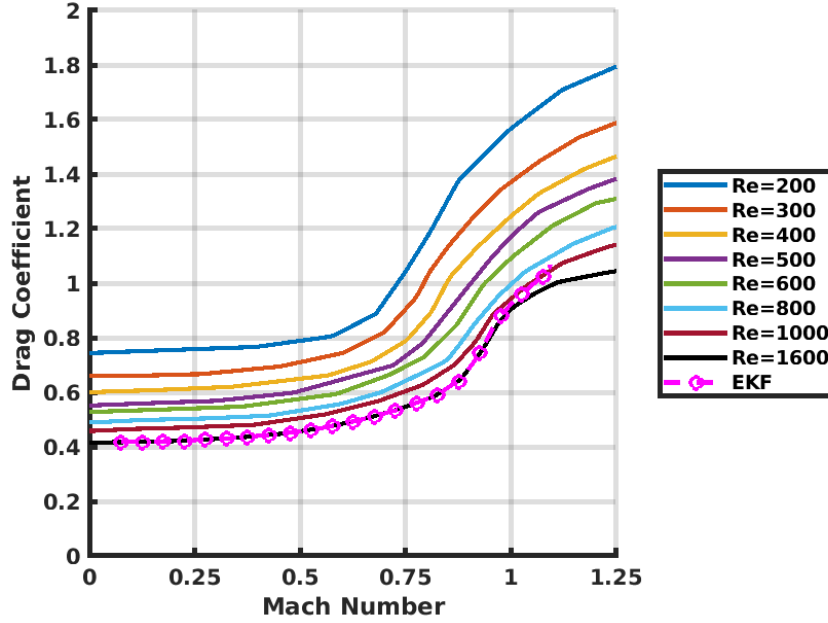


Figure 20: ROBIN sphere drag coefficient output compared to model data. The DDF and UKF curves are similar to the EKF curve and are not shown for clarity (see Figure 19(c)).

5 Conclusions

A new capability for processing ROBIN sphere tracking data has been added to the NewSTEP trajectory reconstruction software. The additions to the code are mainly to the process model used for propagating states forward in time in the filter. The changes to the process model include implementing a drag-only aerodynamic force model. The drag coefficient of the sphere can be any user-specified model, though sample drag coefficient data from prior ROBIN sphere data reduction algorithms was digitized to be included as a default model. The modifications to NewSTEP were tested with a simulation case and actual ROBIN sphere tracking data from a rocket sounding that was launched to provide atmospheric data in support of a flight test. The new ROBIN sphere data reduction capability is expected to provide useful support for future high-altitude flight testing projects.

References

1. Wright, J. B., "The ROBIN Falling Sphere," *Stratospheric Circulation*, Academic Press, Inc., 1969, pp. 115-139. doi: 10.2514/5.9781600864964.0115.0139
2. Wright, J. B., "A Summary of AFCRL Passive-Sphere Development Efforts and Experience," *Status of Passive Inflatable Falling-Sphere Technology for Atmospheric Sensing to 100 km*, NASA SP-219, September 1969, pp. 1-38.
3. Engler, N. A., "The ROBIN System (PWN 12A)," University of Dayton Research Institute, September 1986.
4. Anon., "Designating and Naming Defense Military Aerospace Vehicles," Department of Air Force Instruction 16-401, November 2020.
5. Peterson, J. W., Hansen, W. H., McWatters, K. D., and Bonfanti, G., "Falling Sphere Measurements Over Kwajalein," *Journal of Geophysical Research*, Vol. 70, No. 18, 1965, pp. 4477-4489. doi: 10.1029/JZ070i018p04477
6. Miers, B., T., Avara, E. P., and Olsen, R. O., "Short Time Period Atmospheric Density Variations and Determination of Density Errors from Selected Rocketsonde Sensors," *Monthly Weather Review*, Vol. 100, No. 3, 1972, pp. 189-195. doi: 10.1175/1520-0493(1972)100<0189:STPADV>2.3.CO;2
7. Quiroz, R. S. and Gelmen, M. E., "An Evaluation of Temperature Profiles from Falling Sphere Soundings," *Journal of Geophysical Research*, Vol. 81, No. 3, 1976, pp. 406-412. doi: 10.1029/JC081i003p00406
8. Nestler, M. S., "A Comparative Study of Measurements from Radiosondes, Rocketsondes, and Satellites," NASA CR-168343, April 1983.
9. Schmidlin, F. J., Lee, H. S., and Michel, W., "The Inflatable Sphere: A Technique for the Accurate Measurement of Middle Atmosphere Temperatures," *Journal of Geophysical Research: Atmospheres*, Vol. 96, No. D12, 1991, pp. 22,673-22,682. doi: 10.1029/91JD02395
10. Lübken, F.-J., Hillert, W., Lehmacher, G., von Zahn, U., Bittner, M., Offermann, D., Schmidlin, F. J., Hauchecorne, A., Mourier, M., and Czechowsky, P., "Intercomparison of Density and Temperature Profiles Obtained by Lidar, Ionization Gauges, Falling Spheres, Datasondes and Radiosondes during the DYANA Campaign," *Journal of Atmospheric and Terrestrial Physics*, Vol. 56, Nos. 13-14, 1994, pp. 1969-1984. doi: 10.1016/0021-9169(94)90023-X
11. Anon., "Launch Operation Meteorological Probes PWN-10D, PWN-10B, PWN-11D, and PWN-12A," Space Data Corporation, SDC TM-1782, Rev. A, June 10, 1982.
12. Bollermann, B. and Walker, R. L., "Super Loki Dart Meteorological Rocket System," NASA CR-61238, June 1968.

13. Bollermann, B. and Walker, R. L., "Design, Development and Flight Test of the Super Loki Dart Meteorological Rocket Systems," Air Force Cambridge Research Laboratories, AFCRL-72-0382, May 1972.
14. Krause, D. J., "Rocket Systems for Meteorological and Upper Atmospheric Soundings," *European Rocket and Balloon Programmes and Related Research, Proceedings of the 13th ESA Symposium held 26-29 May, 1997 in Öland, Sweden*. Edited by Brigitte Kaldeich-Schürmann. ESA SP-397. Paris: European Space Agency, 1997, pp. 293-298.
15. Lally, V. E. and Leviton, R., "Accuracy of Wind Determination from the Track of a Falling Object," Air Force Surveys in Geophysics No. 93, Geophysics Research Directorate, Air Force Cambridge Research Laboratories, ASTIA No. AD 146858, March 1958.
16. Leviton, R. and Wright, J. B., "Accuracy of Density from the ROBIN Falling Sphere," Geophysics Research Directorate, Air Force Cambridge Research Laboratories, GRD Research Notes No. 73, AFCRL 1095, December 1961.
17. Engler, N. A., "Development of Methods to Determine Winds, Density, Pressure, and Temperature from the Robin Falling Balloon," Air Force Cambridge Research Laboratories, AFCRL-65-448, 1965.
18. Luers, J. K. and Engler, N., "On Optimum Methods for Obtaining Wind Data from Balloon Sensors," *Journal of Applied Meteorology*, Vol. 6, No. 5, 1967, pp. 816-823. doi: 10.1175/1520-0450(1967)006<0816:OOMFOW>2.0.CO;2
19. Luers, J. K. and Engler, N. A., "High-Altitude ROBIN Data-Reduction Program," *Status of Passive Inflatable Falling-Sphere Technology for Atmospheric Sensing to 100 km*, NASA SP-219, September 1969, pp. 111-143.
20. Luers, J., "A Method of Computing Winds, Density, Temperature, Pressure, and their Associated Errors from the High Altitude ROBIN Sphere Using an Optimum Filter," Air Force Cambridge Research Laboratories, AFCRL-70-0366, July 1970.
21. Luers, J., MacArthur, C. D., and Soltes, A., "Optimum Radars and Filters for the Passive Sphere System," NASA CR-111952, January 1971.
22. Goin, K. L. and Lawrence, W. R., "Subsonic Drag of Spheres at Reynolds Numbers from 200 to 10,000," *AIAA Journal*, Vol. 6, No. 5, 1968, pp. 961-962. doi: 10.2514/3.4648
23. Heinrich, H. G., Niccum, R. J., Haak, E. L., Jamison, L. R., and George, R. L., "Modification of the ROBIN Meteorological Balloon, Vol. II - Drag Evaluations," Air Force Cambridge Research Laboratories, AFCRL-65-735(II), September 1965.
24. Karlgaard, C. D., Tartabini, P. V., Blanchard, R. C., Kirsch, M., and Toniolo, M. D., "Hyper-X Post-Flight Trajectory Reconstruction," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, 2006, pp. 105-115. doi: 10.2514/1.12733

25. Karlgaard, C. D., Beck, R. E., Derry, S. D., Brandon, J. M., Starr, B. R., Tartabini, P. V., and Olds, A. D., “Ares I-X Trajectory Reconstruction: Methodology and Results,” *Journal of Spacecraft and Rockets*, Vol. 50, No. 3, 2013, pp. 641-661. doi: 10.2514/1.A32345
26. Vedvik, S. and Karlgaard, C. D., “Iterated Sigma-Point Kalman Filtering for Trajectory Reconstruction,” NASA/TM-20240001235, March 2024.
27. Tapley, B. D., Schutz, B. E., and Born, G. H., *Statistical Orbit Determination*, Elsevier, Inc., 2004, Chapter 6.
28. Williams, R., Lugo, R., Marsh, S., Hoffman, J., Shidner, J., and Aguirre, J., “Enabling Thread Safety and Parallelism in the Program to Optimize Simulated Trajectories II,” AIAA Paper 2023-0148, January 2023. doi: 10.2514/6.2023-0148
29. Anon. “U.S. Standard Atmosphere, 1962: ICAO Standard Atmosphere to 20 Kilometers, Proposed ICAO Extension to 32 Kilometers, Tables and Data to 700 Kilometers,” U.S. Government Printing Office, Washington, D.C., 1962.
30. Blood, E. M., Ivanov, M., O’Farrell, C., Ginn, J. M., Kutty, P., Karlgaard, C. D., and Dutta, S., “LDSD Supersonic Flight Dynamics Test 1: Post-Flight Reconstruction,” IEEE Aerospace Conference, Big Sky, MT, March 2015. doi: 10.1109/AERO.2015.7119246
31. Clark, I. and Adler, M., “Summary of the Second High-Altitude, Supersonic Flight Dynamics Test for the LDSD Project,” IEEE Aerospace Conference, Big Sky, MT, March 2016. doi: 10.1109/AERO.2016.7500618
32. Karlgaard, C. D., Kutty, P., O’Farrell, C., Blood, E. M., Ginn, J., and Schoenenberger, M., “Reconstruction of Atmosphere, Trajectory, and Aerodynamics for the Low Density Supersonic Decelerator Test Vehicles,” *Journal of Spacecraft and Rockets*, Vol. 56, No. 1, 2019, pp. 221-240. doi:10.2514/1.A34223
33. Picone, J. M., Hedin, A. E., Drob, D. P. and Aikin, A. C., “NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues,” *Journal of Geophysical Research: Space Physics*, Vol. 107, No. A12, 2002, pp. 15-1–15-16, doi: 10.1029/2002JA009430