

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering

Washington, D.C. 20594

November 19, 2018

Aircraft Performance Study

by John O'Callaghan

Location: Rockford, Illinois
Date: December 4, 2017
Time: 18:02 Central Standard Time (CST)
Aircraft: Beechcraft (Textron Aviation) C90 King Air, registration N500KR
NTSB#: CEN18LA047

TABLE OF CONTENTS

A.	ACCIDENT	1
B.	GROUP	1
C.	HISTORY OF FLIGHT	1
D.	DETAILS OF THE INVESTIGATION	3
I.	Airplane position based on radar and Appareo Stratus GPS data	3
	Description of ARSR and ASR Radar Data	3
	Primary and Secondary Radar Returns	3
	Recorded Radar Data	3
	Appareo Stratus 2S ADS-B Receiver Data	4
II.	Crash site and winds aloft information	6
	Crash site information	6
	Winds aloft information	6
III.	Airplane description and Zero Fuel Weight estimate	9
IV.	Fuel burn calculations	9
	AFM “Flight Planning” method	9
	Fuel burn simulation method	13
	Fuel burn simulation results	17
V.	Airplane performance during approach to KRFD	17
E.	CONCLUSIONS	19
F.	REFERENCES	20
G.	GLOSSARY	21
	Acronyms	21
	English symbols	21
	Greek symbols	21
	FIGURES	22

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A. ACCIDENT

Location: Rockford, Illinois

Date: December 4, 2017

Time: 18:02 Central Standard Time (CST)¹

Aircraft: Beechcraft (Textron Aviation) C90 King Air, registration N500KR

NTSB#: CEN18LA047

B. GROUP

Not Applicable

C. HISTORY OF FLIGHT

On December 4, 2017, about 18:02 CST, a Beechcraft (now Textron Aviation) C90 King Air airplane, N500KR, impacted terrain near the Chicago/Rockford International Airport (KRFD), near Rockford, Illinois. The private pilot and one passenger sustained serious injuries and two passengers sustained minor injuries. The airplane sustained substantial fuselage damage during the impact. The airplane was registered to and operated by the pilot as a 14 Code of Federal Regulations Part 91 personal flight. Visual meteorological conditions prevailed in the area about the time of the accident, and the flight requested a local instrument flight rules (IFR) clearance near KRFD. The flight originated from the Kissimmee Gateway Airport (KISM), near Orlando, Florida, about 13:42 and was destined for KRFD.

According to preliminary information from the Federal Aviation Administration (FAA), the airplane's pilot requested and was given an IFR clearance as the airplane was nearing KRFD. The pilot also requested priority handling because he had "lost a transfer pump," had "a little less fuel" than he thought, and didn't "want to come in with a single engine." The pilot was cleared to perform a visual approach to runway 19. As the airplane approached the airport, the pilot requested the runway lights for runway 25 be turned on and stated that he had lost an engine. The airplane was subsequently given a clearance to land on runway 25. The airplane was observed impacting terrain before the threshold for runway 25.

Based on the condition of the airplane at the crash site, investigators suspected that the airplane lost power on approach due to fuel starvation. Consequently, this *Aircraft Performance Study* (the *Study*) presents the results of estimating the amount of fuel remaining in the airplane at the time of the accident, based on information about the initial fuel loading at KRFD for the

¹ Local time at Rockford on the day of the accident was Central Standard Time (CST). CST = UTC - 6 hours. Times in this *Study* are in CST unless otherwise noted.

airplane's prior flight on December 1 from KRFD to KISM, refueling records at KISM, and the estimated fuel burns for the December 1 KRFD-KISM flight and the December 4 KISM-KRFD (accident) flight. Information used to compute the fuel burn during these two flights includes:

- Data recorded on an Appareo Stratus 2S ADS-B receiver carried on board N500KR
- FAA radar surveillance data
- METAR reports at KRFD and KISM for both flights
- Enroute winds aloft forecasts for both flights
- Available weight and balance and fueling information (the pilot, passenger, and baggage loads for both flights were the same, but the fuel loads were different)
- Airplane performance data contained in the Airplane Flight Manual (AFM)

In addition, a High-Resolution Rapid Refresh (HRRR) computer model of the winds aloft over KRFD at the time of the accident was used along with the Stratus data to compute the airplane's lift coefficient (C_L) during the approach, for comparison to the maximum C_L capability of the airplane ($C_{L\max}$). (The results indicate that the airplane C_L did not approach $C_{L\max}$, and that therefore the airplane did not stall.)

Additional information used in this *Study* includes Air Traffic Control (ATC) communications, and the airplane configuration and condition documented at the crash site.

The fuel remaining at the time of the accident is computed in two ways: (1) Using the flight planning methods described in the AFM, using a flight path through eight waypoints in between KISM and KRFD; and (2) Using a fuel burn "simulation" developed from the fuel burn and other performance data published in the AFM. The simulation models fuel burn as a function of engine shaft horsepower (SHP) and pressure altitude, and computes the SHP developed during the flights using AFM performance data, the ground speed and rate of climb recorded by the Stratus device, and winds aloft forecasts. Both methods required computing 8.5 hours of fuel burn over the two KRFD-KISM and KISM-KRFD flights. The calculations assume full fuel at departure for the 4.17-hour KRFD-KISM flight on December 1, and refueling with 150 gallons of fuel at KISM prior to the 4.33-hour return flight to KRFD on December 4.

The results of the "flight planning" method indicate that the airplane could have made the return flight to KRFD with about 119 lb. (18 gal.) of fuel remaining. The results of the "fuel burn simulation" method indicate that the airplane would have run out of fuel on approach to KRFD, about 8.75 minutes before the end of the Stratus data, and about 7 minutes before the calculations show a large decrease in SHP .

These results and the condition of the airplane at the accident site are consistent with a loss of engine power due to fuel starvation during the airplane's approach to KRFD.

For Visual Flight Rules (VFR) flights, 14 Code of Federal Regulations (CFR) §91.151 requires sufficient fuel to fly to the intended destination, and then for another 30 minutes (during the day) or another 45 minutes (at night). For IFR flights, §91.167 requires sufficient fuel to fly to the intended destination, and then for another 45 minutes (and more, if weather forecasts indicate that the ceiling or visibility at the destination may be below 2000 ft. and 3 miles, and the flight needs to divert to an alternate).

The details of these performance estimates, and the data upon which they are based, are presented in the following sections.

D. DETAILS OF THE INVESTIGATION

I. Airplane position based on radar and Appareo Stratus GPS data

Description of ARSR and ASR Radar Data

In general, two types of radar are used to provide position and track information for aircraft cruising at high altitudes between airport terminal airspaces, and for those operating at low altitude and speeds within terminal airspaces.

Air Route Surveillance Radars (ARSRs) are long range (250 nm) radars used to track aircraft cruising between terminal airspaces. ARSR antennas rotate at 5 to 6 RPM, resulting in a radar return every 10 to 12 seconds. Airport Surveillance Radars (ASRs) are short range (60 nm) radars used to provide air traffic control services in terminal areas. ASR antennas rotate at 13 to 14 RPM, resulting in a radar return every 4.3 to 4.6 seconds. N500KR was tracked by multiple ASR and ARSR radars during its December 1st and December 4th flights.

Primary and Secondary Radar Returns

A radar detects the position of an object by broadcasting an electronic signal that is reflected by the object and returned to the radar antenna. These reflected signals are called *primary returns*. Knowing the speed of the radar signal and the time interval between when the signal was broadcast and when it was returned, the distance, or range, from the radar antenna to the reflecting object can be determined. Knowing the direction the radar antenna was pointing when the signal was broadcast, the direction (or bearing, or azimuth) from the radar to the object can be determined. Range and azimuth from the radar to the object define the object's position.

The strength or quality of the return signal from the object depends on many factors, including the range to the object, the object's size and shape, and atmospheric conditions. In addition, any object in the path of the radar beam can potentially return a signal, and a reflected signal contains no information about the identity of the object that reflected it. Many times, these difficulties make distinguishing individual aircraft from each other and other objects (e.g., flocks of birds) based on primary returns alone unreliable and uncertain.

To improve the consistency and reliability of radar returns, aircraft are equipped with transponders that sense beacon interrogator signals broadcast from radar sites, and in turn broadcast a response signal. Thus, even if the radar site is unable to sense a weak reflected signal (primary return), it will sense the response signal broadcast by the transponder and be able to determine the aircraft position. The response signal can also contain additional information, such as the identifying "beacon code" for the aircraft, and the aircraft's pressure altitude (also called "Mode C" altitude). Transponder signals received by the radar site are called *secondary returns*. N500KR was assigned a beacon code of 4211 during the December 1st KRFD-KISM flight, and multiple beacon codes during the December 4 KISM-KRFD accident flight (including 1051 during departure from KISM, 1200 (VFR) during most of the cruise portion of the flight, and 4205 during the approach to KRFD).

Recorded Radar Data

Recorded data from the various radar sites that tracked N500KR was obtained from the Federal Aviation Administration (FAA), and includes the following parameters:

- UTC time of the radar return, in hours, minutes, and seconds.
- Transponder beacon code associated with the return (secondary returns only)
- Transponder reported altitude in hundreds of feet associated with the return (secondary returns only). The transponder reports pressure altitude. The altitude recorded in the file depends on the site recording the data; some sites record both pressure altitude, and pressure altitude adjusted for altimeter setting (MSL altitude). Others record just the MSL altitude. The files for this case just contain pressure altitude. The resolution of the altitude data in the radar file is ± 50 ft.
- Slant Range from the radar antenna to the return, in nm. The accuracy of this data is $\pm 1/16$ nm or about ± 380 ft.
- Azimuth relative to magnetic north from the radar antenna to the return; the magnetic variation from true north depends on the location of each radar site. Azimuth is reported in Azimuth Change Pulses (ACPs). ACP values range from 0 to 4096, where 0 = 0° magnetic and 4096 = 360° magnetic. Thus, the azimuth to the target in degrees would be:

$$(\text{Azimuth in degrees}) = (360/4096) \times (\text{Azimuth in ACPs}) = (0.08789) \times (\text{Azimuth in ACPs})$$

The accuracy of azimuth data is ± 2 ACP or $\pm 0.176^\circ$.

- The latitude and longitude of the return computed by the radar system data processing algorithms.

The recorded radar position data matches the Global Positioning System (GPS) position data recorded by the Stratus device. Since the Stratus position data is more accurate and is recorded at a higher sampling rate (5 Hz) than the radar data, it is used in this *Study* instead of the radar data. However, the Stratus records GPS altitude (i.e., true altitude above MSL), whereas the radar data records pressure altitude. Since pressure altitude is used for flight planning, the cruise pressure altitudes recorded in the radar data are used for the fuel consumption calculations using the “flight planning” method, instead of the GPS altitudes recorded by the Stratus device. However, the Stratus GPS altitudes are used to compute rate of climb and power required as part of the “simulation” fuel consumption calculation method. The Stratus data are also used for the C_L calculations during the approach. The fuel consumption calculations are described in Section D-IV; the C_L on approach calculations are described in Section D-V; and the Stratus data is described below.

Appareo Stratus 2S ADS-B Receiver Data

A Stratus 2S ADS-B receiver carried on N500KR was recovered from the airplane sent to the NTSB recorder laboratory in Washington, D.C. for readout, as documented in Reference 1. Reference 1 describes the Stratus device as follows:

The Appareo Stratus 2S is a battery-operated ADS-B receiver with Global Positioning System (GPS) capability designed to interface with an iPad, iPhone, or iPod Touch running the ForeFlight Mobile application via Wi-Fi. The Stratus uses ADS-B to provide access to NEXRAD radar, METARs, TAFs, NOTAMs and other FAA products via the ForeFlight application installed on a mobile device. The Stratus supports limited reception and display of ADS-B traffic information. Certain models include a complete Attitude Heading Reference System (AHRS) that permits supplemental attitude information on the connected mobile device.

Table 1, taken from Reference 1, lists the parameters recorded by the Stratus device.

Parameter Name	Parameter Description
Epoch time	Date and Time (UTC) recorded
Latitude	Recorded Latitude (degrees)
Longitude	Recorded Longitude (degrees)
Altitude	Recorded Altitude (feet)
Course	Average course between current and previous data point (degrees)
Groundspeed	Average groundspeed between current and previous data point (knots)
Bank	AHRS bank angle (deg)
Pitch	AHRS pitch angle (deg)
Horizontal Error	Accuracy (m)
Vertical Error	Accuracy (m)

Table 1. Stratus 2S ADS-B recorded parameters (from Reference 1).

The Stratus data is recorded at 5 samples / second. To verify the consistency between the recorded time, position, groundspeed, and course parameters, the recorded latitude and longitude during the approach portion of the flight (below 4800 ft. MSL) were transformed² into a north-east Cartesian coordinate system centered at the KRFD runway 25 threshold, and the groundspeed and course computed based on the changes in the north and east coordinates as a function of time. Similarly, rate of climb was computed by the change in the recorded altitude as a function of time.

These calculations were not straightforward, because apparent irregularities in the timing of the data samples, and occasional “jumps” in the values of recorded parameters, introduce severe “noisiness” in the first derivatives of the as-recorded parameters with respect to time. To reduce these artifacts, a constant time increment was imposed on the data (equal to the total time of the recording divided by the number of samples in the recording), and the parameter values themselves were smoothed by removing spikes from their time derivatives (computed using the corrected time), and then re-integrating, with adjustments to force agreement with the original parameter values at the beginning and end of the data. The resulting parameter time derivatives are smooth, and the groundspeed and course (or track angle) computed from the corrected position data matches the as-recorded groundspeed and course. The corrected altitude data were used for rate of climb calculations.

The route of flight from KRFD to KISM on December 1 recorded by the Stratus is shown in Figure 1. The route is labeled every 15 minutes with the time in CST, pressure altitude in ft. MSL, and groundspeed in knots. The radar Mode C pressure altitude and the Stratus GPS altitude for this flight are shown as a function of time in the bottom plot of Figure 3.

The route of flight from KISM to KRFD on December 4 recorded by the Stratus is shown in Figure 6. The route is labeled every 15 minutes with the time in CST, pressure altitude in ft. MSL, and groundspeed in knots. The radar Mode C pressure altitude and the Stratus GPS altitude for this flight are shown as a function of time in the bottom plot of Figure 7.

² The transformation uses the WGS84 ellipsoid model of the Earth.

II. Crash site and winds aloft information

Crash site information

According to the NTSB Investigator In Charge (IIC), after contacting the ground, “the airplane went through the [airport] perimeter fence and came to rest near the localizer array at the approach end of runway 25 at RFD.”

Based on photographs of the airplane at the accident site and its location near the localizer array (see Figure 18), the coordinates of the final resting point are estimated to be:

Latitude 42° 12' 10.45" N

Longitude 89° 04' 57.99" W

Elevation 736 ft. MSL (per *Google Earth*)

These coordinates are about 1073 ft. from the runway 25 threshold (along the extended runway centerline) and 13 ft. to the right of the runway centerline.

The NTSB did not travel to the accident site, and so did not examine the airplane on-scene. However, an on-scene airport operation supervisor stated that “... there was never any visible fuel exiting the aircraft while it was sitting on the ground or while it was being lifted and moved. There was a slight fuel smell around the aircraft but we never saw fuel pooled anywhere.” Subsequent examination of the airplane revealed that the fuel tanks were empty and an unusable amount of fuel was retained in the fuel system. There was no ground fire.

The flap handle in the cockpit was in the “up” position, the flaps were retracted (see Figure 18), and the landing gear handle was selected down. The landing gear were pushed up into the wheel wells, likely as the result of a hard impact with the ground while extended.

Winds aloft information

Winds aloft data for the entire December 1 KRFD-KISM and December 4 KISM-KRFD flight routes are required to compute the fuel burn for each flight, using both the flight planning and the fuel burn simulation methods. In addition, winds aloft over KRFD at the time of the accident are required to compute the airplane’s airspeed from the groundspeed recorded on the Stratus device, and the corresponding C_L .

Wind and other meteorological information for the accident flight is provided in Reference 2. Winds aloft for the December 1 KRFD-KISM flight were provided to the author of this *Study* by an NTSB meteorologist (the author of Reference 2). For both flights, the winds aloft are assumed to correspond to the “Winds and Temperature Aloft Forecasts” (FB forecasts) issued by the National Weather Service (NWS) for the times of each flight.

The winds aloft for the December 1 KRFD-KISM flight are shown in Table 2, and correspond to the FB based on data at 18:00 UTC (12:00 CST) on December 1, valid at 00:00 UTC on December 2 (18:00 CST on December 1), and for use between 20:00 UTC and 03:00 UTC (14:00 – 21:00 CST). The winds aloft for the December 4 KISM-KRFD accident flight are shown in Table 3, and correspond to the FB based on data at 18:00 UTC (12:00 CST) on December 4, valid at 00:00 UTC on December 5 (18:00 CST on December 4), and for use between 20:00 UTC and 03:00 UTC (15:00 – 22:00 CST).

WINDS ALOFT FORECASTS

DATA BASED ON 011800Z

VALID 020000Z FOR USE 2000-0300Z. TEMPS NEG ABV 24000

	3000	6000	9000	12000	18000	24000	30000	34000	39000
MLB	0613	0313+10	3105+07	3214+01	3038-09	2942-21	305337	306047	306559
PIE	0810	0608+11	3209+06	3120+02	3036-09	2937-21	304637	305247	305859
JAX	1705	2809+10	2717+04	2914+00	3021-11	2950-22	306838	307448	307960
TLH	9900	2407+10	2614+05	3014+02	3036-10	2949-22	306037	306647	307259
SAV	2008	2709+08	2611+02	2909+00	3216-13	3038-26	307640	308950	309460
CSG	0105	9900+08	3014+08	2817+01	2821-12	3046-24	297338	307949	308761
ATL	0207	9900+06	2812+07	2713+00	2816-13	2938-26	297640	308950	309561
TYS	9900	2015+06	2407+06	2615+00	2922-14	2931-28	295643	308153	307860
HSV	0405	3007+10	2917+06	3022+00	2723-13	2949-24	297639	298550	299261
BNA	1005	2809+08	2715+05	2813-01	2421-14	2630-27	297641	298752	309861
LOU	1005	2307+04	2817+03	2721-02	2724-15	2836-28	284845	295953	296660
EVV	1006	9900+06	3015+03	2820-03	2526-15	2629-28	285043	296552	297260
IND	9900	2906+03	2818+00	2724-04	2733-16	2843-29	285246	295854	296761
SPI	1610	2312+05	2722+00	2828-05	2634-15	2643-28	284945	285853	287061
JOT	1708	2309+02	2721-03	2832-07	2744-16	2749-29	275745	286455	287363
DBQ	2123	2419+02	2727-01	2731-08	2652-17	2656-30	276546	277355	287963

Table 2. NWS Winds and Temperatures Aloft forecast for December 1 KRFD-KISM flight.

WINDS ALOFT FORECASTS

DATA BASED ON 041800Z

VALID 050000Z FOR USE 2000-0300Z. TEMPS NEG ABV 24000

	3000	6000	9000	12000	18000	24000	30000	34000	39000
MLB	0816	1315+11	1507+06	9900+03	2611-12	2817-24	312241	333249	313455
PIE	0710	1212+11	9900+08	3107+02	2615-11	3017-23	324038	324548	324557
JAX	1213	1909+10	1907+06	2108+02	2318-13	2818-24	333139	323450	324258
TLH	1411	1811+09	2212+07	2314+01	2421-12	2821-22	313838	314449	324360
SAV	1415	1814+07	2411+06	2311+01	2420-14	2721-25	313139	313450	314459
CSG	1617	2017+10	2215+06	2216+00	2423-13	2726-22	304138	304249	314861
ATL	1518	2020+10	2219+06	2418+00	2427-13	2629-23	294239	294349	315461
TYS	1821	2222+11	2326+05	2429-01	2434-14	2634-24	284840	285550	296062
HSV	1731	2227+11	2330+06	2428-01	2430-12	2634-22	285438	285349	296461
BNA	1840	2334+11	2339+04	2335-02	2438-14	2540-23	276239	276450	287962
LOU	1945	2241+10	2245+04	2341-03	2443-15	2549-24	266341	266551	288262
EVV	2044	2450+09	2452+04	2450-02	2340-14	2454-25	267641	268051	279762
IND	2052	2357+09	2353+03	2452-03	2352-15	2462-26	257342	257952	269363
SPI	2151	2452+09	2452+05	2353-03	2366-16	2369-28	259643	750652	751160
JOT	2057	2457+08	2355+03	2355-03	2466-17	2370-29	248644	740053	259860
DBQ	2152	2353+07	2355+02	2355-04	2367-18	2376-31	248746	249753	248657

Table 3. NWS Winds and Temperatures Aloft forecast for December 4 KISM-KRFD (accident) flight.

Tables 2 and 3 are in the NWS FB forecast format. To decode this format, see https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_00-45H.pdf, Section 5.13.

The location of the weather reporting stations listed in the far-left columns of Tables 2 and 3 are depicted in Figure 2.

The winds over KRFD at 18:00 UTC, used to compute the N500KR's airspeed and C_L during its approach, are based on a High-Resolution Rapid Refresh (HRRR) computer model, described in Reference 2. The wind speed, wind direction, and air temperature as a function of altitude from this model are plotted in Figure 12.

Surface winds, temperature, and altimeter setting for the departure and destination airports for the December 1 and December 4 flights were taken from the METAR reports shown in Table 4. Since the winds aloft FB forecasts do not contain data for altitudes below 3000 ft., for the “fuel burn simulation” the winds between the surface and 3000 ft. were approximated as follows:

- For the Dec. 1 departure from KRFD, the average of the KRFD METAR surface winds and the JOT FB 3000 ft. winds were used;
- For the Dec. 1 arrival at KISM and the Dec. 4 departure from KISM, the average of the KISM METAR surface winds and the MLB FB 3000 ft. winds were used;
- For the December 4 arrival at KRFD, the winds between the surface (elevation 736 ft.) and 3000 ft. were approximated by the HRRR model winds at 1900 ft.

The resulting winds between the surface and 3000 ft. for both flights are listed in Table 5.

Event	Winds	Temperature	Altimeter setting	Source
Departure from KRFD 17:00 CST 12/01/2017	190° @ 6 kt.	7° C	30.17 “Hg	KRFD METAR 16:54 CST Dec 1
Arrival at KISM 21:20 CST 12/01/2017	050° @ 3 kt.	20° C	30.16 “Hg	KISM METAR 20:56 CST Dec 1
Departure from KISM 13:45 CST 12/04/2017	100° @ 8 kt.	24° C	30.16 “Hg	KISM METAR 13:56 CST Dec 4
Arrival at KRFD 18:00 CST 12/04/2017	190° @ 18 kt. gusting 25 kt.	16° C	29.49 “Hg	KRFD METAR 17:54 CST Dec 4 ³

Table 4. METAR reports for interpolating winds and temperatures below 3000 ft. MSL.

Event	Winds	ΔT from standard day	Source
Departure from KRFD 17:00 CST 12/01/2017	180° @ 7 kt.	-7° C	Average of KRFD METAR & JOT FB @ 3000 ft.
Arrival at KISM 21:20 CST 12/01/2017	055° @ 8 kt.	5° C	Average of KISM METAR & MLB FB @ 3000 ft.
Departure from KISM 13:45 CST 12/04/2017	90° @ 12 kt.	9° C	Average of KISM METAR & MLB FB @ 3000 ft.
Arrival at KRFD 18:00 CST 12/04/2017	187° @ 47 kt.	3° C	KRFD HRRR model @ 1900 ft.

Table 5. Assumed winds between surface and 3000 ft. for “fuel burn simulation.”

³ The December 4 17:54 CST METAR for KRFD also indicated overcast clouds at 3,800 ft. with a visibility of 10 statute miles. A peak wind of 27 kt. from 190° was recorded at 17:31 CST.

III. Airplane description and Zero Fuel Weight estimate

The Beechcraft (now Textron Aviation) C90 King Air is a twin-engine turboprop airplane powered by Pratt & Whitney PT6A-21 engines rated at 550 SHP, with a maximum takeoff weight of 9650 lb.⁴ N500KR, serial number LJ-708, was manufactured in 1977.⁵ A three-view drawing of the King Air C90, taken from Reference 3, is shown in Figure 16. A pre-accident photograph of N500KR is shown in Figure 17.

The weight and balance form for N500KR lists the airplane empty weight as 6233 lb. Per agreement with the NTSB IIC, the weights of the pilots, passengers, and baggage used for the fuel burn calculations used for this *Study* are as listed in Table 6. The airplane was similarly loaded (same pilot, passengers, and baggage) on both the December 1 KRFD-KISM and December 4 KISM-KRFD flights, so the ZFW for both flights would have been the same.

Item	Weight, lb.
Empty weight	6233
Pilot	180
Pax 1	130
Pax 2	130
Pax 3	100
Baggage	50
Zero Fuel Weight	6823

Table 6. Airplane Zero Fuel Weight estimate (same for both the December 1 and December 4 flights).

Evidence collected by the NTSB IIC indicated that the airplane departed KRFD on December 1 with full fuel, corresponding to 384 gallons (2573 lb. at an assumed Jet A fuel density of 6.7 lb./gal.), and was serviced with 150 gal. of Jet A (1005 lb.) at KISM. This information is used in both the “flight plan” and “fuel burn simulation” methods for computing the total airplane weight, fuel consumption, and fuel remaining.

IV. Fuel burn calculations

As mentioned above, in this *Study* the fuel remaining in N500KR at the time of the accident is computed in two ways: (1) Using the flight planning methods described in the AFM, using a flight path through eight waypoints in between KISM and KRFD; and (2) Using a fuel burn “simulation” developed from the fuel burn and other performance data published in the performance section of the AFM. The simulation models fuel burn as a function of engine shaft horsepower (*SHp*) and pressure altitude, and computes the *SHp* developed during the flights using AFM performance data, the ground speed and rate of climb recorded by the Stratus device, and winds aloft forecasts.

AFM “Flight Planning” method

The “flight planning” method for computing the fuel requirements of a flight is described in Section V of the AFM, titled “Performance.” The beginning of this section, “Introduction to Performance and Flight Planning,” states:

⁴ Per Reference 3.

⁵ Per Reference 4.

The graphs and tables in this section present performance information for takeoff, climb, landing and flight planning at various parameters of weight, power, altitude and temperature. All FAA approved performance information is included within this section. Examples have been presented on all performance graphs. In addition, the calculations for flight time, block speed, and fuel required for a proposed flight are presented

...

The AFM then illustrates how the fuel required for an example flight from Billings, Montana (KBIL) to Denver, Colorado (KDEN) would be computed. The route of the trip is identified by waypoints along the route from KBIL to KDEN, and the atmospheric conditions (winds and temperature) on each leg from waypoint to waypoint are identified. Then, the performance charts in the AFM are used to compute the following (among other items):

- Time, fuel, and distance to climb
- True airspeed for cruise
- Maximum cruise power
- Fuel flow
- Time, fuel, and distance to descend
- Time and fuel used at maximum cruise power

The sum of the fuel required to climb, cruise, and descend is the total fuel required to complete the flight. The AFM example then adds a 45-minute reserve at cruise power to this total to arrive at the minimum amount of fuel that should be on board prior to takeoff.

The fuel required for N500KR's flights from KRFD to KISM and back using the AFM flight planning method are presented in this section of the *Study*. Waypoints defining the route of flight were chosen to closely match the actual routes flown, as recorded by the Stratus device. Since the Stratus routes were essentially almost direct great-circle routes between KRFD and KISM, the same waypoints were used for the flights in both directions (with the order of waypoints reversed). The selected waypoints are listed in Tables 7 and 8 and depicted in Figure 2. Tables 7 and 8 show the time, distance, winds, temperature, airspeed, groundspeed, course, weight, fuel required, and fuel remaining for each leg of the route between waypoints, computed per the methods described in the AFM and illustrated by the KBIL-KDEN AFM example. The winds aloft FB forecast station used for each leg is also listed. Table 7 shows the calculations for the December 1 KRFD-KISM flight, and Table 8 shows the calculations for the December 4 KISM-KRFD (accident) flight.

As shown in Table 7, if N500KR departed KRFD with full fuel, the flight plan predicts it would have arrived at KISM with 144 gal. (963 lb.) of fuel remaining. If the airplane was refueled with 150 gal. (1005 lb.) of Jet A, then it would have departed KISM for the return flight with 294 gal. (1968 lb.) of fuel on board. Table 8 indicates that the return flight would consume 276 gal. (1849 lb.), leaving 18 gal. (119 lb.) at arrival at KRFD. Using the 435 lb./hr. fuel flow for the leg between RBS and the top of the descent, 119 lb. of fuel would provide a reserve of about 16 minutes. A 45-minute reserve at KRFD, using the 435 lb./hr. fuel flow, would require 326 lb. (49 gal.) of fuel over KRFD, or almost three times the amount of fuel remaining at KRFD per the flight plan. If the airplane had been refueled with an additional 31 gal. (208 lb.) at KISM, for a total fuel load of 325 gal. (2178 lb.), it should have been able to complete the flight with a 45-minute reserve.⁶

⁶ Small discrepancies between the sums of fuel quantities in pounds and gallons in this discussion are the result of round-off error when converting between gallons and pounds using the fuel density of 6.7 lb./gal.

Applicable winds aloft	Final weight lb.	Initial weight lb.	Final fuel lb.	Fuel enroute lb.	Initial fuel lb.	Time enroute minutes	Time CST (start)	Time EST (start)	Time UTC (start)	Heading degrees magnetic	Heading degrees true	Ground speed knots	Wind correction angle, deg.	Tailwind, knots	Crosswind (+/-from left), knots	Wind speed knots	Wind direction degrees true	Course degrees true	Magnetic variation, degrees	Course degrees magnetic	Max cruise fuel flow total lb/hr	Max cruise Airspeed KTAS	Delta temp from ISA, deg C	ISA temp at altitude, deg C	Temp at altitude, deg C	Distance NM	Altitude end ft MSL	Altitude start ft MSL	To Waypoint	Name	From Waypoint	Number		
None (POH CLIMB TABLE)	9206	9396	2383	190	2573	22	17:05	18:05	23:05		POH CLIMB TABLE	POH CLIMB TABLE				POH CLIMB TABLE	POH CLIMB TABLE	POH CLIMB TABLE	2	158		POH CLIMB TABLE			-22.5	62	21000	742	Top of climb	Chicago/Rockford International Airport, Rockford, IL	KRFD	1		
JOT 020000Z	9129	9206	2306	76	2383	12	17:27	18:27	23:27	170	168	223	12	19	-42	47	270	156	2	158	386	208	4.1	-26.6	-22.5	44	21000	21000	RBS	Top of climb		2		
IND 020000Z	9000	9129	2177	129	2306	20	17:38	18:38	23:38	153	150	233	8	26	-28	38	275	142	3	145	386	209	4.1	-26.6	-22.5	78	21000	21000	TTH	ROBERTS VOR		3		
EVV 020000Z	8811	9000	1988	189	2177	30	17:58	18:58	23:58	159	155	215	7	8	-26	28	255	148	4	152	384	209	5.1	-26.6	-21.5	106	21000	21000	MYS	TERRE HAUTE VOR		4		
BNA 020000Z	8557	8811	1734	254	1988	40	18:28	19:28	00:28	162	158	211	7	4	-25	26	250	151	4	155	381	209	6.1	-26.6	-20.5	141	21000	21000	HCH	MYSTIC VOR		5		
HSV 020000Z	8421	8557	1598	136	1734	22	19:08	20:08	01:08	170	165	227	8	20	-30	36	280	157	5	162	377	210	8.1	-26.6	-18.5	82	21000	21000	NELLO	HINCH MOUNTAIN VOR		6		
ATL 020000Z	8228	8421	1405	194	1598	30	19:30	20:30	01:30	168	163	228	6	17	-21	27	285	157	5	162	383	212	5.6	-26.6	-21	115	21000	21000	MCN	NELLO intersection		7		
TLH 020000Z	8011	8228	1188	217	1405	35	20:00	21:00	02:00	163	158	243	7	34	-25	43	295	151	5	156	371	210	10.6	-26.6	-16	142	21000	21000	TAY	MACON VOR		8		
TLH 020000Z	7932	8011	1109	79	1188	13	20:35	21:35	02:35	174	168	240	8	30	-30	43	295	160	6	166	371	212	10.6	-26.6	-16	51	21000	21000	GNV	TAYLOR VOR		9		
PIE 020000Z	7875	7932	1052	57	1109	9	20:48	21:48	02:48	162	156	241	6	30	-21	37	295	150	6	156	369	212	11.6	-26.6	-15	37	21000	21000	Top of descent	GATORS VOR		10		
None (POH Descent Table)	7786	7875	963	89	1052	18	20:57	21:57	02:57		POH Descent Table	POH Descent Table				POH Descent Table	POH Descent Table	POH Descent Table	6	156		POH Descent Table				58	82	21000	Top of descent	KISM	Top of descent		11	
					963		21:15	22:15	03:15																					Kissimmee Gateway Airport, Orlando, FL	KISM	12		
				1609		Total fuel used, lb.:																				916	Total distance, nm:							
				240		Total fuel used,gal.:																												
				963		Fuel remaining, lb.:																												
				144		Fuel reamaining, gal.:																												
								Total time:																										
						250.48498																												
						4.1747497																												
																												</						

Table 7. Flight plan for December 1 KRFD – KISM flight.

Applicable winds aloft	Final weight lb.	Initial weight lb.	Final fuel lb.	Fuel enroute lb.	Initial fuel lb.	Time enroute minutes	Time CST (start)	Time EST (start)	Time UTC (start)	Heading degrees magnetic	Heading degrees true	Ground speed knots	Wind correction angle, deg.	Tailwind, knots	Crosswind (+/-from left), knots	Wind speed knots	Wind direction degrees true	Course degrees true	Magnetic variation, degrees	Course degrees magnetic	Max cruise fuel flow total lb/hr	Max cruise Airspeed KTAS	Delta temp from ISA, deg C	ISA temp at altitude, deg C	Temp at altitude, deg C	Distance NM	Altitude end ft MSL	Altitude start ft MSL	To Waypoint	Name	From Waypoint	Number	
None (POH CLIMB TABLE)	8641	8791	1818	150	1968	16	13:44	14:44	19:44		POH CLIMB TABLE	POH CLIMB TABLE				POH CLIMB TABLE	POH CLIMB TABLE	POH CLIMB TABLE	6	338		POH CLIMB TABLE			-8.8	42	17000	82	Top of climb	Kissimmee Gateway Airport, Orlando, FL	KISM	1	
PIE 041800Z	8534	8641	1711	108	1818	15	14:00	15:00	20:00	335	329	207	-3	-6	13	14	268	332	6	338	421	214	9.9	-18.7	-8.8	53	17000	17000	GNV	Top of climb	Top of climb	2	
TLH 041800Z	8435	8534	1612	99	1711	14	14:15	15:15	20:15	342	336	219	-5	4	19	20	238	341	6	347	424	215	8.9	-18.7	-9.8	51	17000	17000	TAY	GATORS VOR	GNV	3	
TLH 041800Z	8155	8435	1332	280	1612	40	14:29	15:29	20:29	335	330	217	-5	2	20	20	238	335	5	340	424	215	8.9	-18.7	-9.8	143	17000	17000	MCN	TAYLOR VOR	TAY	4	
ATL 041800Z	7930	8155	1107	225	1332	32	15:08	16:08	21:08	333	328	218	-7	2	26	26	240	335	5	340	426	217	7.9	-18.7	-10.8	115	17000	17000	NELLO	MACON VOR	MCN	5	
HSV 041800Z	7771	7930	948	159	1107	22	15:40	16:40	21:40	331	326	217	-8	2	30	30	240	334	5	339	425	217	8.5	-18.7	-10.2	81	17000	17000	HCH	NELLO intersection	NELLO	6	
BNA 041800Z	7495	7771	672	276	948	39	16:03	17:03	22:03	327	323	219	-10	3	38	38	238	333	4	337	429	219	6.7	-18.7	-12	141	17000	17000	MYS	HINCH MOUNTAIN VOR	HCH	7	
EVV 041800Z	7289	7495	466	206	672	29	16:41	17:41	22:41	324	320	223	-11	7	41	42	232	331	4	335	429	220	6.7	-18.7	-12	107	17000	17000	TTH	MYSTIC VOR	MYS	8	
IND 041800Z	7134	7289	311	155	466	22	17:10	18:10	23:10	312	309	215	-14	1	52	52	232	323	3	326	431	220	5.7	-18.7	-13	77	17000	17000	RBS	TERRE HAUTE VOR	TTH	9	
JOT 041800Z	7014	7134	191	120	311	17	17:32	18:32	23:32	318	316	217	-17	6	64	64	238	333	2	335	435	221	4	-18.7	-14.7	60	17000	17000	Top of descent	ROBERTS VOR	RBS	10	
None (POH Descent Table)	6942	7014	119	72	191	18	17:48	18:48	23:48		POH Descent Table	POH Descent Table				POH Descent Table	POH Descent Table	POH Descent Table	2	335		POH Descent Table				46	742	17000	KRFD	Top of descent	Top of descent	11	
					119		18:06	19:06	00:06																					Chicago/Rockford International Airport, Rockford, IL	KRFD	12	
				1849		Total fuel used, lb.:																				916		Total distance, nm:					
				276		Total fuel used,gal.:																											
				119		Fuel remaining, lb.:																											
				18		Fuel reamaining, gal.:																											
																																Empty =	6233
																																Pilot =	180
																																Pax 1 =	130
																																Pax 2 =	130
																																Pax 3 =	100
																																Bags =	50
																																Fuel =	1968
																																	294
																																	(gallons)
																																	(fuel density)
																																Total =	8791
																																ZFW =	6823

Table 8. Flight plan for December 4 KISM – KRFD (accident) flight.

The flight plan method fuel burn calculations indicate that while the airplane could not complete the KISM-KRFD flight with at least a 45 minute fuel reserve (as required by 14 CFR §91.151 and §91.167)⁷, they also suggest that the airplane would have made it to KRFD with 18 gallons of fuel to spare. Since the events of the accident suggest that the airplane ran out of fuel *before* arriving at KRFD (i.e., during the approach), a second, more precise calculation, that attempts to account continuously for the actual power requirements throughout each of the two flights, was performed for comparison with the flight planning method predictions. This second calculation is the “fuel burn simulation method” described below.

Fuel burn simulation method

The “fuel burn simulation” method for computing the fuel consumed during N500KR’s flights consists of first analyzing the AFM performance charts to determine the aerodynamic characteristics of the airplane, and the fuel flow required to produce a given engine power at different atmospheric conditions; and then to use this information to compute the power and fuel flow required at each point along the flights based on the recorded Stratus data and an estimate of the winds aloft. The fuel flow is integrated over time to compute the total fuel burn.

Airplane engines convert chemical energy stored in the fuel into the mechanical energy required to sustain flight. The rate of consumption of fuel therefore depends on the rate of consumption of energy (the power demand), and the efficiency of the energy conversion process. The total efficiency of the process depends on both the thermodynamic efficiency of the engines (the efficiency with which energy in the fuel is converted into shaft horsepower (*SHP*) driving the propellers), and the aerodynamic efficiency of the propellers themselves (not all of the *SHP* delivered to the propellers results in thrust on the airframe).

For small angles of attack (for which thrust can be assumed to be essentially parallel to the airstream), the power required to sustain steady-state (unaccelerated) flight is

$$P_R = TV_T = (D + W \sin \gamma)V_T = DV_T + W\dot{h} \quad [1]$$

Where:

P_R = power required

T = total thrust (i.e., the sum of the thrust of each engine)

V_T = true airspeed

D = aerodynamic drag

W = airplane weight

γ = flight path angle

$\dot{h} = dh/dt$ = time rate of change of altitude (rate of climb h = altitude; t = time)

(See Figure 19.) The drag D is given by

$$D = C_D \bar{q} S \quad [2]$$

⁷ 14 CFR 1.1 defines “night” as “the time between the end of evening civil twilight and the beginning of morning civil twilight.” The end of evening civil twilight at Rockford on December 4, 2017 was at 16:55 CST (see <https://www.timeanddate.com/sun/usa/rockford?month=12&year=2017>), and so §91.151 would require a 45 minute fuel reserve.

Where:

C_D = drag coefficient

S = wing reference area (= 293.94 ft² per Reference 3)

And

$$\bar{q} = \text{dynamic pressure} = \frac{1}{2} \rho V_T^2 \quad [3]$$

Where

ρ = freestream air density

The drag coefficient C_D for a particular airplane configuration (e.g., flaps and gear up) is a function of the angle of attack (α) and Mach number (M), though at relatively low Mach numbers ($M < 0.4$) the Mach effect is small and can be ignored.⁸ Likewise, the airplane's lift coefficient (C_L) is also a function of α and M , with the M effect negligible at lower M . Since in the normal (unstalled) flight regime both C_L and C_D have unique values at each α , and in keeping with the principles of three-dimensional wing theory, C_D is often modeled as a quadratic function of C_L , which is the approach taken in this *Study*:

$$C_D = c_0 + c_1 C_L + c_2 C_L^2 \quad [4]$$

Where c_0 , c_1 , and c_2 are constants.

The lift coefficient is given by

$$C_L = \frac{L}{\bar{q}S} \quad [5]$$

Where L is the aerodynamic lift. Per Figure 19, for steady-state, wings-level flight

$$L = W \cos \gamma \quad [6]$$

Using Equations [1]-[6], the power that must be delivered to the airframe (P_R) for steady-state flight at a given altitude, temperature, speed, and rate of climb can be computed. However, as noted above, because the propellers are not 100% efficient, the engines must develop *more* power than P_R . The actual power (*SHP*) developed by the engines is

$$SHP = \frac{P_R}{\eta_p} = \frac{P_R}{\eta_0 \eta_I} \quad [7]$$

Where

η_p = total propeller efficiency

η_0 = propeller profile efficiency

η_I = ideal propeller efficiency

The ideal propeller efficiency, η_I , is the maximum efficiency a propeller can theoretically attain, based on the laws of conservation of mass and momentum as applied to the air flowing through the propeller. The propeller profile efficiency, η_0 , accounts for energy loss as the air flows

⁸ N500KR's cruise M during the KRFD-KISM and KISM-KRFD flights was below 0.36.

through the propeller (e.g., from the drag of the propeller itself). η_0 can be assumed to be approximately constant at $\eta_0 = 0.9^9$, but η_I depends on the thrust loading on the propeller and the freestream dynamic pressure. For each engine, let

$$k = 4\bar{q} \left(\frac{A}{T} \right) \quad [8]$$

Where A is the disk area of the propeller, and for a twin-engine airplane the thrust T per engine is half of the total thrust given by Equation [1]. Then

$$\eta_I = \frac{-k + \sqrt{k^2 - 4k}}{2} \quad [9]$$

η_I increases with increasing k , that is, with increasing $\bar{q}$ and decreasing thrust load on the propeller (i.e., increasing A/T)¹⁰.

Equation [7] specifies the *total* power that must be developed by the airplane's engines. The *SHP* developed by *each* engine on a twin-engine airplane (such as the King Air) is half of the *SHP* given by Equation [7] (assuming each engine produces equal power). The *SHP* developed by a given engine is equal to

$$SHP_i = Q_i \omega_i \quad [10]$$

Where

i = subscript indicating engine number

Q = torque delivered to propeller shaft

ω = angular velocity of propeller shaft

ω in radians per second is related to the propeller speed in revolutions per minute (*RPM*) by

$$\omega = \frac{(RPM)2\pi}{60} \quad [11]$$

The fuel flow required for each engine to produce its share of the total *SHP* depends on the thermodynamic efficiency of the engine itself, which in turn depends on the flight condition, as reflected in the performance charts published in the AFM.¹¹

As noted above, the "fuel burn simulation" method for computing the fuel consumed during N500KR's flights consists of first analyzing the AFM performance charts to determine the C_L and C_D characteristics of the airplane, and the fuel flow required to produce a given total *SHP* at a given combination of atmospheric temperature and pressure; and then to compute the C_L , C_D , T , P_R , *SHP*, and fuel flow ($\dot{f}$) at each point along the flight based on the recorded Stratus data and an estimate of the winds aloft. The $\dot{f}$ is integrated over time to compute the total fuel burn, and the corresponding reduction in airplane weight.

⁹ In this *Study*, $\eta_0 = 0.9$ was assumed during cruise and descent, and $\eta_0 = 0.87$ during climb was required to keep the C_L and C_D values computed for sea-level climb consistent with the values computed for cruise.

¹⁰ During cruise, the computed η_I is about 0.976; with $\eta_0 = 0.9$, the resulting $\eta_p = 0.878$.

¹¹ For the conditions considered in this *Study*, the engine fuel flow values published in the AFM were satisfactorily modeled as being dependent only on the *SHP* produced by the engine, and pressure altitude.

The following AFM charts were used to compute the airplane aerodynamic and fuel flow characteristics of the airplane:

MAXIMUM TWO ENGINE CRUISE POWER chart (see sample in Figure 20): This chart lists the Q and $\dot{f}$ per engine and resulting calibrated airspeed (V_C) and true airspeed (V_T) at three different weights, as a function of pressure altitude (h_p) and temperature differential (ΔT) from standard day. Propeller speed is constant at 1900 RPM. The data on this chart allows the SHP per engine to be computed (using Equations [10-11]), and the associated total thrust T on the airplane (using Equations [1] and [7-9]). Once T has been computed, the drag D can be computed using Equation [1], and then C_D and C_L follow from Equations [2] and [5]. The range of V_C speeds obtained as altitude increases provides for C_L and C_D values across a corresponding α range. The SHP and $\dot{f}$ values provide data points for modeling $\dot{f}$ as a function of SHP , h_p , and ΔT .

MAXIMUM RANGE POWER chart (see sample in Figure 21): This chart provides similar information as the MAXIMUM TWO ENGINE CRUISE POWER chart, but for reduced power settings and speeds that provide for maximum range. The lower speeds provide for a different range of α , C_L and C_D than the higher maximum cruise speeds, and the lower SHP and $\dot{f}$ provide additional points for modeling $\dot{f}$ as a function of SHP , h_p , and ΔT .

TIME, FUEL, AND DISTANCE TO CLIMB chart (see Figure 22): This chart is used to determine time and fuel required to climb between two pressure altitudes, and the horizontal distance over the ground that will be covered while doing so. The “associated conditions” on the chart list propeller speed as 2000 RPM and Q as 1315 ft-lb., which allows SHP to be computed per Equations [10-11], but this SHP is only valid where the listed Q can be achieved; as indicated in the MAXIMUM TWO ENGINE CRUISE POWER chart, the available Q (and SHP) decrease with h_p . However, the SHP on the climb chart is valid at sea level, and the resulting rate of climb implied by the chart can be used to extract P_R , T , C_L , and C_D at sea level.¹²

The C_L and C_D points from the MAXIMUM TWO ENGINE CRUISE POWER chart, MAXIMUM RANGE POWER chart, and sea-level data on the TIME, FUEL, AND DISTANCE TO CLIMB chart can be used to find a quadratic fit for C_D as a function of C_L , per Equation [4]. This fit can be used to determine C_D (and P_R and SHP) at higher altitudes in the TIME, FUEL, AND DISTANCE TO CLIMB chart, where SHP cannot be computed directly because Q is unknown. This yields high-power points for modeling $\dot{f}$ as a function of SHP , h_p , and ΔT .

TIME, FUEL, AND DISTANCE TO DESCEND chart (see Figure 23): This chart is used to determine time and fuel required to descend between two pressure altitudes, and the horizontal distance over the ground that will be covered while doing so. As with the climb chart, Equation [4] can be used to determine C_D , P_R and SHP during the descent, yielding low-power points for modeling $\dot{f}$ as a function of SHP , h_p , and ΔT .¹³

The $\dot{f}$ for the conditions of the two N500KR flights examined in this *Study* could be satisfactorily modeled as a 2D surface dependent only on SHP and h_p , independent of ΔT .

¹² C_L can be computed from weight, the V_C for climb listed in the box at the top of the chart, and temperature and pressure as depicted in the chart.

¹³ C_L (needed as input for Equation [4]) can be computed from weight, and the $V_C = 169$ kt. for descent listed in the chart, and assuming standard day temperature and pressure for each h_p .

Fuel burn simulation results

The results of the fuel burn simulation for the December 1 KRFD-KISM flight are shown in Figures 3-5, and the results for the December 4 KISM-KRFD (accident) flight are shown in Figures 7-9. Figures 3 and 7 show the distance flown, speeds, and altitudes as a function of time for the two flights. Figures 4 and 8 show the winds and temperatures aloft used in the simulations; these data are computed using a weighted average of the FB forecasts from the three nearest reporting stations (the sudden jumps in the data are the result of the simulation dropping the data from one station and picking up the data from another as the airplane gets further from the first and closer to the second). Figures 5 and 9 show the $\dot{f}$, SHP , fuel weight, and total airplane weight as a function of time for each flight.

The information from the “flight planning” method for computing fuel burn, shown in Tables 7 and 8, is also overlaid on the “fuel burn simulation” results plotted in Figures 3-5 and 7-9. The green vertical lines in the Figures indicate the times at which the airplane passes the flight plan waypoints used in Tables 7 and 8.

The simulation predicts that the flight from KRFD to KISM on December 1 would have required 1748 lb. of fuel to fly for the time recorded on the Stratus. Assuming a full fuel load of 2573 lb. on departure from KRFD, the simulation predicts it would have arrived at KISM with 825 lb. of fuel remaining. Refueling with 150 gal. (1005 lb.) of fuel, the airplane would have departed KISM with 1830 lb. of fuel on board.

The simulation predicts that the accident flight from KISM to KRFD on December 4 would have required 1873 lb. of fuel to fly for the time recorded on the Stratus. With only 1830 lb. of fuel on board when departing KISM, the simulation computes a deficit of -43 lb. of fuel at the end of the Stratus data. The simulation predicts that the fuel would have been exhausted (reached 0 lb.) at 17:54:57, or 8 minutes and 27 seconds (00:08:27) before the end of the data at 18:03:24, and 00:06:48 before the simulation computes a sudden drop in SHP starting at 18:01:45. If the sudden drop in SHP is the result of loss of engine power due to fuel starvation, then the simulation misses the actual event by being 00:06:48 early. Considering that the calculations simulate 8.5 hours of fuel burn (4.17 hours from KRFD to KISM and 4.33 hours from KISM to KRFD), a 00:06:48 error is equivalent to about 1.3% of the total calculation time. Given the uncertainties in the actual winds over the route of flight, this error is small, and the results of the simulation are consistent with a loss of power resulting from fuel exhaustion at about 18:01:45.

V. Airplane performance during approach to KRFD

A more detailed examination of the performance of the airplane during the approach to KRFD than that provided by the fuel burn simulation is of interest, to determine whether the airplane impacted the ground in controlled flight or not. For the purposes of this *Study*, the airplane is assumed to be in “controlled flight” if it did not stall prior to ground contact. “Stall” is defined here as reaching the maximum C_L (C_{Lmax}) implied by the stall speeds published in the AFM. The fuel burn simulation computes the C_L at every point in the Stratus data, but below 3000 ft. uses an average wind from the HRRR model to compute airspeed from the groundspeed recorded on the Stratus device. A more accurate estimate of wind, airspeed, and C_L below 3000 ft. can be obtained by using the actual HRRR wind values presented in Figure 12.

As noted in Section D-II, at the crash site the airplane’s the flaps were found retracted, and the landing gear were extended (though pushed up into the wheel wells). This suggests that the

pilot extended the landing gear, but not the flaps, during the approach. Hence, the flaps-up stall speeds are used to determine C_{Lmax} .

The results of the performance calculations for the approach to KRFD are shown in Figures 10-15. Figures 10 and 11 are plan-view plots of the flight path, overlaid with labels every 15 seconds indicating the CST time and MSL altitude. The location and content of the KRFD Air Traffic Control Tower (ATCT) communications with N500KR are also overlaid on the plot.¹⁴

Figure 13 shows the altitude, terrain elevation, speed, and rate of climb as a function of time during the approach. As noted above, the airspeeds are computed from the Stratus groundspeed and the HRRR wind data plotted in Figure 12. Figure 13 indicates that at the end of the Stratus recording, V_C was about 84 kt., the groundspeed was about 73 kt., and the rate of descent was about 1200 ft./min.

Figure 14 presents the Euler angles (pitch, roll, and heading) angles during the approach, as well as the flight path angle, drift angle, track angle, and angle of attack. The pitch, roll, and track angles were recorded on the Stratus device, and the other angles are computed. Angle of attack is estimated as the difference between the pitch angle and flight path angle (which is exact for zero bank and sideslip angle), and the heading angle and drift angles are computed assuming zero sideslip (coordinated flight). The Figure indicates that the flight path angle relative to the ground at the end of the Stratus data was about -8° .

Figure 15 shows the distance from the KRFD runway 25 threshold, the P_R required to fly the approach assuming the flaps and gear up configuration C_L and C_D derived as described in Section D-IV, and the C_L required for 1-G unaccelerated flight. The Figure also shows the flaps up C_{Lmax} implied by the AFM wings-level stall speed at 7000 lb. (79 KCAS, which is equivalent to a C_{Lmax} of 1.13). The plot shows that while C_L started to increase sharply at about 18:01:50, the highest value attained (at the end of the data) was 0.96, well below the C_{Lmax} of 1.13. Consequently, the calculations indicate that the airplane did not stall before the end of the data and was therefore under control at impact with the ground (the altitude and elevation plotted in Figure 13 indicates that the end of the data coincides with ground contact). The roll angle of less than 10° at the end of the data is also consistent with controlled flight at that time.

Figure 15 also shows the drop in P_R at about 18:01:45 noted earlier, which could be consistent with a loss of power due to fuel exhaustion. The P_R drops to between 0 and -100 HP between 18:01:55 and 18:02:05, consistent with approximately zero power; however, the P_R then drops further, to -470 HP at 18:02:14, before oscillating between about -100 and -300 HP. Negative P_R indicates more drag on the airplane than was assumed in the power calculation; since the calculation assumes a cruise configuration (flaps and gear up) but the gear were found extended in the wreckage, the drop in P_R after 18:02:05 could be the result of additional drag due to the landing gear. If the propellers were not completely feathered after the engines lost power, they could also be a source of drag.¹⁵

¹⁴ These communications were transcribed by the author from an audio file provided by the FAA. To save space in Figures 10 and 11, transcribed numbers and call signs have been abbreviated instead of phonetically spelled out. A recording of the communications between N500KR and the ATC approach controller who handled the flight prior to the KRFD ATCT was not available as of this writing.

¹⁵ The Textron Aviation party member who examined the airplane was asked about the feather condition of the propellers in the wreckage, and answered that "the right propeller control in the cockpit was in the feathered position. Left propeller control in the cockpit was in the middle of its travel range. Both propellers appeared to be feathered when we looked at the plane; however, the springs in the propellers would have pushed the blades to

E. CONCLUSIONS

This *Aircraft Performance Study* presents the results of estimating the amount of fuel remaining in the airplane at the time of the accident, based on information about the initial fuel loading at KRFD for the airplane's prior flight on December 1 from KRFD to KISM, refueling records at KISM, and the estimated fuel burns for the December 1 KRFD-KISM flight and the December 4 KISM-KRFD (accident) flight. In addition, the *Study* compares the airplane's C_L during the approach to the airplane's flaps-up $C_{L\ max}$. The C_L calculations indicate that C_L did not approach $C_{L\ max}$, and that therefore the airplane did not stall.

Additional information used in these calculations and presented in this *Study* includes Air Traffic Control (ATC) communications and the airplane configuration and condition documented at the crash site.

The fuel remaining at the time of the accident computed using the flight planning methods described in the AFM indicates that the airplane could have made the return flight to KRFD with about 119 lb. (18 gal.) of fuel remaining. The fuel remaining computed using a fuel burn "simulation" developed from the fuel burn and other performance data published in the performance section of the AFM indicates that the airplane would have run out of fuel on approach to KRFD, about 8.75 minutes before the end of the Stratus data, and about 7 minutes before the calculations show a large decrease in engine horsepower.

These results and the condition of the airplane at the accident site are consistent with a loss of engine power due to fuel starvation during the airplane's approach to KRFD.

For Visual Flight Rules (VFR) flights, 14 CFR §91.151 requires sufficient fuel to fly to the intended destination, and then for another 30 minutes (during the day) or another 45 minutes (at night). For IFR flights, §91.167 requires sufficient fuel to fly to the intended destination, and then for another 45 minutes (and more, if weather forecasts indicate that the ceiling or visibility at the destination may be below 2000 ft. and 3 miles, and the flight needs to divert to an alternate).

John O'Callaghan
National Resource Specialist – Aircraft Performance
Office of Research and Engineering

feather by the time we looked at the plane. The FAA onsite photos appear to show the right propeller feathered while the left one is not. Of course, both propellers impacted the terrain so that can drive the blades out of position."

F. REFERENCES

1. National Transportation Safety Board, Office of Research and Engineering, *Specialist's Factual Report, ADS-B Device, Beech C90A / N500KR, Rockford, IL, December 4, 2017*, NTSB Accident Number CEN18LA047 (Washington, DC: NTSB, April 10, 2018). (Contact NTSB at pubinq@ntsb.gov.)
2. National Transportation Safety Board, Office of Aviation Safety, *Meteorology Weather Study, Beech C90A, Registration N500KR, Rockford, IL, December 4, 2017*, NTSB Accident Number CEN18LA047 (Washington, DC: NTSB, February 12, 2018). (Contact NTSB at pubinq@ntsb.gov.)
3. Raytheon Aircraft (now Textron Aviation), *Beech King Air C90 Pilot's Operating Handbook and FAA Approved Airplane Flight Manual (Serials LJ-668 thru LJ-1010, except LJ-670, LJ-986 and LJ-996)*. P/N 90-590010-61B Reissued: April, 1980; P/N 90-5900-10-61810 Revised: April, 2002. RAYTHEON AIRCRAFT COMPANY, P.O. Box 85, Wichita, Kansas 67201.
4. Federal Aviation Administration, *FAA Registry N-Number Inquiry Results for N500KR*. See https://registry.faa.gov/aircraftinquiry/NNum_Results.aspx?NNumbertxt=500KR.

G. GLOSSARY

Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
AFM	Airplane Flight Manual
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
CFR	Code of Federal Regulations
CST	Central Standard Time
FAA	Federal Aviation Administration
FB	Wind and Temperature Aloft Forecast
GPS	Global Positioning System
HRRR	High-Resolution Rapid Refresh
IFR	Instrument Flight Rules
IIC	Investigator In Charge
KISM	Kissimmee Gateway Airport, Orlando, FL
KRFD	Chicago/Rockford International Airport, Rockford, IL
METAR	Aviation Routine Weather Report
MSL	Mean Sea Level
NTSB	National Transportation Safety Board
NWS	National Weather Service
UTC	Universal Coordinated Time
VFR	Visual Flight Rules

English symbols

A	Propeller disk area
C_D	Drag coefficient
C_L	Lift coefficient
$C_{L\max}$	Maximum lift coefficient
D	Aerodynamic drag
$\dot{f}$	Fuel flow rate
h	Altitude
$\dot{h}$	dh/dt = time rate of change of altitude
h_p	Pressure altitude
k	Combination of $\bar{q}$, A , and T used to compute η_I (see Equation [8])
L	Aerodynamic lift
M	Mach number
P_R	Power required
$\bar{q}$	Dynamic pressure
Q	Engine torque
RPM	Propeller angular velocity, revolutions per minute
S	Wing reference area
SHP	Shaft horsepower
t	Time
T	Thrust
ΔT	Temperature difference from standard-day temperature
V_C	Calibrated airspeed
V_T	True airspeed
W	Airplane weight

Greek symbols

α	Angle of attack
γ	Flight path angle
ρ	Freestream air density
η_0	Propeller profile efficiency
η_I	Ideal propeller efficiency
η_p	Total propeller efficiency
ω	Propeller angular velocity, radians/sec

FIGURES

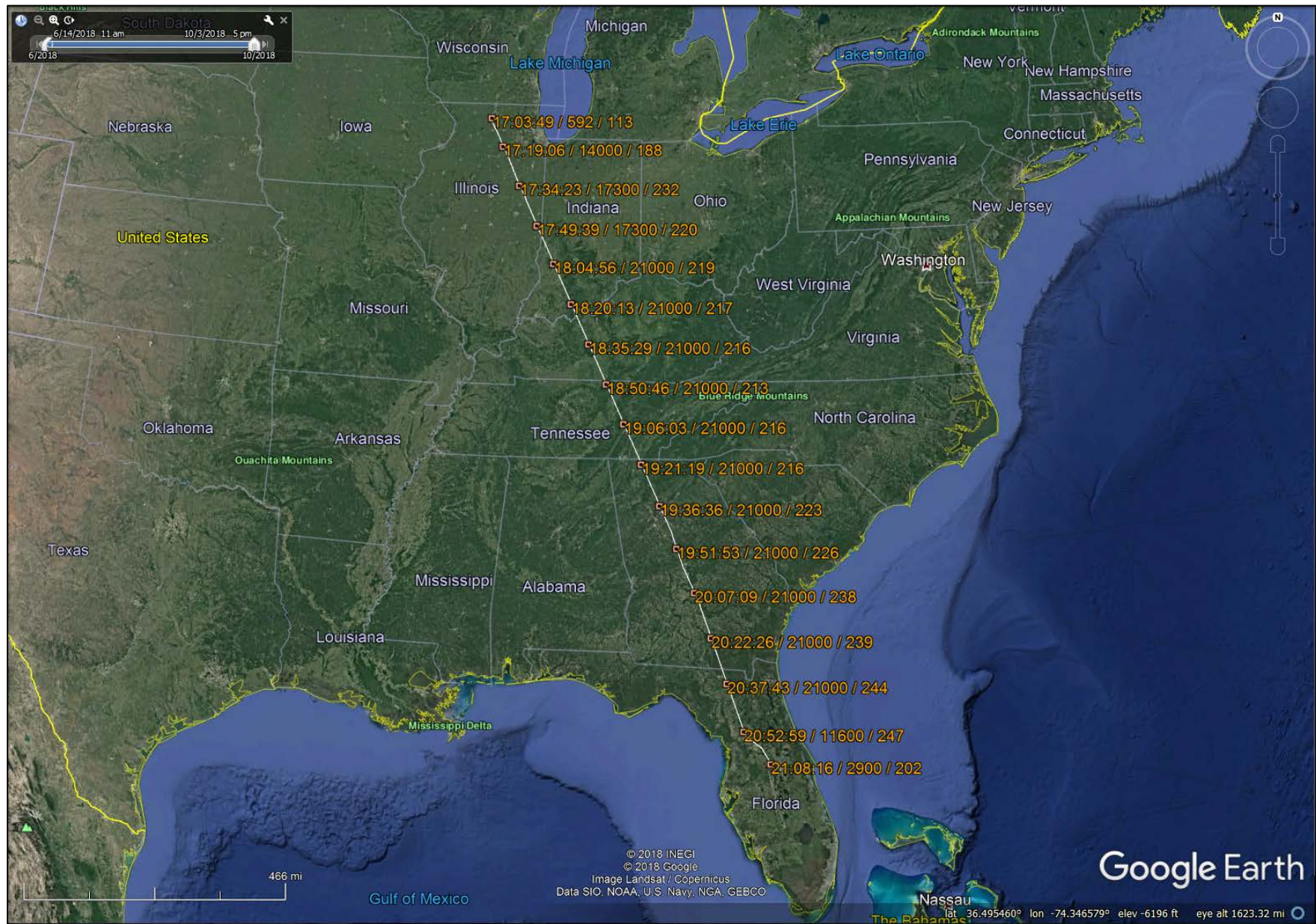


Figure 1. Route of December 1, 2017 KRFD-KISM flight, based on Appareo Stratus data.
Data labels are: Time, CST / pressure altitude, ft. MSL / groundspeed, knots.

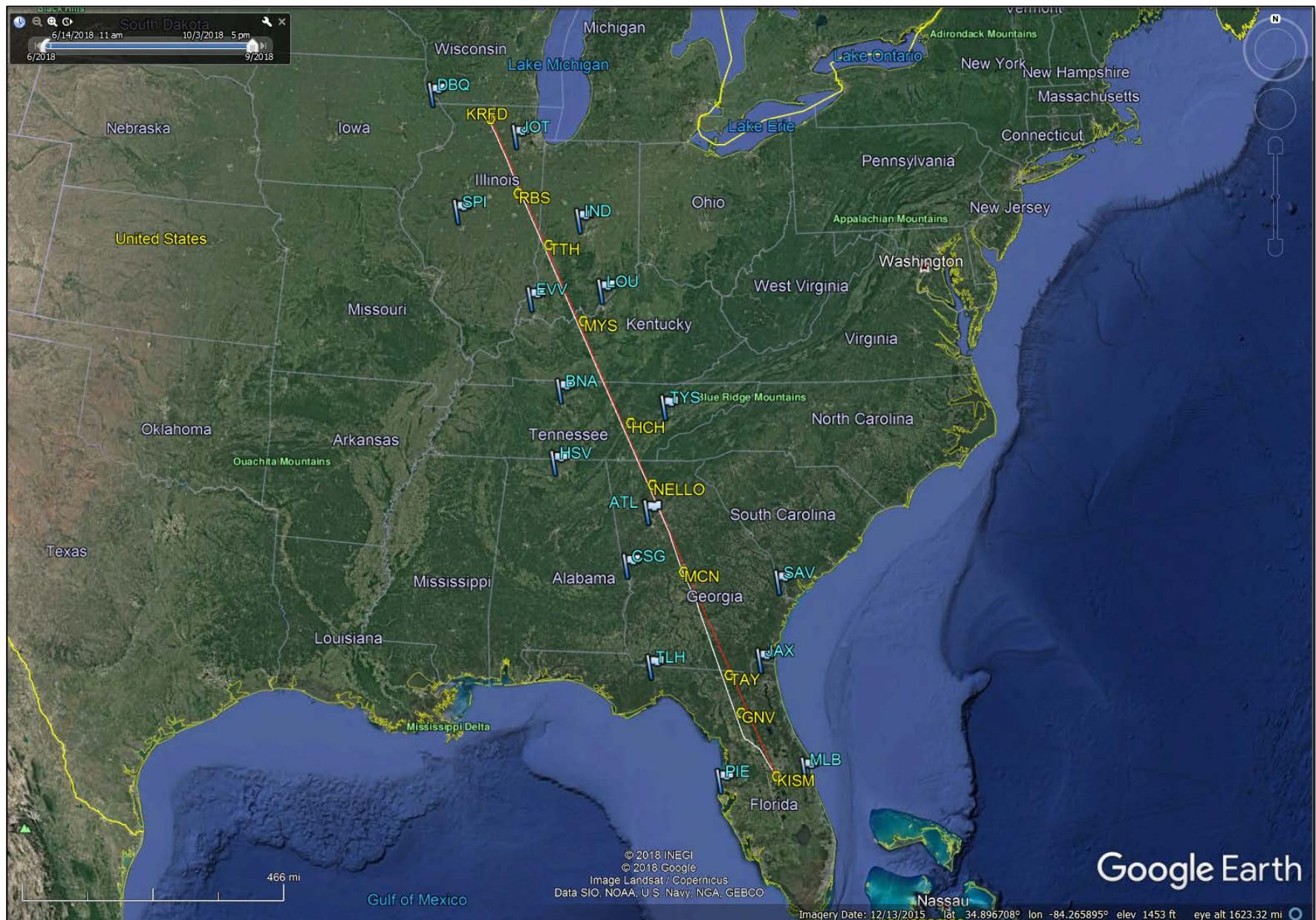


Figure 2. Waypoints for KRFD-KISM and KISM-KRFD flight plans (yellow hexagons), and nearby winds aloft forecast stations (blue flags). White line is December 1 KRFD-KISM Stratus data; red line is December 4 KISM-KRFD Stratus data.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Distance, speed, and altitude for 12/01/2017 KRFD-KISM flight

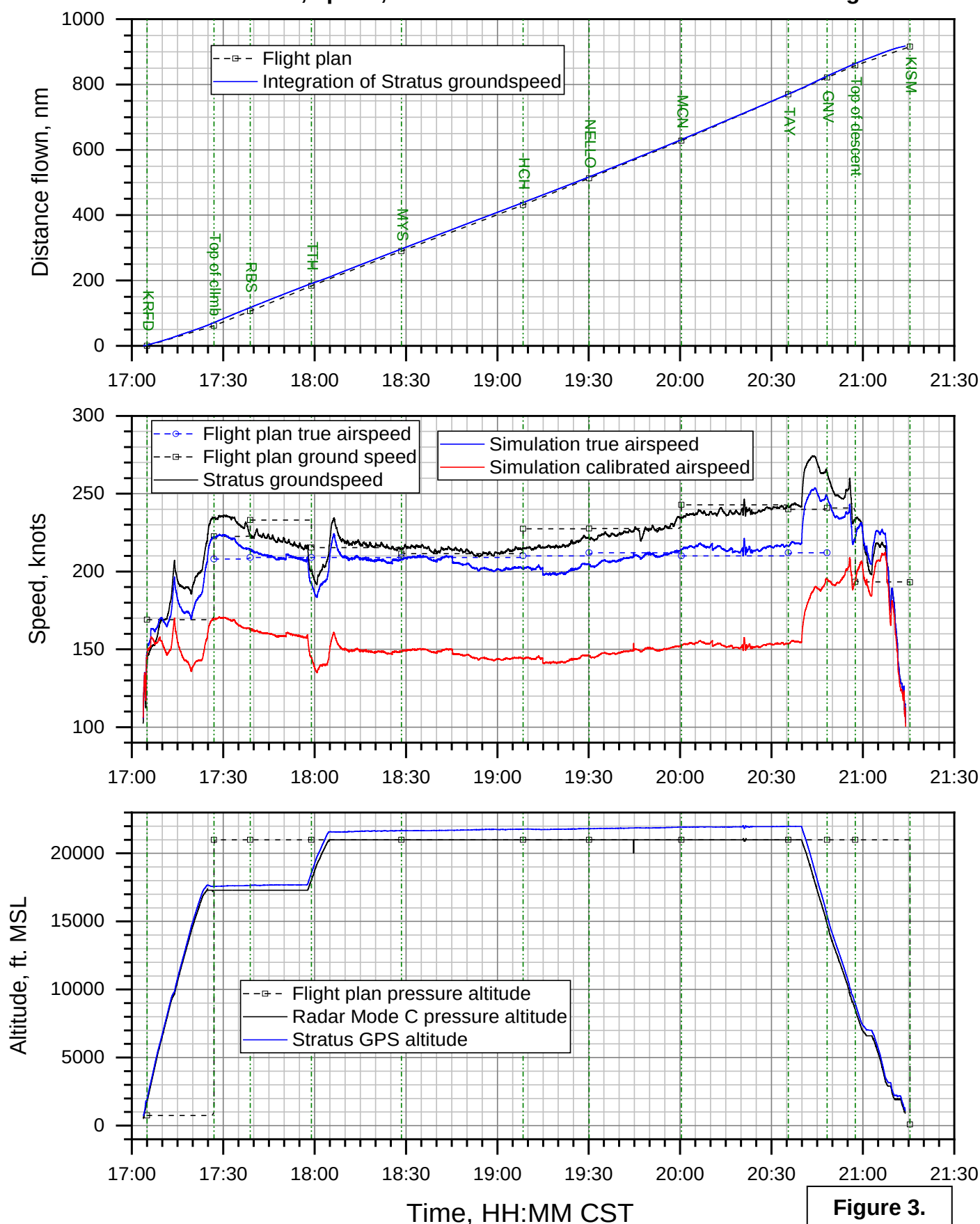
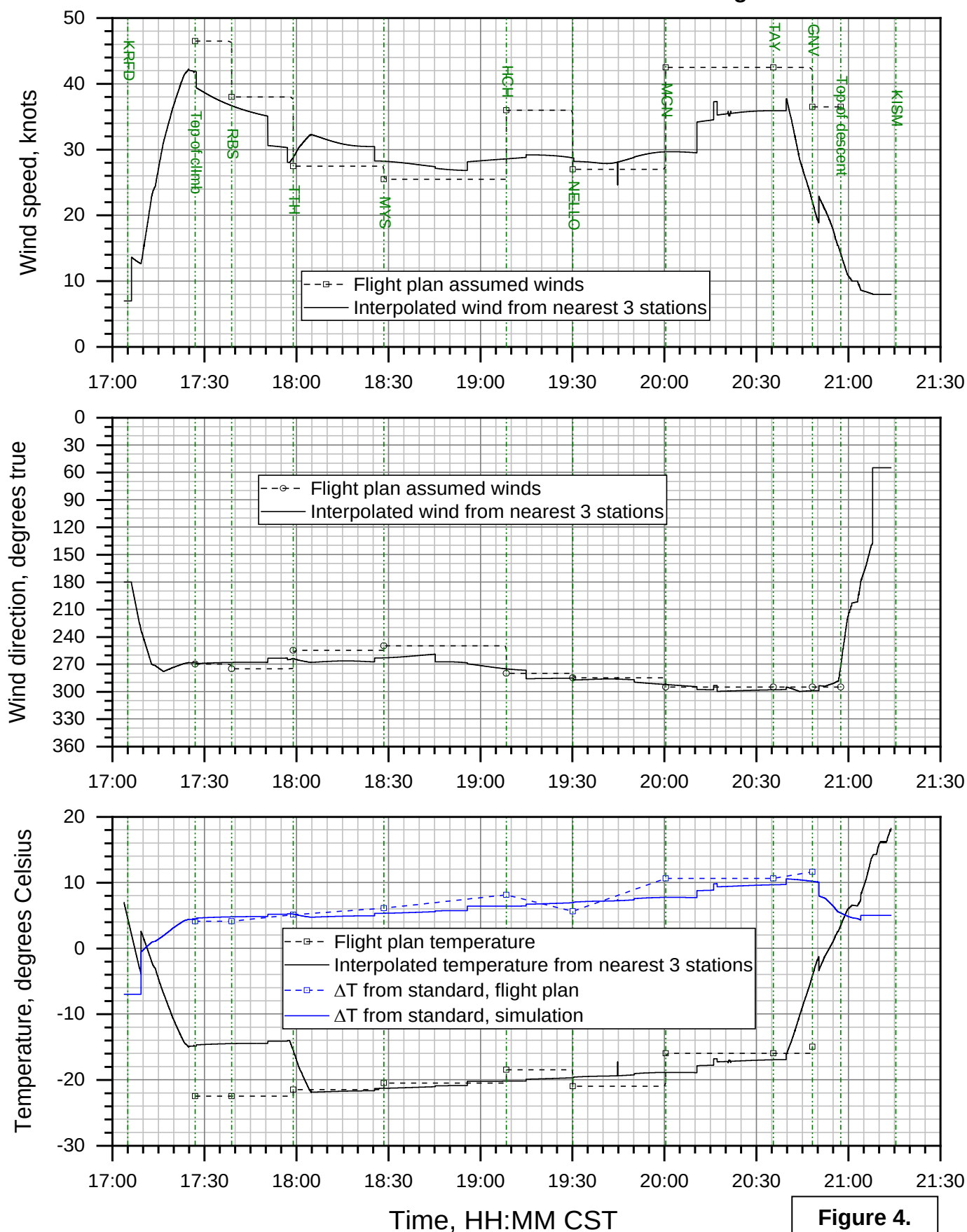


Figure 3.

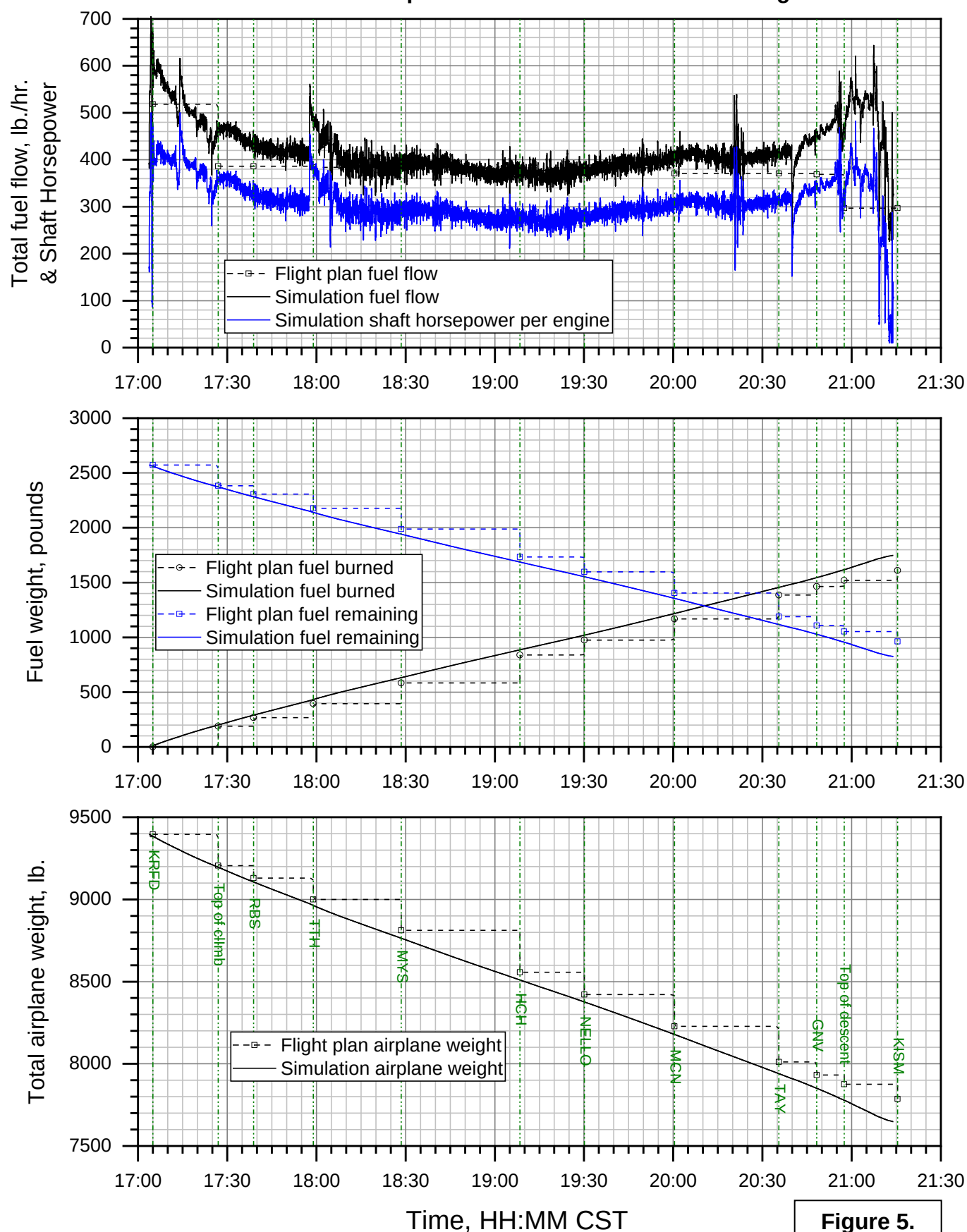
CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Winds aloft for 12/01/2017 KRFD-KISM flight


Figure 4.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Fuel consumption for 12/01/2017 KRFD-KISM flight


Figure 5.

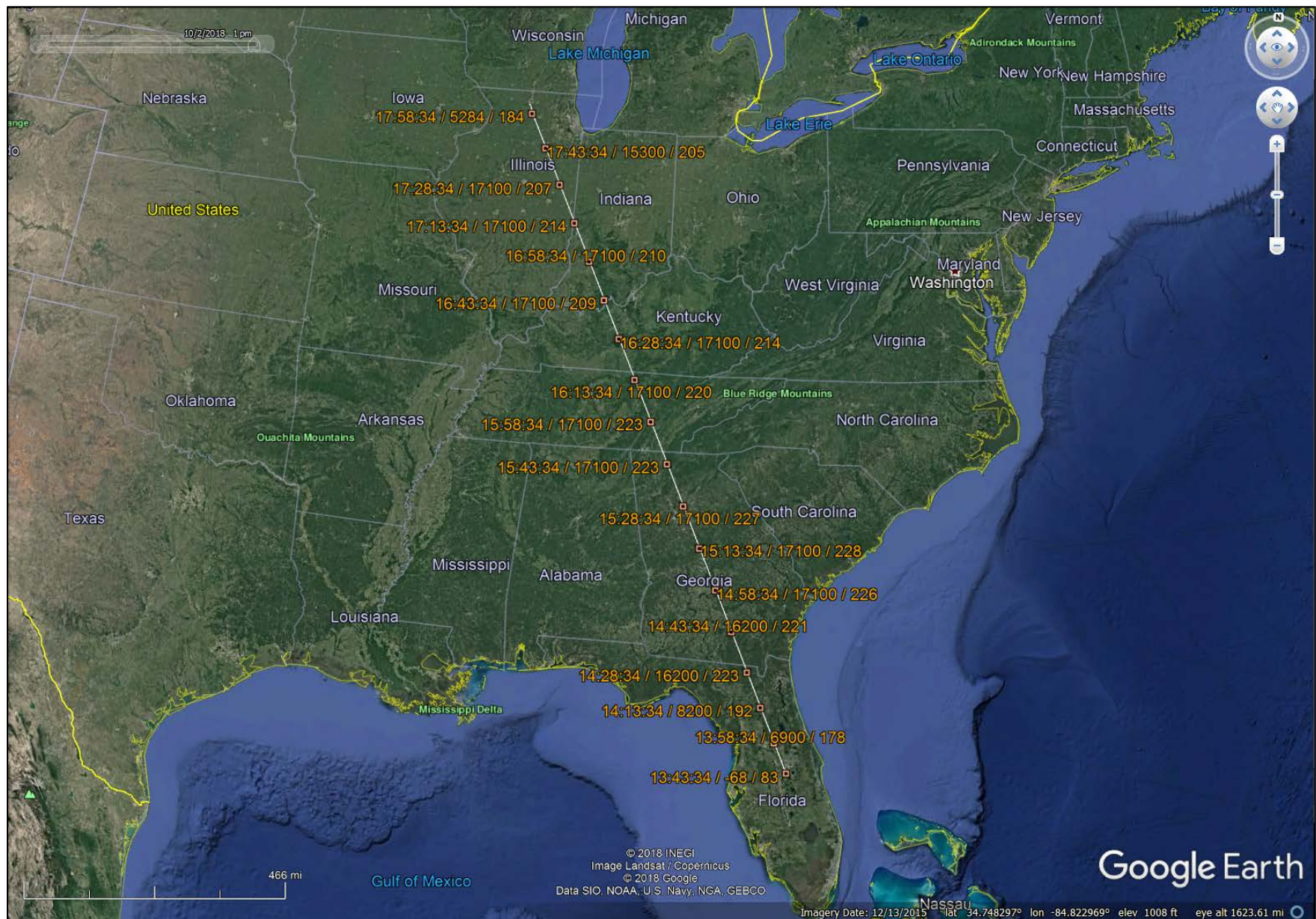


Figure 6. Route of December 4, 2017 KISM-KRFD (accident) flight, based on Appareo Stratus data. Data labels are: Time, CST / pressure altitude, ft. MSL / groundspeed, knots.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Distance, speed, and altitude for 12/04/2017 KISM-KRFD (accident) flight

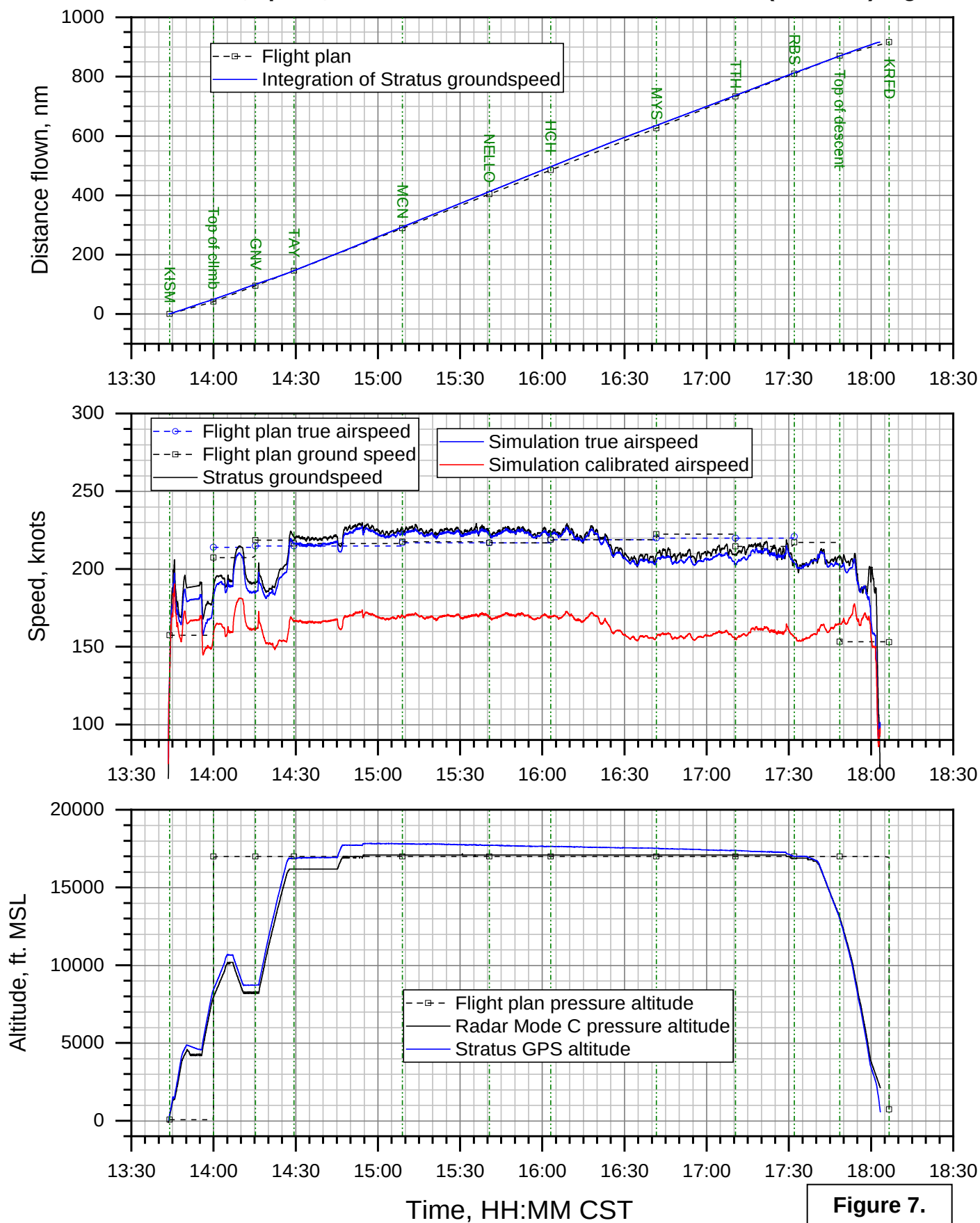
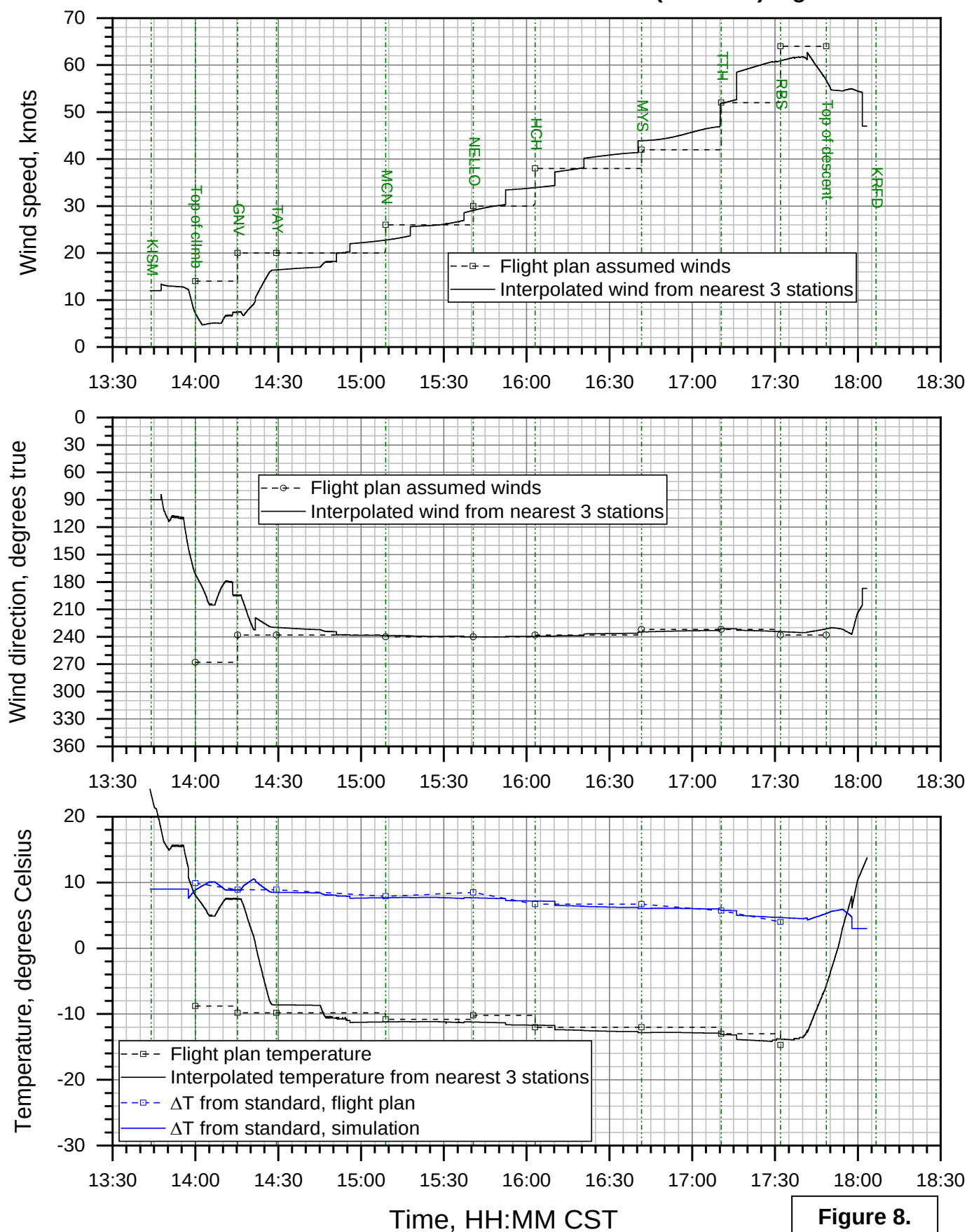


Figure 7.

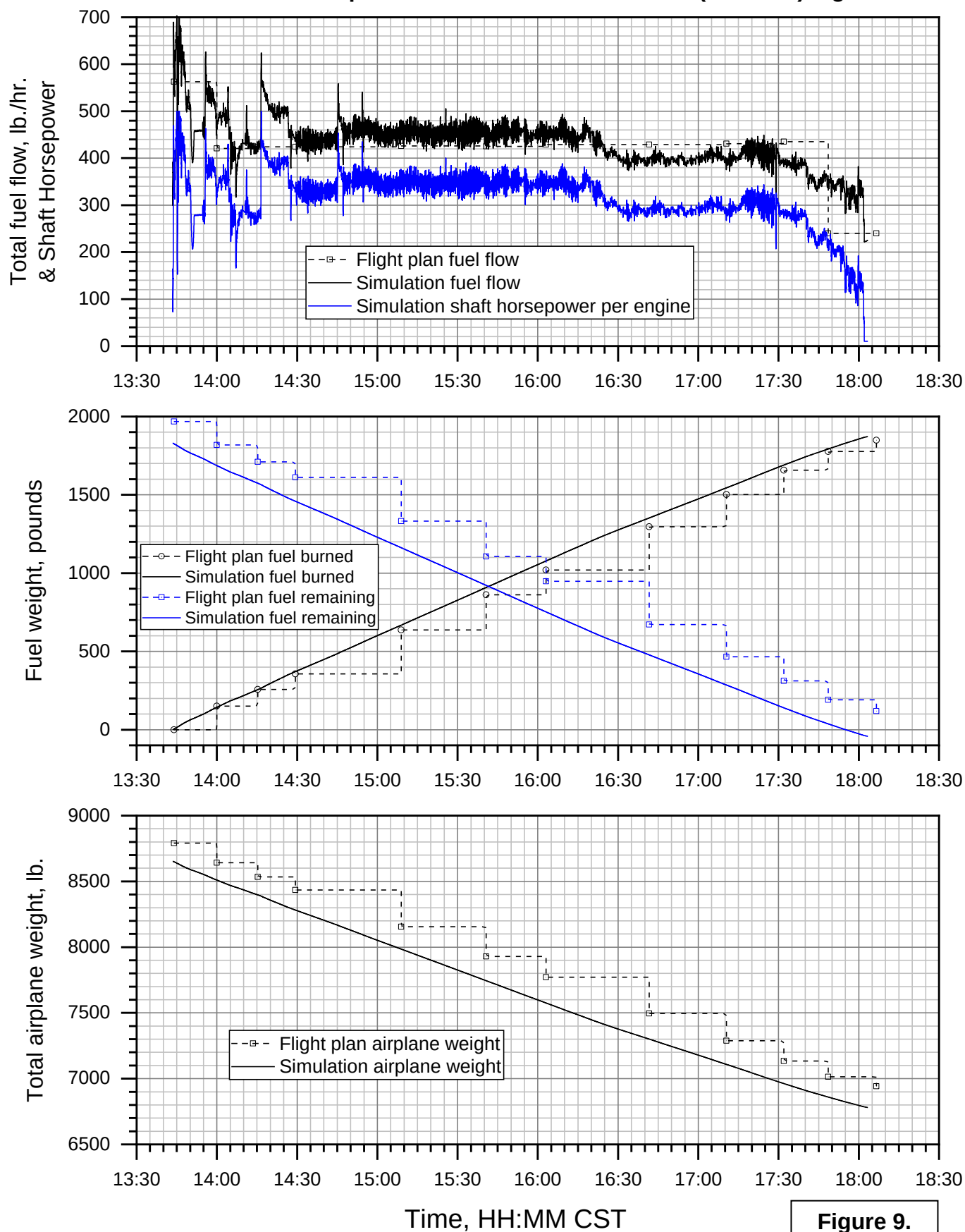
CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Winds aloft for 12/04/2017 KISM-KRFD (accident) flight


Figure 8.

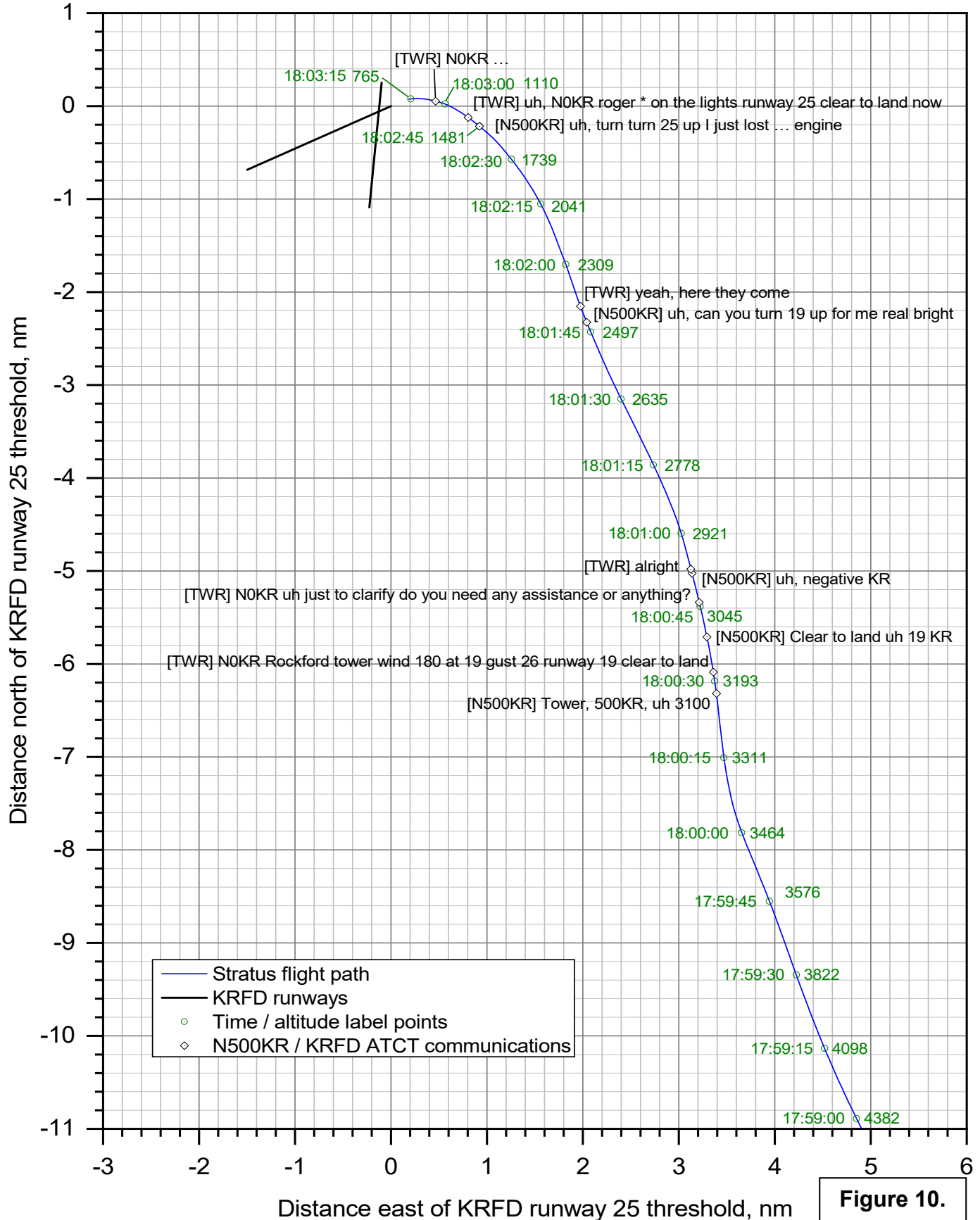
CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Fuel consumption for 12/04/2017 KISM-KRFD (accident) flight


Figure 9.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Plan view of approach for 12/04/2017 KISM-KRFD (accident) flight



CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

Plan view of approach for 12/04/2017 KISM-KRFD (accident) flight

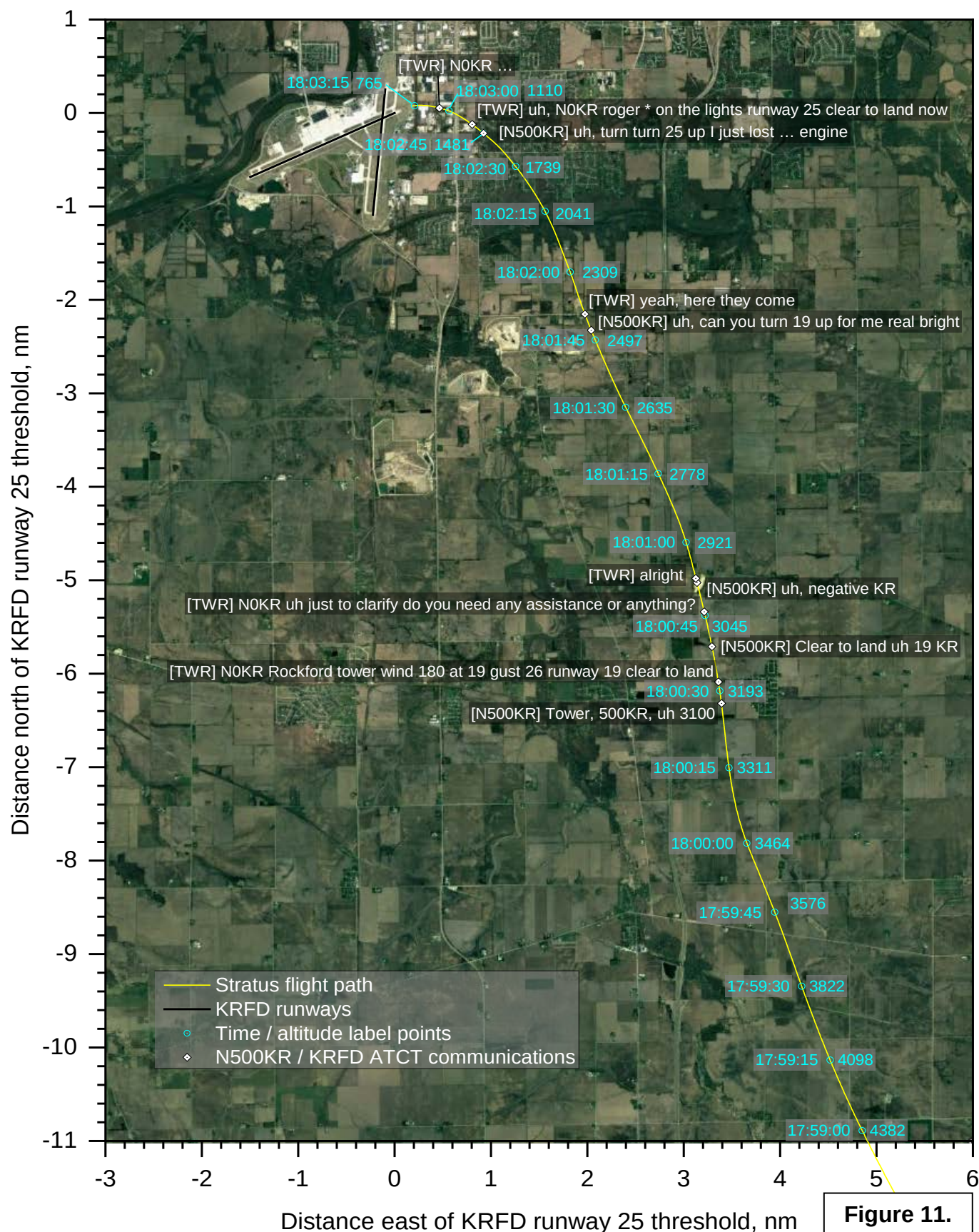


Figure 11.

Winds aloft from HRRR model sounding over KRFD at 1800 CST

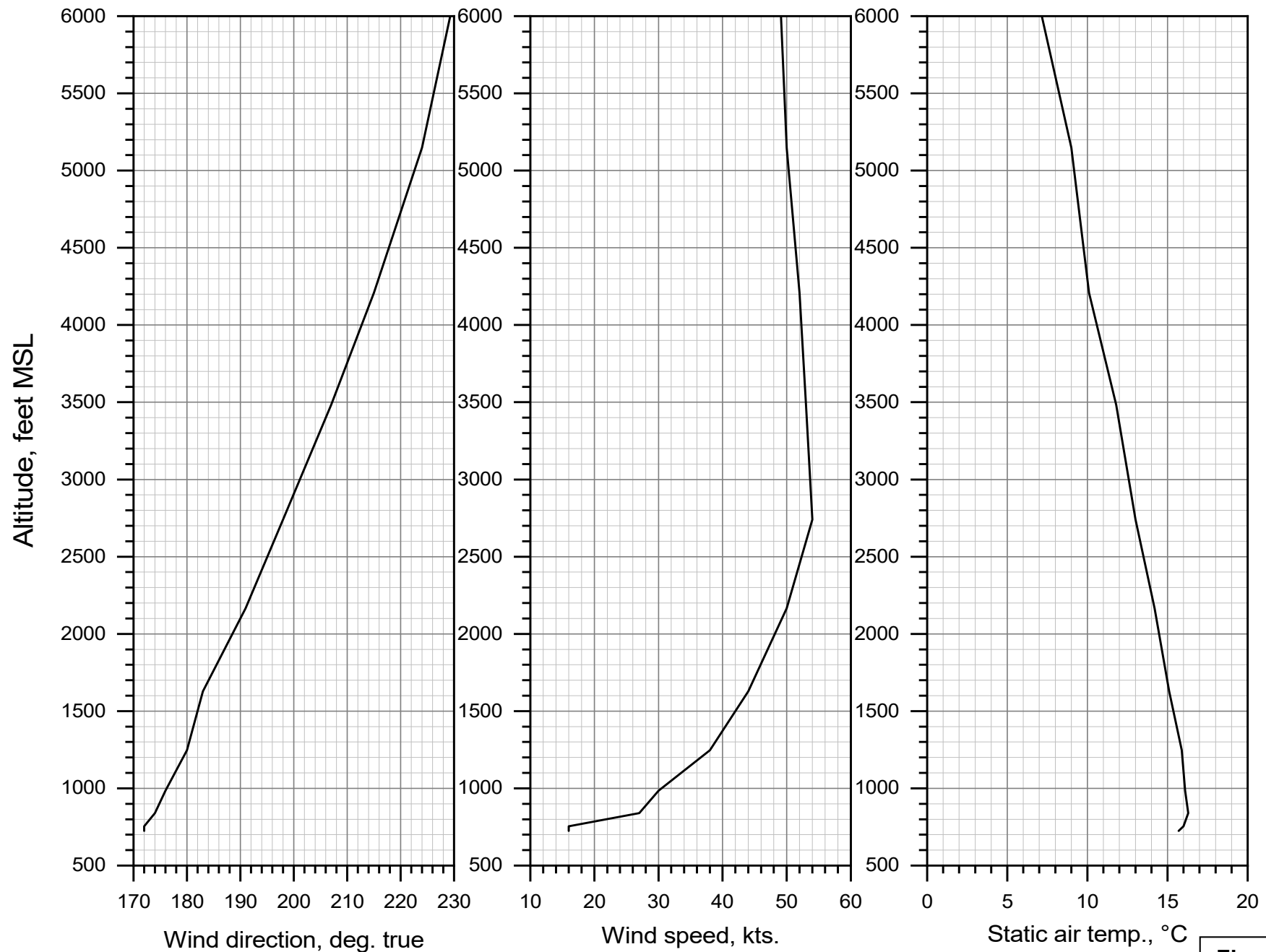
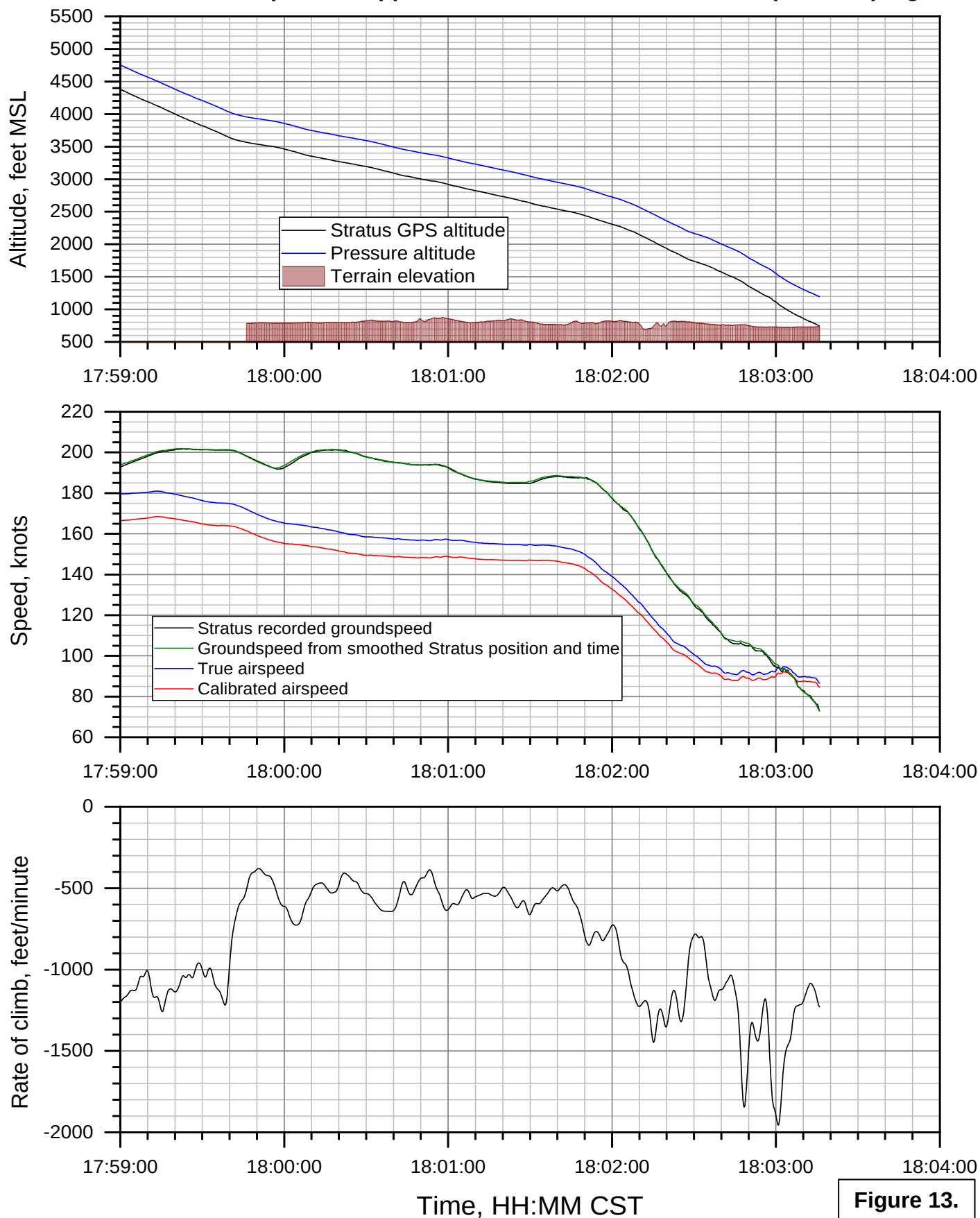
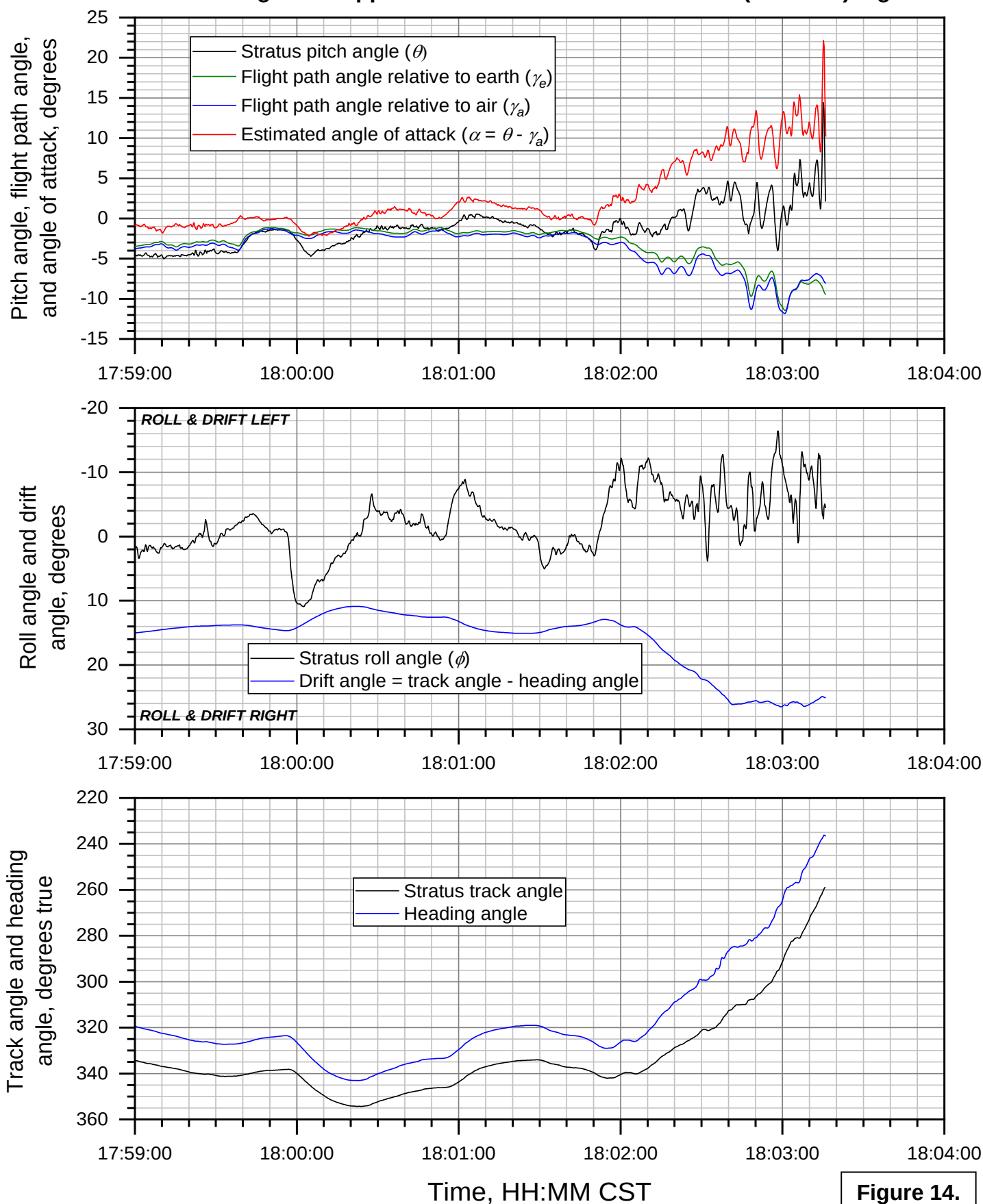


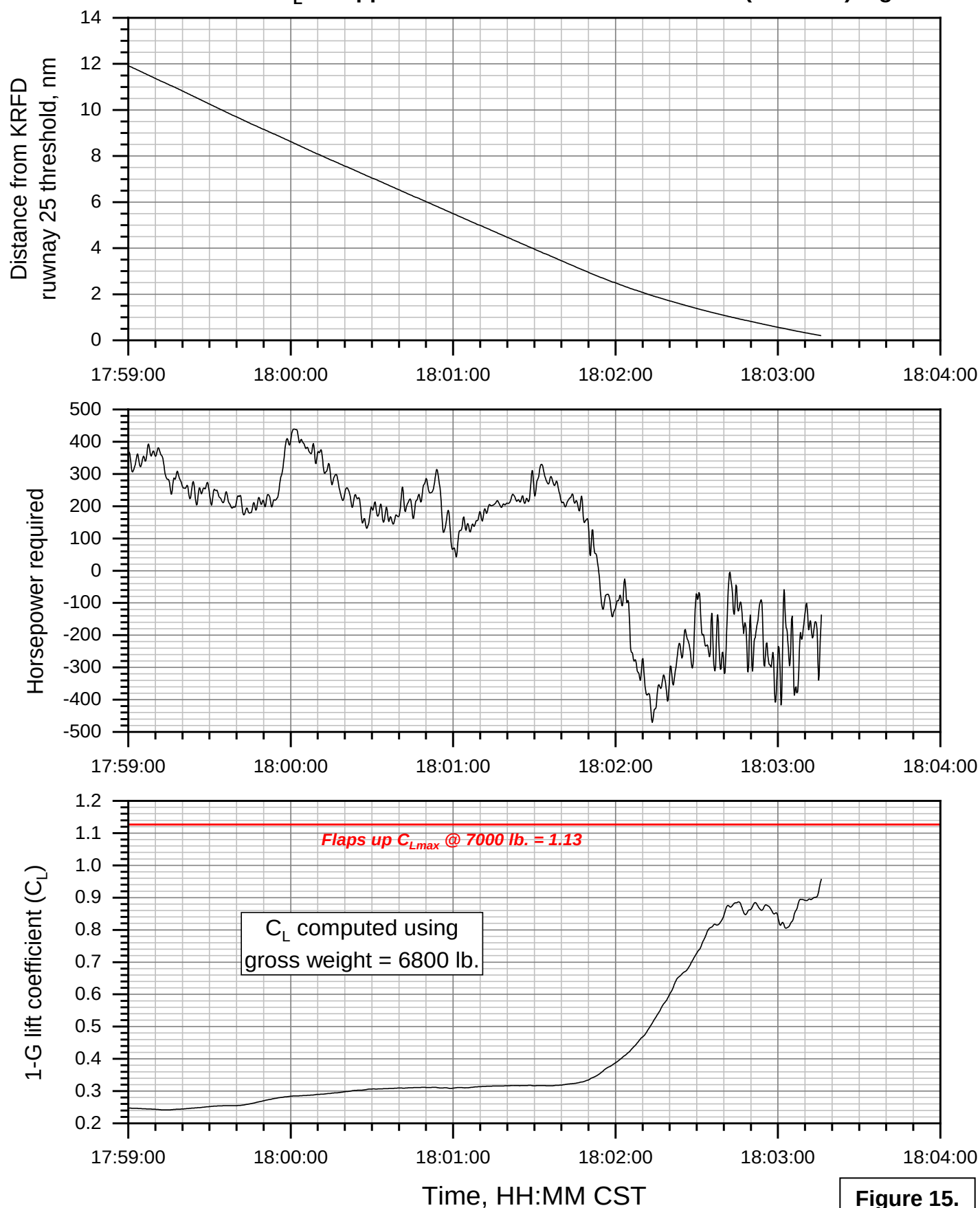
Figure 12.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017**Altitude and speed on approach for 12/04/2017 KISM-KRFD (accident) flight****Figure 13.**

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017

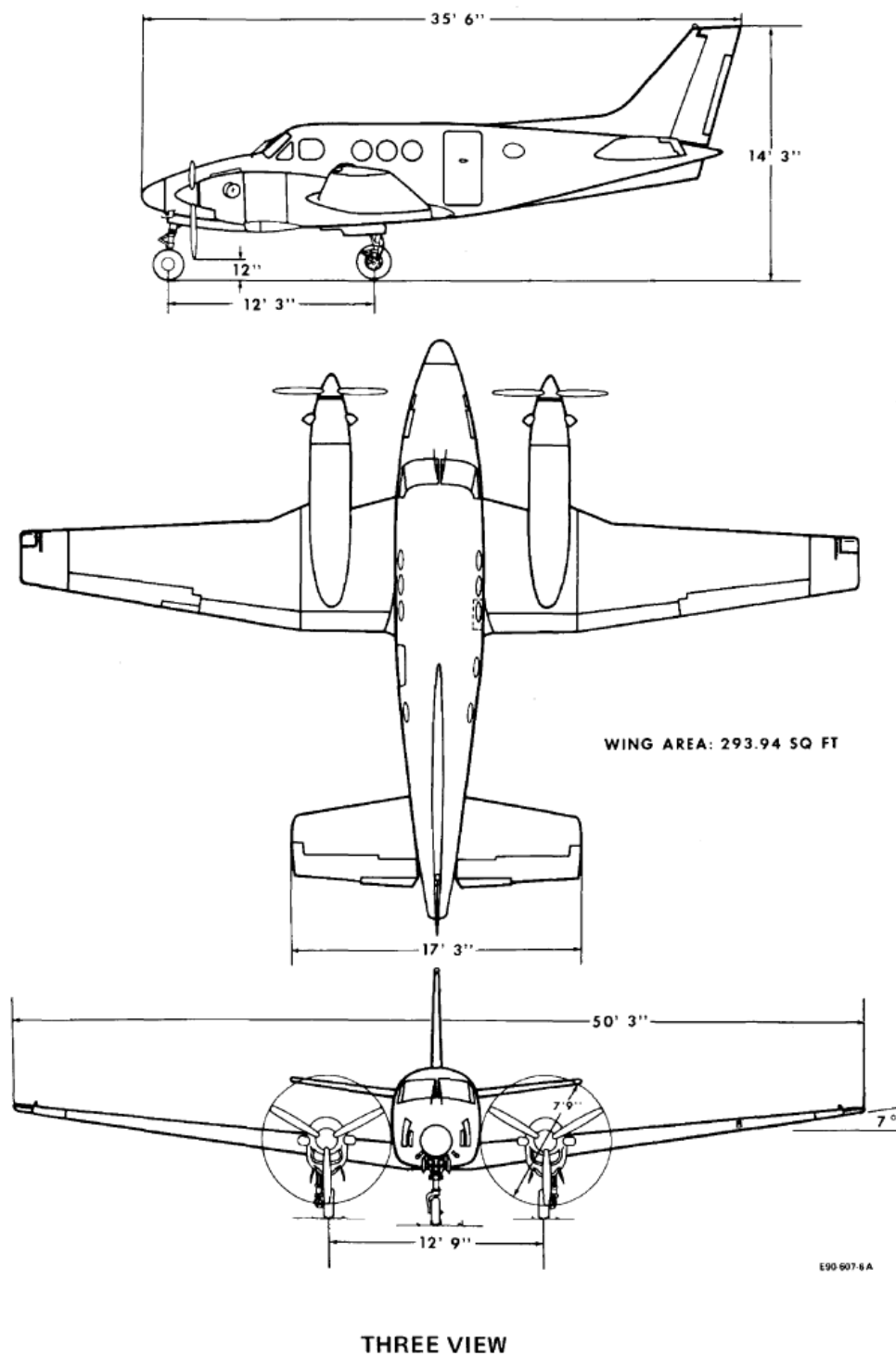
Euler angles on approach for 12/04/2017 KISM-KRFD (accident) flight


Figure 14.

CEN18LA047: Beechcraft C90 King Air, N500KR, Rockford, IL, 12/04/2017**Power and C_L on approach for 12/04/2017 KISM-KRFD (accident) flight**

Section I
General

BEECHCRAFT King Air C90
LJ-668 and after except LJ-670



E90 607-6 A

Figure 16. Beechcraft King Air C90 three-view in AFM (Reference 3).



Figure 17. Pre-accident photograph of N500KR (courtesy of www.FlightAware.com).



(a)



(b)



(c)



(d)

Figure 18. Photographs of N500KR at accident site.

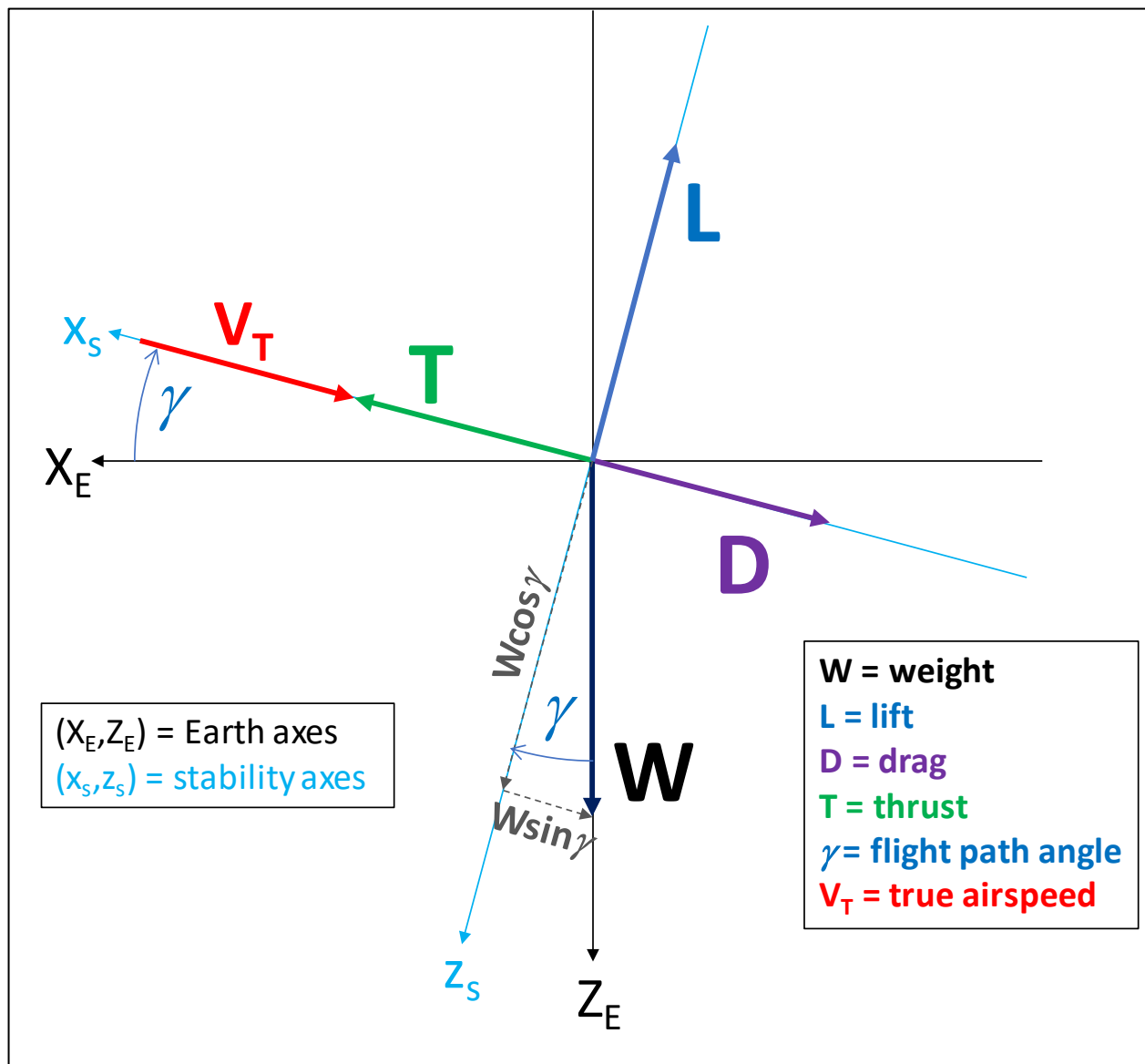


Figure 19. Forces on an airplane in steady wings-level flight. Thrust is assumed parallel to x_s .

Section V
Performance

BEECHCRAFT King Air C90
LJ-668 and after except LJ-670

MAXIMUM TWO ENGINE CRUISE POWER

ISA

1900 RPM

PRESSURE ALTITUDE FEET	IOAT		TORQUE PER ENGINE FT LBS	FUEL FLOW PER ENGINE LBS/HR	TOTAL FUEL FLOW LBS/HR	AIRSPEED KNOTS					
	°C	°F				9500 LBS		8500 LBS		7500 LBS	
						CAS	TAS	CAS	TAS	CAS	TAS
SL	19	66	1245	322	644	208	208	208	208	208	208
2000	15	59	1279	319	638	208	214	208	214	208	214
4000	12	53	1308	316	632	206	218	208	220	208	220
6000	8	46	1266	303	606	201	220	203	222	204	223
8000	4	39	1212	288	576	196	220	198	222	199	224
10000	0	32	1151	272	544	190	220	192	222	193	224
12000	-4	24	1090	257	514	183	219	186	222	187	224
14000	-8	17	1023	243	486	176	217	179	220	181	223
16000	-12	10	963	229	458	169	215	172	219	175	222
18000	-16	3	909	216	432	162	214	166	218	169	222
20000	-20	-5	857	204	408	155	211	159	217	163	221
22000	-24	-12	805	192	384	148	208	153	214	156	219
24000	-28	-19	756	181	362	140	203	145	212	150	218
26000	-33	-27	707	170	340	130	197	138	208	143	215
28000	-37	-34	658	159	318	119	185	129	202	136	212
29000	-39	-38	633	153	306	109	173	124	198	132	209

Figure 20. Sample MAXIMUM TWO ENGINE CRUISE POWER chart in AFM (Reference 3). Similar charts are provided for ΔT ranges from -30°C to +37°C.

April 1980

MAXIMUM RANGE POWER

ISA + 10°C 1900 RPM

PRESSURE ALTITUDE	I.O.A.T.		9500 POUNDS				8500 POUNDS				7500 POUNDS			
			TORQUE PER ENG	FUEL FLOW PER ENG	FUEL FLOW TOTAL	TAS	TORQUE PER ENG	FUEL FLOW PER ENG	FUEL FLOW TOTAL	TAS	TORQUE PER ENG	FUEL FLOW PER ENG	FUEL FLOW TOTAL	TAS
FEET	°C	°F	FT LB	LB/HR	LB/HR	KNOTS	FT LB	LB/HR	LB/HR	KNOTS	FT LB	LB/HR	LB/HR	KNOTS
SL	28	82	865	263.9	527.8	180	786	251.2	502.4	176	719	240.3	480.6	171
2000	24	75	841	251.0	502.0	181	767	239.1	478.2	177	707	229.2	458.4	173
4000	20	68	821	239.1	478.2	183	757	228.9	457.8	179	699	219.4	438.8	176
6000	16	61	801	228.2	456.4	184	749	219.6	439.2	182	690	210.1	420.2	178
8000	12	54	784	218.3	436.6	185	737	210.4	420.8	184	680	201.1	402.2	180
10000	8	47	765	208.6	417.2	186	720	200.8	401.6	185	669	192.4	384.8	182
12000	4	40	750	200.3	400.6	187	699	191.6	383.2	186	653	183.6	367.2	184
14000	0	33	750	195.2	390.4	190	681	183.4	366.8	186	636	175.5	351.0	185
16000	-3	26	753	190.9	381.8	194	667	176.2	352.4	188	619	167.7	335.4	186
18000	-7	19	747	185.8	371.6	196	661	170.7	341.4	190	603	160.5	321.0	187
20000	-11	12	728	180.8	361.6	196	668	169.4	338.8	194	587	155.0	310.0	188
22000	-15	5	...	...	...	...	657	164.4	328.8	195	578	149.8	299.6	189
24000	-19	-2	...	...	...	...	642	159.3	318.6	195	580	147.0	294.0	193
26000	-23	-9	...	...	...	...	...	...	...	...	575	143.8	287.6	195
28000	-27	-16	...	...	...	...	...	...	...	...	563	140.0	280.0	195
29000	-29	-20	...	...	...	...	...	...	...	...	561	139.0	278.0	196

NOTE: Use Maximum Two Engine Cruise Power tables for altitude values which have been omitted.

Figure 21. Sample MAXIMUM RANGE POWER chart in AFM (Reference 3). Similar charts are provided for ΔT ranges from -30°C to +37°C.

TIME, FUEL, AND DISTANCE TO CLIMB

ASSOCIATED CONDITIONS:

PROPELLER SPEED 2000 RPM
TORQUE 1315 FT LBS
OR ITT 645°C

ALTITUDE ~ FT			CLIMB SPEED ~ KTS
SL	TO	10,000	150
10,000	TO	20,000	130
20,000	TO	25,000	120
25,000	TO	30,000	110

EXAMPLE:

TAKE-OFF OAT 25°C
PRESSURE ALTITUDE 3965 FT
CRUISE OAT 10°C
PRESSURE ALTITUDE 17,000 FT
INITIAL WEIGHT 9650 LBS

TIME TO CLIMB (18-4) = 14 MIN
FUEL TO CLIMB (166-40) = 126 LBS
DISTANCE TO CLIMB (48-8) = 40 NM

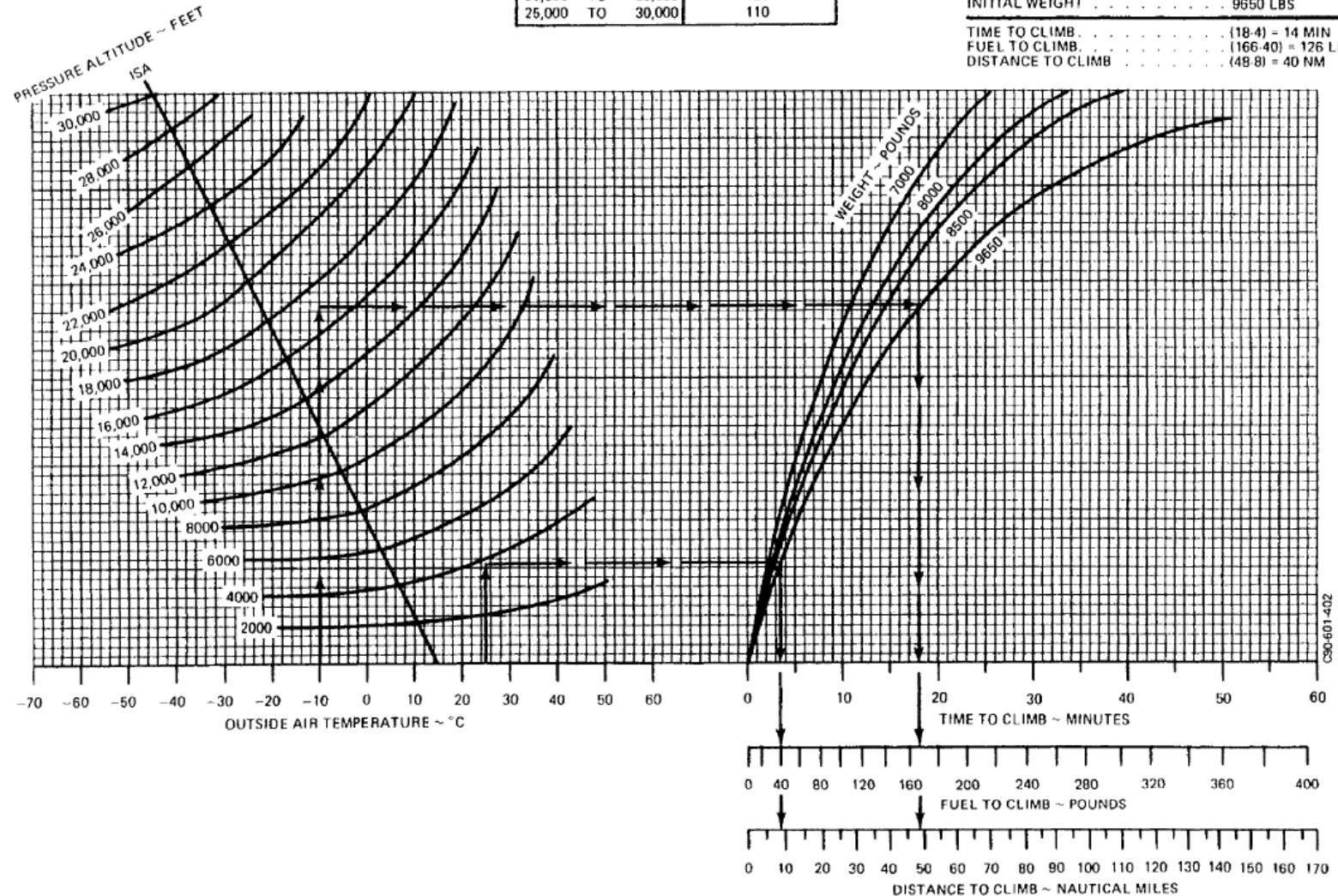


Figure 22. TIME, FUEL, AND DISTANCE TO CLIMB chart in AFM (Reference 3).

BEECHCRAFT King Air C90
LJ-668 and after except LJ-670

Section V
Performance

TIME, FUEL, AND DISTANCE TO DESCEND

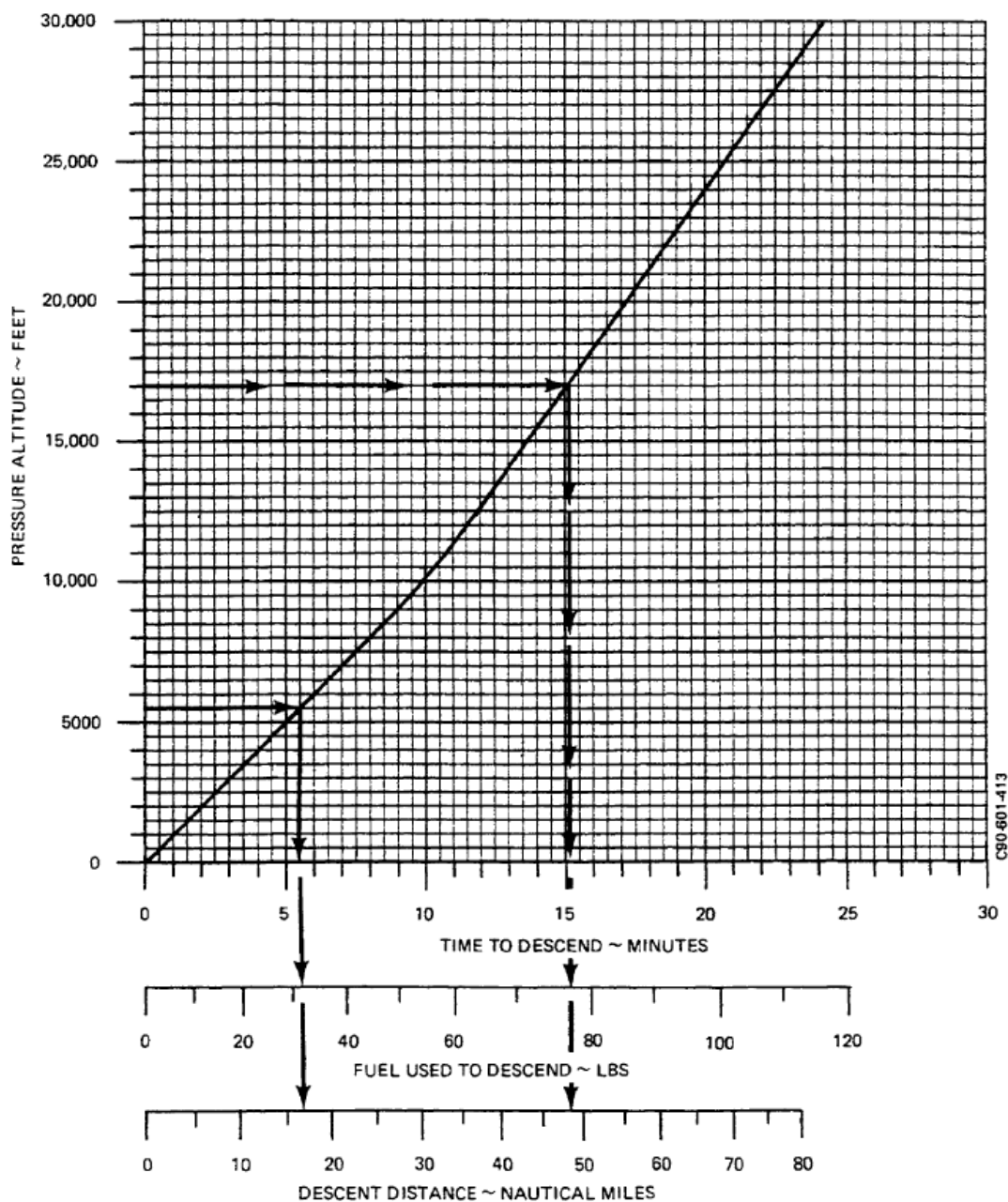
DESCENT SPEED-169 KNOTS

ASSOCIATED CONDITIONS:

POWER AS REQUIRED TO DESCEND AT
1500 FT/MIN; 1000 FT/MIN
BELOW 10,000 FEET
LANDING GEAR UP
FLAPS UP (0%)
PROPELLER SPEED 1900 RPM

EXAMPLE:

INITIAL ALTITUDE 17,000 FT
FINAL ALTITUDE 5651 FT
TIME TO DESCEND (15-5.5) = 9.5 MIN
FUEL TO DESCEND (77-31) = 46 LBS
DESCENT DISTANCE (48-16) = 32 NM



April 1980

5-63

Figure 23. TIME, FUEL, AND DISTANCE TO DESCEND chart in AFM (Reference 3).

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