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# Documentation for UPOS Product Atmospheric Contrail Layer Calculator

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## I. Overview

The Atmospheric Contrail Layer Calculator (ACLC) is a tool for pilots interested in aircraft exhaust condensation trail (contrail) forecasts for flight planning purposes. Contrail layer forecasts are of practical importance for the military due to the adverse effect on aircraft camouflage; contrails may further have an influence on local climate (IPCC 1999). The ACLC combines a conventional theory of mixing clouds and Airforce Weather Agency's (AFWA) MM5 weather forecast model. MM5 (Mesoscale Model, Version 5) is the fifth-generation mesoscale model developed by the National Center for Atmospheric Research (NCAR) and the Pennsylvania State University. The ACLC is written in Interactive Data Language (IDL); parts and some features of the ACLC code are based on the Atmospheric Profile Generator (APG) developed by Marc A. Kolodner at the Space Department of Johns Hopkins University Applied Physics Laboratory (<http://sd-www.jhuapl.edu/UPOS/APG/index.html>).

The ACLC enables users to obtain direct information of layers in the atmosphere, where contrails are likely to be formed. The user may select a flight route and obtains consequently a cross section showing the altitudes of forecasted contrail formation (contrail layer altitudes). Different aircraft types and engines are taken into account using a variety of contrail factors. Appropriate contrail factors, MM5 theater, model initialization times and forecast periods can be selected by the user via a graphical user interface (GUI).

The used theory is based on the calculation of threshold temperatures for contrail formation (Schmidt, 1941, Appleman, 1953). Besides the effects of phase changes due to mixing of exhaust fumes with ambient air, Schumann (1996) also considers the transformation of combustion heat into kinetic energy of the aircraft's wake motion. Contrail factors (CF) determine the critical slope for threshold temperature calculation. CF values parameterize the mixing of water vapor included in aircraft exhaust gases with the ambient air (Wendler and Stuefer, 2002). Threshold temperatures for contrail formation are derived for all MM5 grid points and model levels along the flight path.

## II. Graphical User Interface

A graphical user interface window appears when the program 'contrail02' is called from the IDL command line. The developed widget-based GUI for these codes consists of lists, which the user must select 1 item from, and buttons which perform specific operations. A sample GUI window for each scenario type is presented in Figure 1.

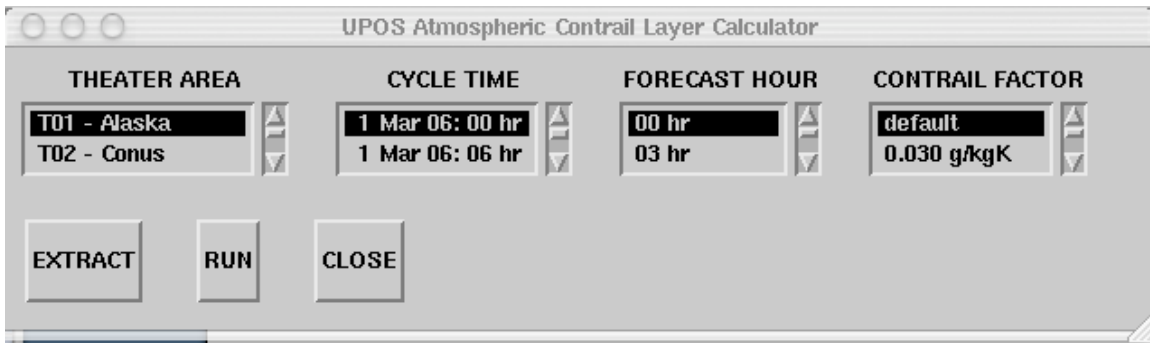


Figure 1: User Interface to choose area, time, forecast hour and contrail factor of interest.

### (a) Theater Area List

The theater area list allows the user to choose the specific MM5 theater area of interest. Currently, only the coarse theater areas are listed as options, but the finer nested theaters could be added if desired. The current list of MM5 theater areas along with their properties (grid size, grid resolution, and map projection) is presented in Table 1.

### (b) Cycle Time List

The cycle time denotes the UTC date and time when the AFWA MM5 analysis run was performed. Analysis runs are carried out every 6 hours for some theaters and every 12 hours for others.

### (c) Forecast Hour List

AFWA produces forecasts from 3 hours out to 72 hours in advance relative to the cycle time, in 3-hour increments. This list allows the user to choose the forecast hour of interest. A 00 hour forecast indicates that the analysis run for the chosen cycle time will be used.

#### - **File Naming Convention**

The theater area, cycle time, and forecast hour lists are needed only for the purpose of identifying which MM5 slimgrib data file is to be accessed. The term 'slimgrib' refers to the fact that the MM5 data files we receive each day from AFWA have a select number of parameters. The files vary in size from 5 to 145 Metabytes depending on theater area coverage and grid resolution (40x40 km or 15x15 km). The AFWA naming convention for these files is as follows:

MM5 data file label = us057 g1 010 t AA N CC00 0FF00.

The label 'us057' is the AFWA WMO identifier and 'g1' indicates that the data is in GRIB edition 1 format. The numbers '010' refer to the process or model ID, namely MM5, and the letter 't' represents the word 'theater'. The letters 'AA' represent the theater area number from the first column of Table 1. The letter 'N', representing the theater nest, will be a 'w', 'y', or 'z' for the slimgrib data. The ACLC currently picks out the 45 by 45 km course grid- or the 15 by 15 km fine grid MM5 data files. The letters 'CC' represent the UTC cycle time hour and the 2 zeros that always follow the cycle time minute. The letters 'FF' represent the forecast hour and the 2 zeros that always follow the forecast minute. Note that AFWA does not include the date in their naming labels. That information is contained in the header of the MM5 data file.

### (d) Contrail Factor List

The contrail factor,  $CF$ , is described as the ratio of the change in the mixing ratio,  $\Delta r_f$ , to the temperature change  $\Delta T$  due to the mixing of exhaust gases with the ambient air. The contrail factor can be considered as ratio of changes of the partial pressure of the vapor,  $\Delta e$ , to temperature (T) changes:

$$CF = \frac{\Delta r_f}{\Delta T} \cong \frac{622\Delta e}{p\Delta T} = \frac{622G}{p} \quad (1)$$

Considering the propulsion efficiency,  $\eta$ , of an aircraft's engine, the parameter  $G$  ( $= \frac{\Delta e}{\Delta T}$ ) is defined as:

$$G = \frac{k_{H_2O} c_p P}{0.622Q(1-\eta)} \quad (2)$$

with the parameters:

$k_{H_2O}$  = emission index for water vapor (amount of water vapor produced by the combustion of 1 kg of fuel)

$c_p$  = specific heat of air at constant pressure

$p$  = air pressure

$Q$  = liberated heat by the combustion of one mass unit of fuel

The combination of equations 1 and 2 leads to:

$$CF = \frac{k_{H_2O} c_p 1000}{Q(1-\eta)} \quad (3)$$

This equation differs from equation 3, derived by Appleman (1953), only by the factor  $(1-\eta)$  in the denominator, which accounts for the amount of work performed for the aircraft drag (Busen and Schumann, 1995, Schumann, 1996).

**Table 1: Theater Areas and Properties**

Theater Number	Theater Name	Grid Size	Grid Resolution	Map Projection
T01	Alaska	115 x 96	15 km	Polar
T02	Conus	192 x 139	45 km	Stereographic
T03	Europe	119 x 104	15 km	Lambert
T04	Southwest Asia	149 x 139	45 km	Conformal
T05	South America	168 x 142	45 km	Lambert
T06	West Pacific	199 x 149	45 km	Mercator
T07	China	149 x 119	45 km	Lambert
T08	Atlantic	*	*	Conformal
T09	Africa	210 x 120	45 km	*
T10	New Zealand	159 x 119	45 km	Mercator
T11	East Pacific	*	*	*
T12	Indonesia	*	*	*
T13	Antarctic	*	*	*
T14	Russia	115 x 96	45 km	Polar
				Stereographic

\* Theater data not currently available

A default contrail factor (CF) of  $0.037 \text{ g}(\text{kgK})^{-1}$  has been defined for commercial jet aircraft (Stuefer et al., 2004). CF values range from non-bypass engine types with characteristic contrail factors of about  $0.030 \text{ g}(\text{kgK})^{-1}$ , to low-bypass engine  $0.034 \text{ g}(\text{kgK})^{-1}$ , and to the high-bypass engine with  $\text{CF} = 0.039 \text{ g}(\text{kgK})^{-1}$ . The *bypass ratio* is defined as the ratio of bypassed air mass to combustor air mass; it is an important parameter for aircraft engine classification. A logical approach to improving fuel consumption is higher bypass technology. Engineers designed high bypass engines for highly efficient air transport; these engines are of main importance for economic commercial aircrafts. In contrast military combat aircrafts use mostly engines of low-bypass type.

### **(e) Extract Button**

Pressing the EXTRACT button instructs the code to call upon the external executable program 'wgrib-afwa' to extract data from the MM5 data file which has been selected based on the information provided in the first 3 GUI lists. Now if the selected file is not currently available, a pop-up window appears to indicate that and asks for a different file to be selected. If the file is available, a pop-up window appears to inform the user that the extraction process is taking place (Figure 2).

The following data are extracted over the entire theater area:

- Latitude and Longitude
- Surface Elevation (above sea level)
- Surface Pressure, Temp, and Relative Humidity
- Surface Wind Speed (u and v components)
- Surface Terrain Type (sea, rural, ice, barren, urban)
- Precipitation Type (no precip, rain)
- Geopotential Height Profiles (versus pressure)
- Temperature Profiles (versus pressure)
- Relative Humidity Profiles (versus pressure)

The process takes approximately 10-15 seconds to complete. The pop-up window also indicates when the extraction is complete and instructs the user to click the RUN button to display the theater area.

### **(f) Run Button**

Pressing the RUN button initiates the execution of the main body of the program. The first order of business is to determine the latitudes and longitudes of an individual flight route. This starts with a window display of the entire theater area. Figures 3a and 3b show examples of the theater area displays for Alaska and the continuous United States.

Note that each grid point is color-coded based on the surface terrain type. As the user moves the mouse around the display, the latitude and longitude numbers on the lower left-hand corner change accordingly. Once the general

region of interest is determined, a click of the mouse by the user will produce a new window displaying a zoom in of that region. The size of the zoomed in region is 40 deg longitude by 20 deg latitude (Figure 4a). At this resolution, the MM5 grid points are easily distinguishable from one another and the user can home in on the specific area of interest. A sample zoom display is given on Figure 4a for the main Alaska region.

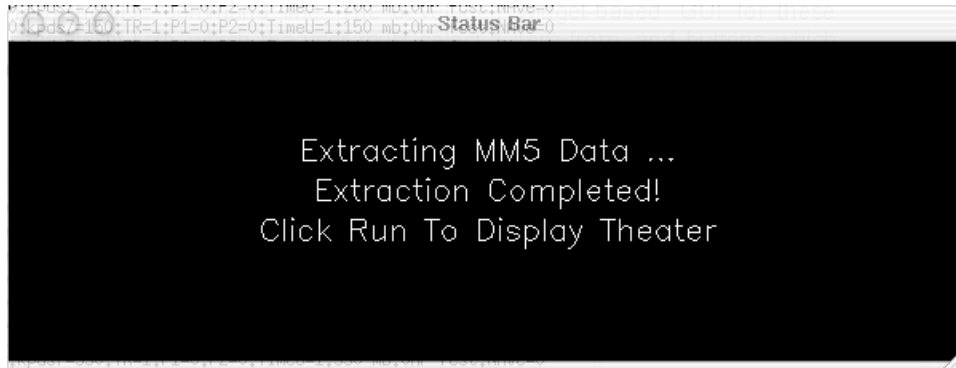


Figure 2: Pop-Up window indicating that the AFWA MM5 source data file is available and extracted.

At this point the flight route has to be selected by three\* clicks of the mouse. The first click indicates the origin of the flight, the second click marks the position of a corner point along the flight path, and the third mouse click is set at the flight destination. The third mouse click automatically triggers the calculation of profiles of critical temperatures. All MM5 grid-points closest along the flight path are chosen. Sometimes a zick-zack shaped line appears, which shows the considered grid-points for the calculation of contrail formation on the map display (Figure 4b). Depending on the length of the selected path and the processor speed, the calculation of profiles may take several seconds. Once finished a window with resulting contrail layer graphics appears automatically (Figure 5).

\* Flight path selection in version 2 of the ACLC has been restricted by 3 locations. A more versatile flight path selection procedure can be produced as version 3 of the ACLC upon request.

### **(g) Close Button**

Pressing the CLOSE button will close all windows including the GUI interface and return the user to the IDL command line. If the user wishes to pick a different path instead of closing, the user can simply press the RUN button again and the program will reinitiate, starting with the current theater area display. The user can also opt to change the contrail factor before pressing RUN. If the user, though, wishes to change the theater area, cycle time, and/or forecast hour, the EXTRACT button must be pressed (to extract data from a new MM5 file) before pressing the RUN button.

### III. Operational Requirements

#### (a) Operating System

While the IDL script and supporting codes can run on both UNIX and Windows systems, it is recommended for MM5 data acquisition purposes that it be run on a UNIX system (such as an SGI, SUN, or HP) which can be accessed either from a workstation or from a PC through an X- terminal software such as XVision or Exceed. Mac OSX is supported.

#### (b) Software

The code `'contrail02.pro'`, which is discussed in this User's Guide is compatible with IDL 5.4 (or higher).

We do have another code available called `'contrail01.pro'`, which is compatible with IDL 5.4 (or higher). It provides single MM5 grid point profiling of temperature, humidity and threshold temperatures for contrail formation of the ACLC.

Finally, the MM5 portable data extractor `'wgrib'` or `'wgrib-afwa'` must be accessible.

#### (c) Disk Space

The largest consumers of disk space are the actual Airforce Weather Agency's (AFWA) 5<sup>th</sup> generation Mesoscale Model (MM5) source data files themselves which can vary in size from 5 to ~150 Metabytes; depending on theater area and resolution (45x45 km or 15x15 km). It is thus recommended that a server with at least 500 Mb of available disk space be used.

#### (d) File Organisation

The file directory of the ACLC has to be specified in line 163 of the `contrail02.pro` code.

The following files have to be available in the same directory:

- => `'contrail02.pro'`: the IDL program code
- => `'wgrib'` or `'wgrib-afwa'`: the wgrib data extractor
- => the MM5 output source data for the theater of interest  
(f.i. `'us057g1010t02b060001800'`)

### IV. Summary of Contrails Forecast Technique Requirements

1. The Contrail Forecast Technique (CFT) process is applicable for pre-defined model grid- points of different MM5 theater areas (geographic latitude and longitude) (Stuefer et al., 2005).

2. The CFT process uses contrail factors as parameterization for the aircraft specific combustion and the state of the aircraft performance (Schrader, 1997). An adiabatic mixing of the aircraft exhaust and the surrounding air is assumed (Wendler and Stuefer, 2002).
3. The CFT process shall incorporate vertical profiles of air-pressure, temperature and humidity at the locations (grid points) of interest.
4. The CFT Process shall store critical temperatures defining the threshold for saturation (over water) of the aircraft wake, which is responsible for contrail formation (Schmidt, 1941, Appleman, 1953).
5. The CFT Process shall present the lower and upper contrail layer limits in m a.s.l. as output chart.

Interface Requirements / Input Interfaces:

The Contrail Forecast Process shall ingest pressure (Pa), height (m), temperature (K), and water vapor mixing ratio (kg/kg) contained in the input file. These data files must be formatted to ACLC specifications, which are listed below:

<b>Record #</b>	<b># of items</b>	<b>Description of items</b>
1	2	year-mon-mday_hour:min corresponding to date/hour of first forecast; number of hours past initialization
2..n	5	pressure(Pa) height(m) temperature(K) vapor mixing ratio (kg/kg) Contrail Factor (CF)

The aircraft specific contrail factor is defined using the GUI after starting the contrail02.pro program. The default value represents an average contrail factor of 0.0370 g/kgK .

## V. Output chart examples

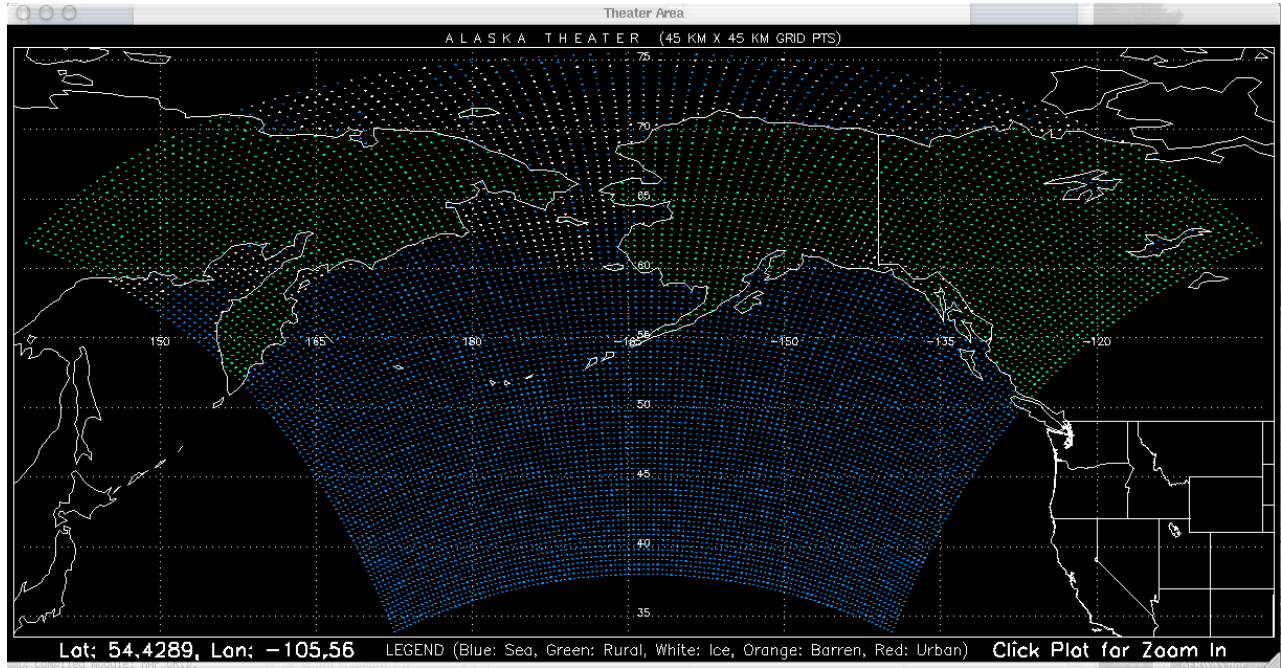


Figure 3a: Map of the 45 x 45 km MM5 grid for the Alaska (T01) theater

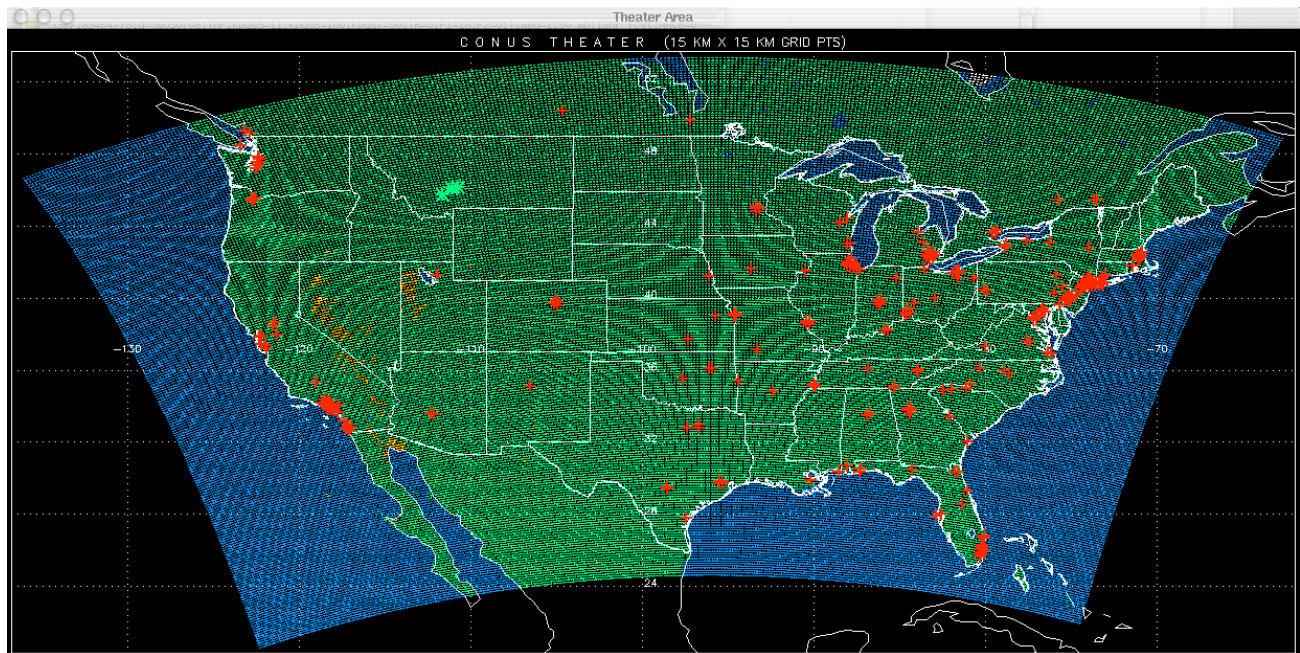


Figure 3b: Map of the 15 x 15 km MM5 grid for the continental United States (T02) theater

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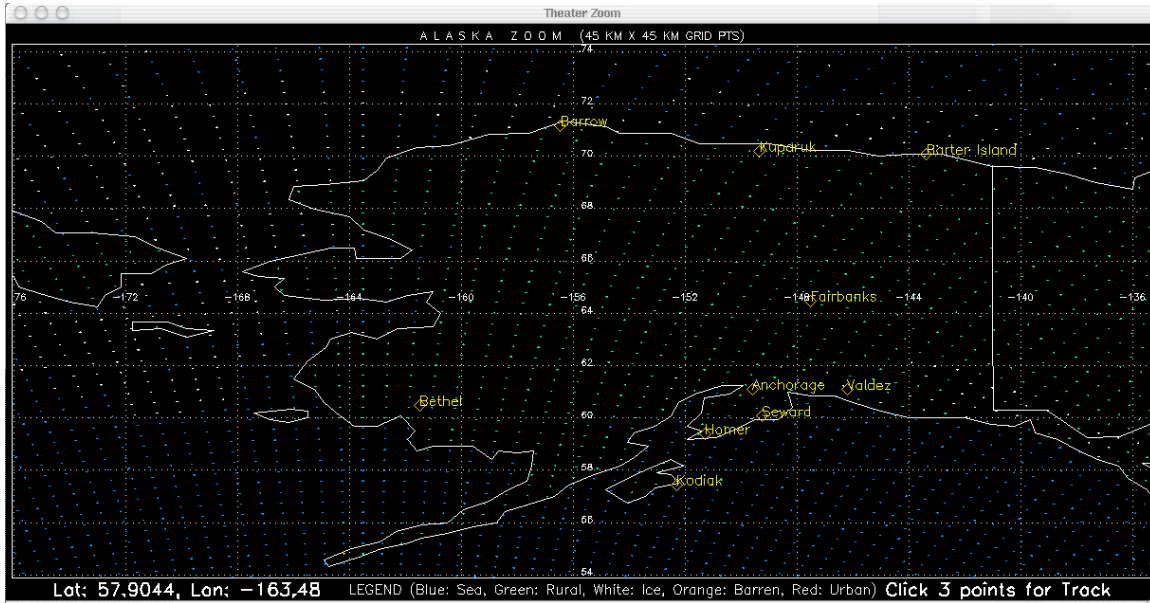


Figure 4a: Zoom Map of the 45 x 45 km MM5 grid for the Alaska (T01) theater

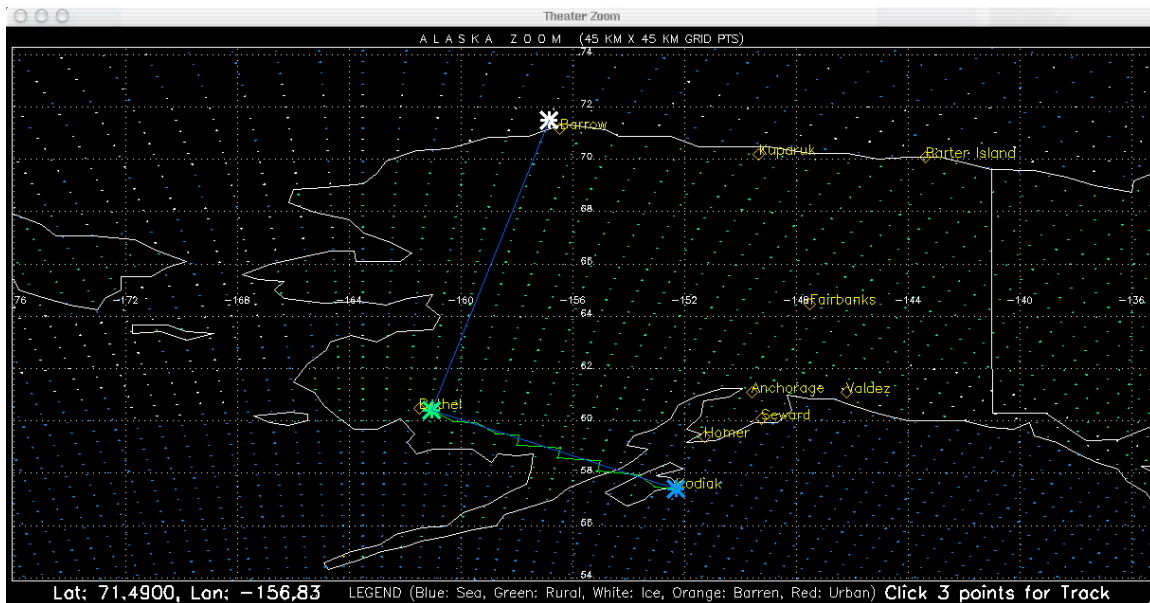


Figure 4b: Zoom Map of the 45 x 45 km MM5 grid for the Alaska (T01) theater with freely selected flight path

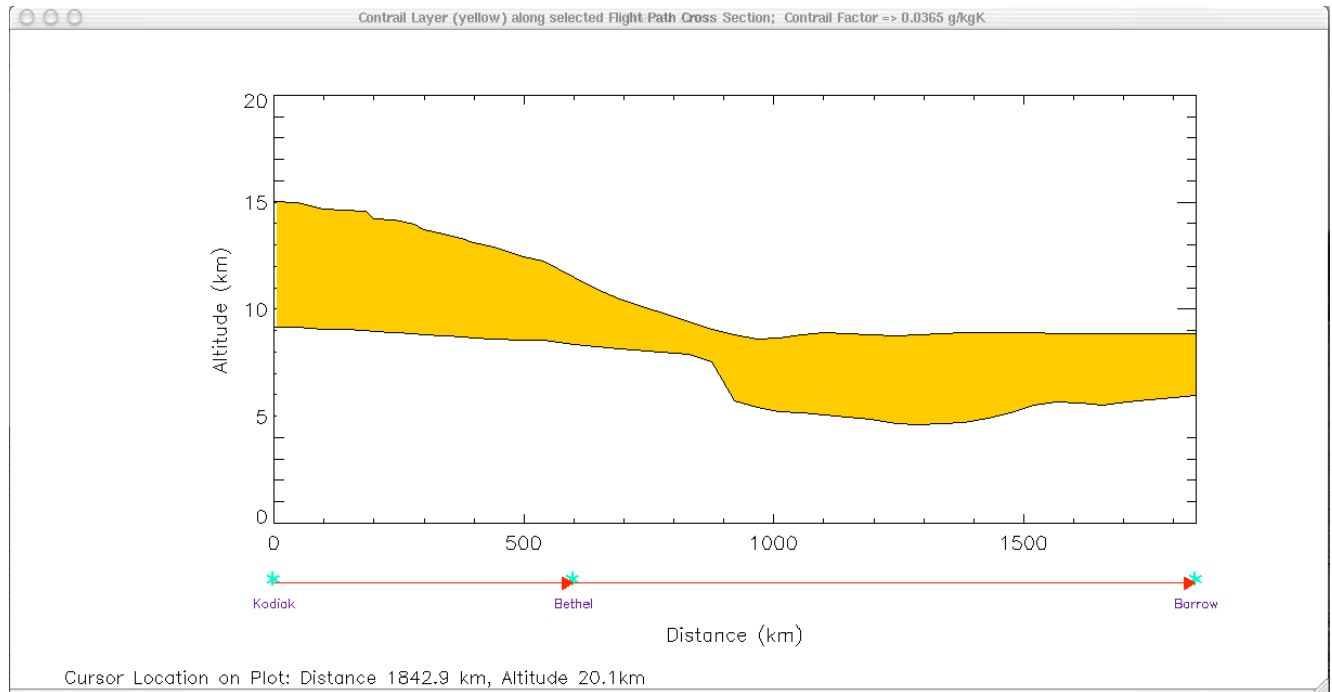


Figure 5: Chart of resulting contrail layer altitudes along a selected flight path

## VI. References

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## **VII. Contacts**

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## Acronyms and Abbreviations

Acronym	Definition
AACGM	Attitude Adjusted Corrected Geomagnetic
ACE	Advanced Composition Explorer
ACLC	Atmospheric Contrail Layer Calculator
AFCCC	Air Force Combat Climatology Center
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AFSCN	Air Force Satellite Control Network
AFSPACECOM	Air Force Space Command
AFSWC	Air Force Space Weather Center
AFWA	Air Force Weather Agency
AFWIN	Air Force Weather Information Network
AF/XOW	Air Force Director of Weather
APL	Applied Physics Laboratory of Johns Hopkins University
ASCII	American Standard Code for Information Interchange
ASPAM	Atmospheric Slant Path Analysis Model
AVHRR	Advanced Very High Resolution Radiometer
AVN	Aviation Model
AVO	Alaska Volcano Observatory
BATS	Biosphere-Atmosphere Transfer Scheme
CARMA	Community Aerosol Research Model from Ames/NASA
CLASS	Canadian Land Surface Scheme
CME	Coronal Mass Ejections
COE	Common Operating Environment
DII	Defense Information Infrastructure
DMSP	Defense Meteorological Satellite Program
Dst	Disturbance, storm
ECMWF	European Center for Medium-Range Weather Forecasts
EIT	Extreme Ultraviolet Imaging Telescope
EVA	Extravehicular Activities
FAC	Field Aligned Currents
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FSL	Forecast Systems Laboratory
FTP	File Transfer Protocol
GI	Geophysical Institute
GIC	Ground Induced Currents
GIF	Graphic Interchange Format
GIT	Georgia Institute of Technology
GMT	Generic Mapping Tools

GOLD	Geophysical On-Line Data
GOES	Geostationary Operational Environment Satellite
GRIB	Gridded Binary
GSE	Geocentric Solar-Ecliptic
GSFC	Goddard Space Flight Center
HLBL	High Latitude Boundary Layer
IDL	Interactive Data Language
IMF	Interplanetary Magnetic Field
ISS	International Space Station
JHU	Johns Hopkins University
Kp	Planetary Index of Geomagnetic Activity
LAN	Local Area Network
LAPS	Local Analysis and Prediction System
LASCO	Large Angle Spectroscope Coronagraph
LEO	Low-attitude Earth Orbit
LSM	Land Surface Model
MATCH	Model of Atmospheric Transport and Chemistry
MeV	Million Electron Volts
MM5	Fifth Generation Mesoscale Model
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
netCDF	Network Common Data Form
NGDC	National Geophysical Data Center
NGM	Nested Grid Forecast Model
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
OWS	Operational Weather Squadron
PACE	Polar Anglo-American Conjugate Experiment
PBL	Planetary Boundary Layer
PCA	Polar Cap Absorption
PFRR	Poker Flat Research Range
PNG	Portable Network Graphics
RBE	Radiation Belt Environment
SAA	South Atlantic Anomaly

SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
SD	Space Department of the Applied Physics Laboratory
SDFM	Surface Dust Flux Model
SDP	Software Development Plan
SEC	Space Environment Center
SEE	Solar EUV Experiment
SEON	Solar Electro-optical Observing Network
SEP	Solar Energetic Particles
SFOC	Space flight Operations Center
SOHO	Solar and Heliospheric Observatory
SPE	Solar Particle Event
STP	Solar Terrestrial Physics
SWOC	Space Weather Operations Center (Offutt)
SWXS	Space Weather Squadron
SXI	Soft X-ray Imager
Tcl	Tool Command Language
Tk	Toolkit
Tix	Tk Interface Extension
UAF	University of Alaska, Fairbanks
UCAR	University Corporation for Atmospheric Research
UCB	University of Colorado, Boulder
UPOS	University Partnering for Operational Support
UTC	Coordinated Universal Time
WDC	World Data Center
WF	Weather Flight
WMO	World Meteorological Organization
XDR	External Data Representation