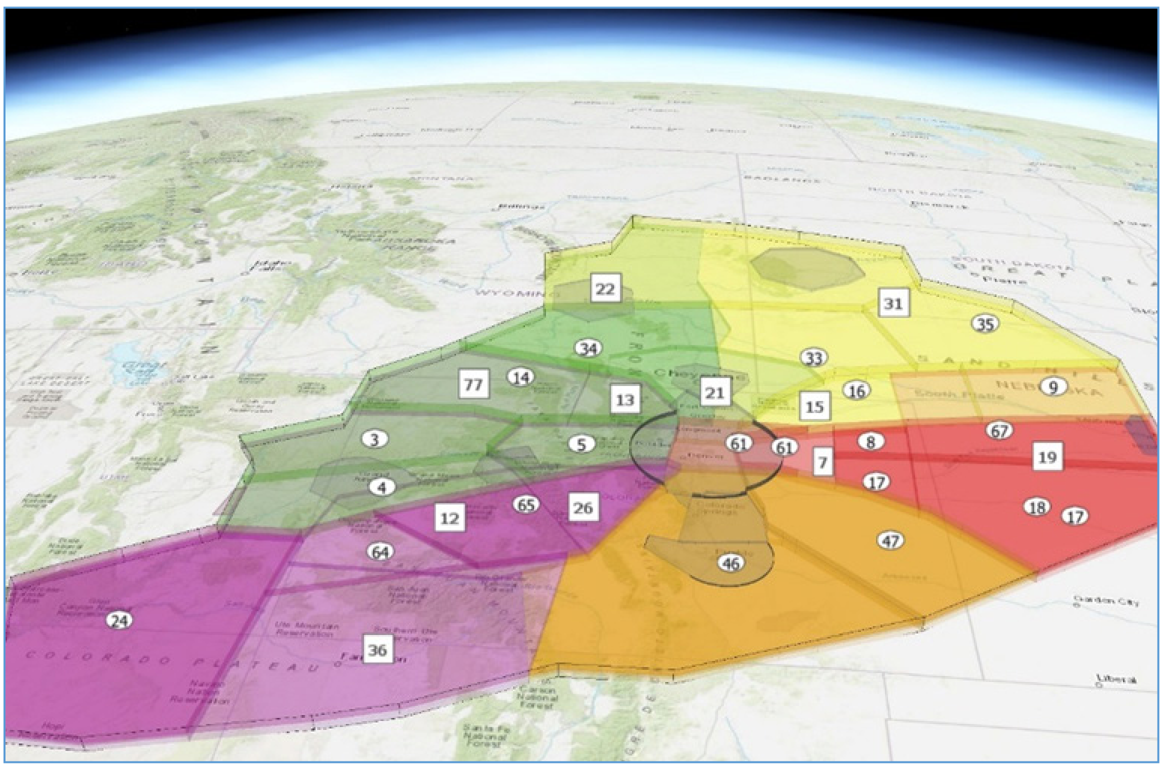
ZDV-3D

A Modern 3D Visualization and Analysis Tool for Denver Air Route Traffic Control Center



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Contents

1. Abstract

Air traffic control (ATC) manages complex, three-dimensional airspace. In particular, Denver Air Route Traffic Control Center (Denver Center) is responsible for a 60,000-ft. tall volume of airspace covering over 265,000 square miles. Denver Center needs a modern 3D GIS platform capable of depicting its numerous aeronautical features including ATC areas, sectors, minimum safe altitudes, airways, military airspace, airports, navigation equipment, communication information, and surveillance infrastructure. The main objective of this study is to incorporate these entities into a 3D digital twin of Denver Center, titled ZDV-3D. ZDV-3D intends to produce an intuitive platform for visualizing and analyzing ATC system interrelationships. Esri technology applications are evaluated, including ArcGIS Pro, ArcGIS Online, and ArcGIS Earth. Capabilities and limitations of Denver Center's current geospatial tools are reviewed, and benefits of implementing the latest ArcGIS 3D rendering capabilities into this project are highlighted. Production challenges, plans for further ZDV-3D development, and ways to share outcomes with other ATC facilities are also addressed. ZDV-3D enables Denver Center to provide optimized efficiency and safety for all who fly in our increasingly crowded skies.

2. Background

Air Traffic Control (ATC) provides separation services between aircraft. The FAA (Federal Aviation Administration) delivers ATC through three main types of facilities: Towers, TRACONs, and Centers. The facility providing these services at any given time is determined largely by the aircraft's phase of flight (see Figure 1).

Air Traffic Control Towers provide separation for aircraft taxiing on the ground, during takeoff, local traffic patterns, and final approach. TRACON (Terminal Radar Approach Control) facilities separate aircraft on departure, arrival, and on initial approach.

En Route Centers, or Air Route Traffic Control Centers, normally provide services for aircraft during the cruise portion of flight. They also provide ATC for airports that do not have a Tower and areas without a servicing TRACON. There are twenty Air Route Traffic Control Centers across the continental United States (see Figure 2). They control a significantly larger volume of airspace compared to TRACONs and Towers.

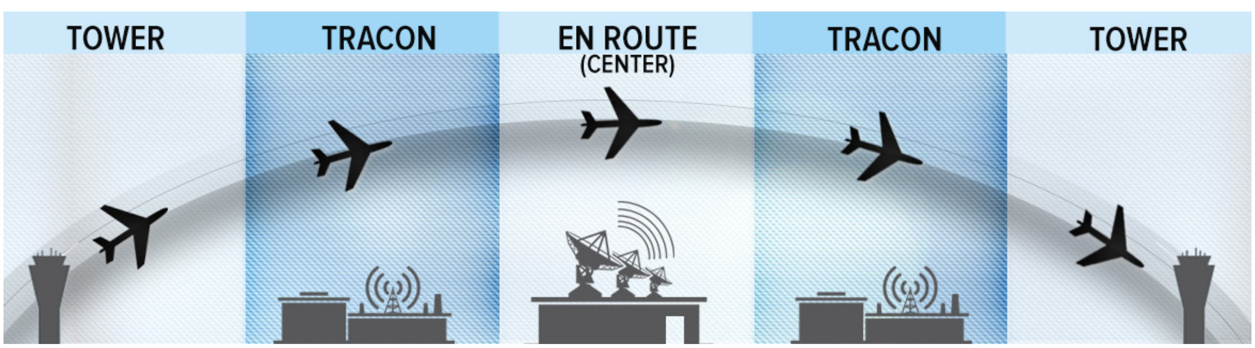


Figure 1. FAA En Route Traffic Control Centers role compared to Towers and TRACONs (Aviation Stack Exchange, 2016).

Denver Center, coded ZDV by the FAA, controls the airspace above Colorado and surrounding states. It is one of the largest air route traffic control centers in the U.S., with a footprint of over 265,000 square miles. ZDV extends vertically up to 60,000 feet. It principally handles aircraft in en route phases of flight. Like other centers, it also controls departures and arrivals for airports that do not have an air traffic control tower or overlying approach control.

Denver Center controls approximately 5,000 flights per day. ZDV is comprised of 28 high and 16 low altitude air traffic control sectors split up among six areas. There are nearly 200 minimum safe altitude (MIA) sectors, 100 airways, 500 airports, 27 low-level training routes, 20 aerial refueling routes and 50 special use airspace (SUAs) areas for military operations and glider soaring activity. ZDV contains hundreds of waypoints and navigational aids (NAVAIDS), as well as numerous arrival, departure, and instrument approach procedures. There are nine approach control airspaces within Denver Center and five adjacent air route traffic control centers.

When looking up at the vast blue sky, the airspace above appears simple, with a lot of wide-open space. However, Denver Center handles a complex, closely orchestrated, 3D system of airspace, airways, and procedures invisible to the naked eye (see Figure 3). Air traffic controllers and associated support personnel are often challenged with translating 2D representations (controller charts) of 3D airspace in their minds.

Management program analysts for Denver Air Route Traffic Control Center (Denver Center) produce aeronautical controller charts and perform air traffic analysis using GIS. Controller charts are updated every 56-days and placed overhead each air traffic control position as a ready reference for routing and separating aircraft. Charts are also used to train new controllers and memorize the host of the aeronautical features which populate their geographic areas of responsibility. Further, FAA management, support personnel, and stakeholders benefit from airspace studies performed using geospatial analysis. Understanding the interrelationships of these aeronautical features in three-dimensional space is key to maintaining a safe and optimized air transportation network for the flying public. Denver Center needs a modern tool to visualize and analyze all of these aeronautical components: ZDV-3D.

Figure 2. ZDV in relation to FAA En route Traffic Control Centers. Created in ArcGIS Pro (Esri, 2018).

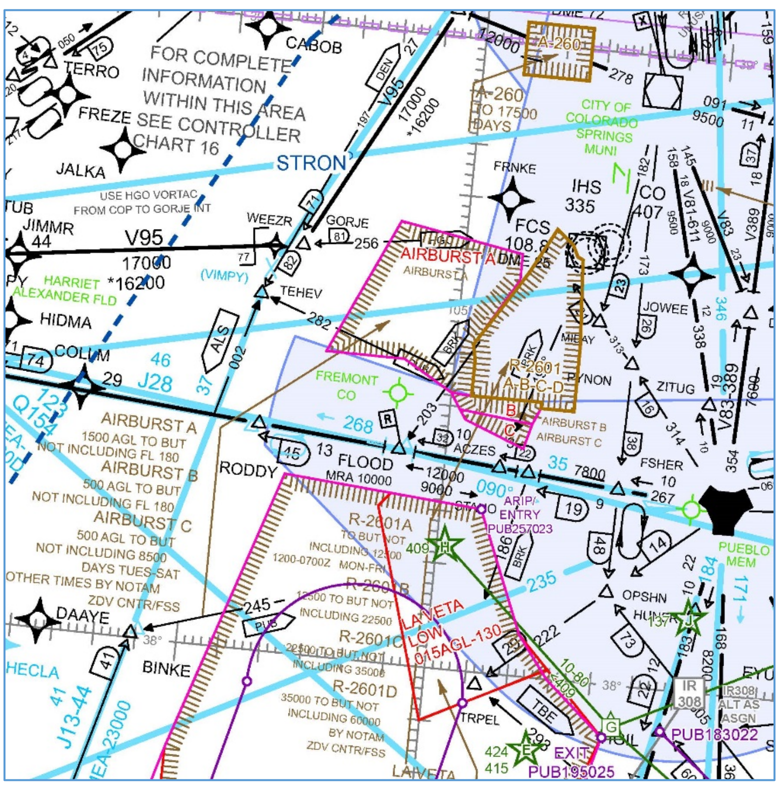


Figure 3. A chart inset depicting the complexity of the airspace in ZDV, above southern Colorado. Created in ArcGIS Pro (Esri, 2018).

2.1 Description of the Problem

There are many tasks that analysts and controllers need to perform and questions they need to answer. These extend beyond standard procedures to include things like: assessing the impact on civilian air traffic when a multi-tiered military airspace goes active; rescheduling or rerouting DIA (Denver International Airport) departures and arrivals in response to nearby spaceport launches; or calculating the lowest safe aircraft vectoring altitude above a new windmill construction proposal. Determining which ATC sectors are impacted by UAS (unmanned aircraft systems) activity, the proximity of a flight track to a mountain peak, or the optimum routing procedures for adjacent facility air traffic are several of the many questions that a comprehensive 3D GIS of Denver Center could answer.

While some software is currently available at Denver Center for managing airspace and procedures matters, the process for analyzing and visualizing aeronautical spatial relationships can be challenging and often takes longer than necessary. It is difficult, with current resources, to expedite time-sensitive airspace studies, reports and investigations, especially in 3D. Additionally, the quality, content, and user interface of existing airspace modeling venues needs updating. This document reviews current air traffic support tools, their strengths and limitations, and establishes the need for a modern 3D GIS visualization and analysis platform. The intended output, titled ZDV-3D, aims to create a three-dimensional digital twin of ZDV, incorporating ATC data from a variety of sources.

2.2 Concepts

Concepts and definitions are included in this section to help comprehend the aeronautical components ZDV-3D intents to implement.

En Route Center airspace is composed of areas and sectors. Major areas are subdivided into smaller sectors. Each sector is usually managed by one controller, although sectors may be staffed by several controllers or consolidated based on traffic volume. Each sector has a low, high, or sometimes a ultra-high altitude stratum.

Denver Center Air Traffic Control (ATC) airspace consists of six major areas. These areas, labeled Areas 1 – 6, are subdivided into smaller sectors, with six to eight sectors per area. ZDV's low sectors usually control traffic from the surface to 26,000 ft. MSL (mean sea level) while high sectors manage traffic above 27,000 ft. Some areas include ultra-high sectors consisting of airspace above 36,000 ft. Each sector is also given a unique numerical identifier (see Figure 4).

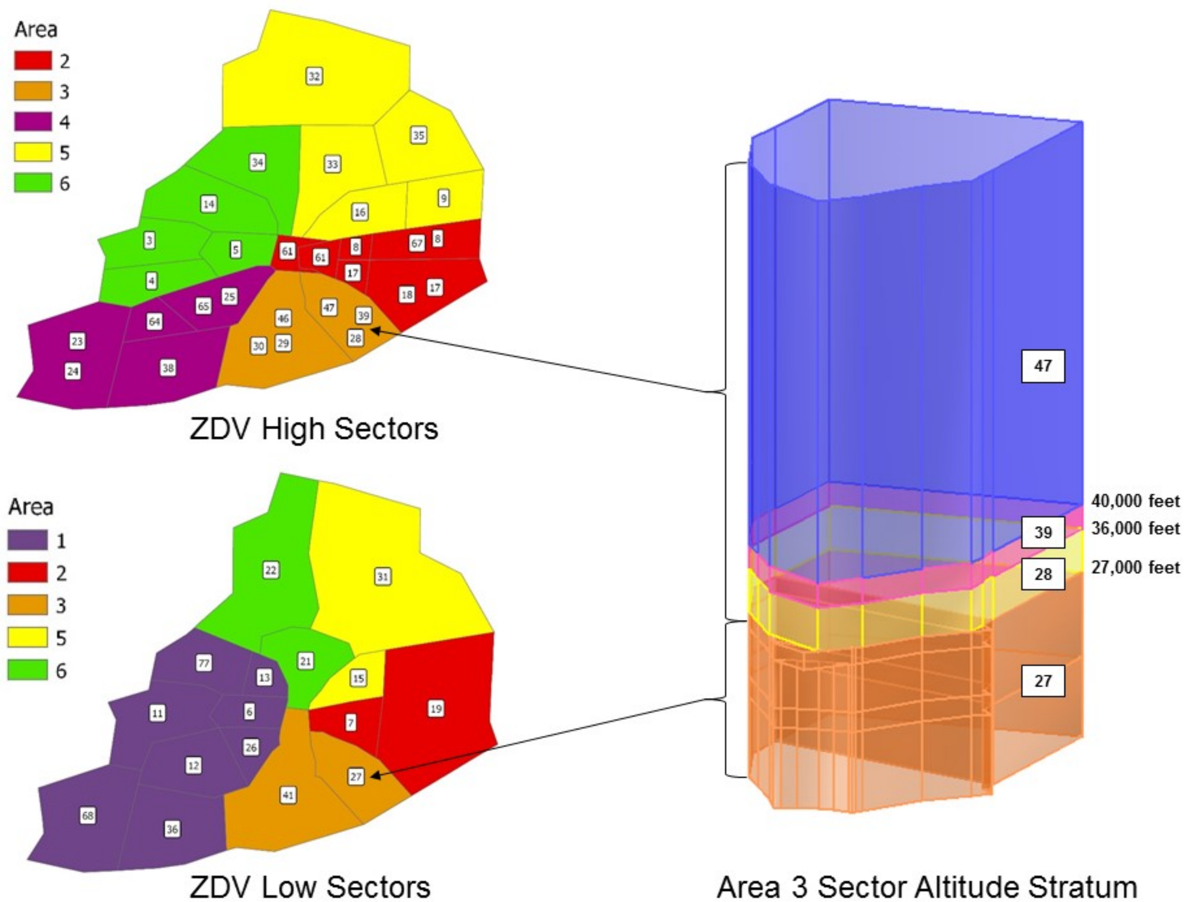


Figure 4. Denver Center High and Low Areas and Sectors with associated numerical labels. Created in ArcGIS Pro (Esri, 2018) and PDARS (2012).

Denver Center overlies several air traffic approach control airspaces, sometimes referred to as Terminal Radar Approach Control (TRACON) or Radar Approach Control (RAPCON), which serve busier arrival and departure areas. These areas are controlled by civilian and military controllers separate from Denver Center. Each of these approach airspaces have unique geographic dimensions, with altitude stratums from the surface up to ceilings varying from 12,000 ft. to 23,000 ft. MSL. The names of these approach areas are shaded gray in Figure 5:

- Aspen Approach (ASE)
- Casper Approach (CPR)
- Cheyenne RAPCON (CYS)
- Colorado Springs TRACON (COS)
- Denver TRACON
    - Denver Terminal Area (D01)
    - Grand Junction (JNC)
    - Pueblo Terminal Area (PUB)
- Ellsworth Approach (RCA)

Figure 5. ZDV low altitude structure. Approach airspace is shaded gray, low altitude airways are blue, and sectors are black-dashed lines. Created in ArcGIS Desktop (Esri, 2017).

In addition to Denver Center and approach airspace, the FAA has established various classes of controlled (and uncontrolled) airspace to regulate safe aircraft equipment requirements and operating procedures. This airspace is identified as Class A through Class G, with Class A being the most restrictive (see Figure 6). Class A airspace is located above 18,000 ft. MSL where an ATC clearance is required for flight. As DIA is one of the nation's busiest airports, it is surrounded by Class B airspace. Class C airspace includes airports with a significant number of flight operations, but is not as congested as Class B. The City of Colorado Springs Municipal Airport is in Class C airspace, for example. Smaller towered airports with lower traffic counts, such as Grand Junction Regional Airport, are contained within Class D airspace, while other non-towered airports with minimal traffic counts are often located in Class E airspace. The smallest airfields with the least amount of traffic often have Class G, or uncontrolled, airspace immediately above them.

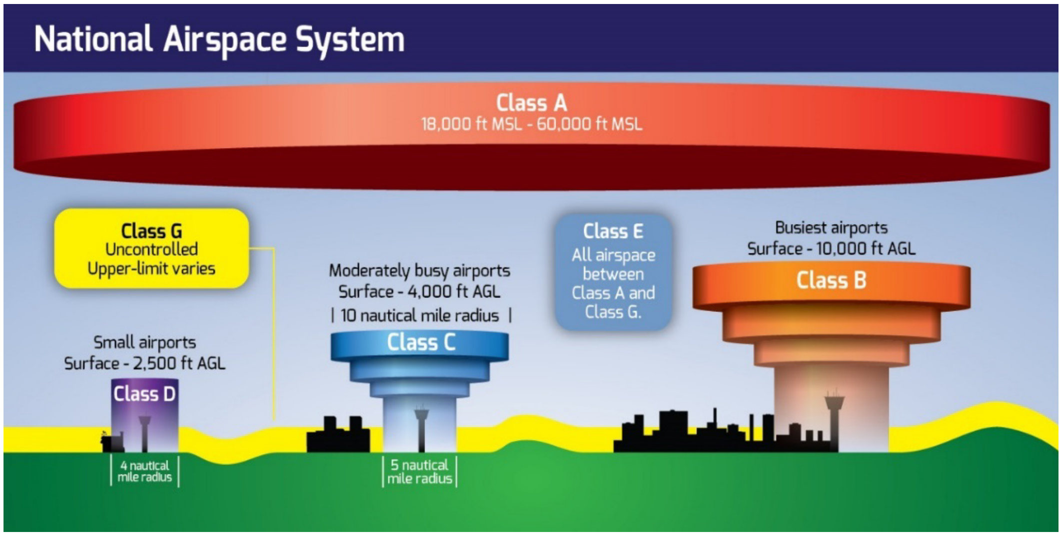


Figure 6. Various U.S. classes of controlled and uncontrolled airspace (National Airspace System, n.d.).

Special Use Airspace (SUA) is used for primarily by the military. However, soaring areas are also used for civilian glider operations. SUA types are listed below along with a brief summary of their intended use. They include:

- MOAs (Military Operating Areas) – flight training operations below 18,000’ MSL
- Restricted Areas – artillery, bombing, and other potentially hazardous military operations
- ATCAAS (Air Traffic Control Assigned Airspace) – flight training operations at/above 18,000’ MSL
- Air Refueling Anchors/Tracks – racetrack or linear air refueling operations
- Military Training Routes – low level flight training
- Orbit Areas – used for surveillance or command and control missions
- Soaring Areas – designated for glider activity

SUA examples are depicted in Figure 7. Denver Center keeps non-participating aircraft (airliners and general aviation) clear of active SUAs.

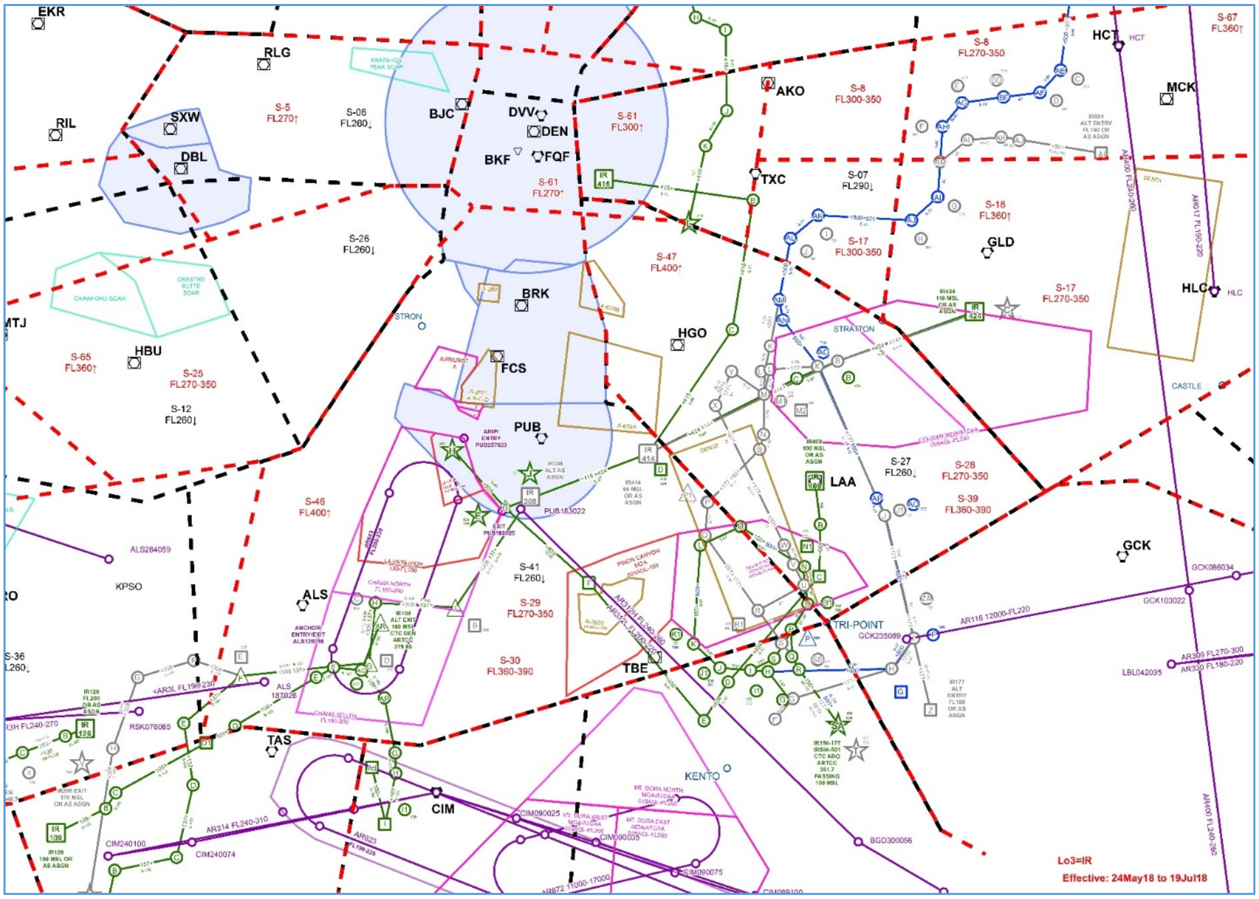


Figure 7. Denver Center SUA (Special Use Airspace) Chart. Created in ArcGIS Desktop (Esri, 2017).

Denver Center has many airways and instrument procedures. Airways are used for aeronautical navigation much like roads are for terrestrial navigation. There is a low altitude and high altitude airway structure split above/below 18,000' MSL. They are also classified by the navigation equipment required for use, whether it be traditional ground-based, or more modern GNSS (Global Navigation Satellite System). These highways in the sky include:

- Victor airways – low altitude ground-based navigational routes (below 18,000' MSL)
- Jet routes – high altitude ground-based navigational routes (at/above 18,000' MSL)
- T-routes - low altitude GNSS (GPS) navigational routes (below 18,000' MSL)
- Q-routes - high altitude GNSS (GPS) navigational routes (at/above 18,000' MSL)

Instrument procedures are used much closer to the ground. They are designed to guide aircraft to and from an airport under instrument meteorological conditions (IMC, or in the clouds). They provide safe and efficient navigation procedures for aircraft on departure, arrival, and on final approach phases of flight. They include:

- Standard Terminal Arrivals (STARS) – arrival procedures prior to approach
- Standard Instrument Departures (SIDS) – departure procedures from major airports
- Instrument Approach Procedures – guides aircraft to runway

Finally, ZDV hosts many different types of aviation reference data. These features are used by pilots and controllers for navigation, safety, surveillance, communication, and situational awareness. Some of these components are charted on aeronautical charts while others are not. This data includes:

- NAVAIDS (Navigational Aids) – ground-based location emitters
- Waypoints and navigational fixes – locations referred to by pilots and controllers
- Communication sites/frequencies – used for pilot-to-controller communications
- Radar sites – provides aircraft location information to controllers
- Minimum IFR Altitudes (MIAs) – lowest safe instrument flight rule altitude in a particular area
- Obstacle data – Towers, buildings, windmills, etc. tall enough to impact aviation

The background and concepts provided in this section are intended to provide an overview of the vast amount of aeronautical information and system interrelationships associated with ZDV-3D.

2.3 Trends

This section provides a brief evolution of controller chart production and reviews current visualization and analysis software tools. It then compares and contrasts current platforms available to the FAA, specifically those used at Denver Air Route Traffic Control Center.

Historically, aeronautical controller charts were generated by hand. At one time, Denver Center employed three full-time cartographers to manually produce aeronautical charts posted above each air traffic controller position. With aeronautical data changing every 56 days, and approximately 100 control room positions, that required a significant amount of manual map making.

Thankfully, the digital transformation of aeronautical chart production has automated these processes significantly. Denver Center has progressed from manual paper chart publication, to a CAD-based system, and now to almost exclusively to GIS. Python computer scripts automate much of the 56-day controller chart production. In fact, Denver Center no longer has a designated cartographer. The job has been replaced by a management program analyst position which devotes approximately 10% of the time to chart production and the other 90% to airspace/procedure analysis and support.

Airspace support and procedural analysis involves studying interrelationships between the vast array of aeronautical features described in Section 2.2. Customized platforms are available for performing various types of analysis, based on particular user needs. Many different modeling tools are used throughout the aviation industry, from simple to complex in capability; servicing flight operations, air traffic control, and our nation's aviation infrastructure as a whole.

The intended output of this project is develop a specific analysis and support tool for Denver Center. Lessons learned from this project also have the potential to benefit other air traffic control centers, expanding into entire National Airspace Structure (NAS).

Current trends for depicting and analyzing aeronautical data are presented next. First, products available to the general public are briefly discussed. Then an extensive look at the major FAA platforms used by analysts at Denver Center is provided.

Skyvector (Skyvector, n.d.), iFlightPlanner Aviation Charts (iFlightPlanner, n.d.), and Google Earth (Google Earth, n.d.) are all popular websites commonly used by aviation enthusiasts to view digital aeronautical charts (see Figures 8-10). Pilots and air traffic support personnel access various layers of aeronautical data including real-time feeds. Of the three, Google Earth is the only one that supports 3D visualization (Ison, 2008). They are all great quick reference tools and excel at their respective design purposes. However, they are characteristically limited in areas of custom graphic representation, analysis, basic printing, and export capabilities. Although Denver Center analysts periodically access these websites for information gathering, other tools are required for more advanced aeronautical studies.

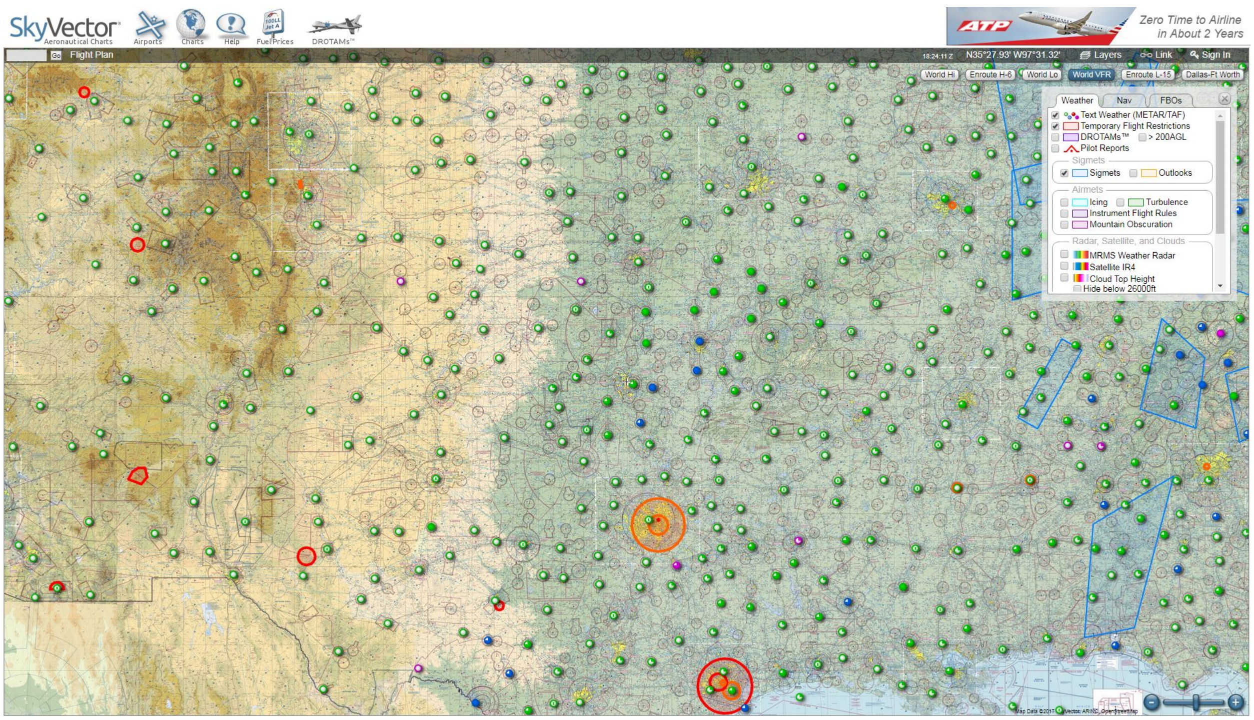


Figure 8. SkyVector with Sectional base map and layering menu (Skyvector, n.d.).

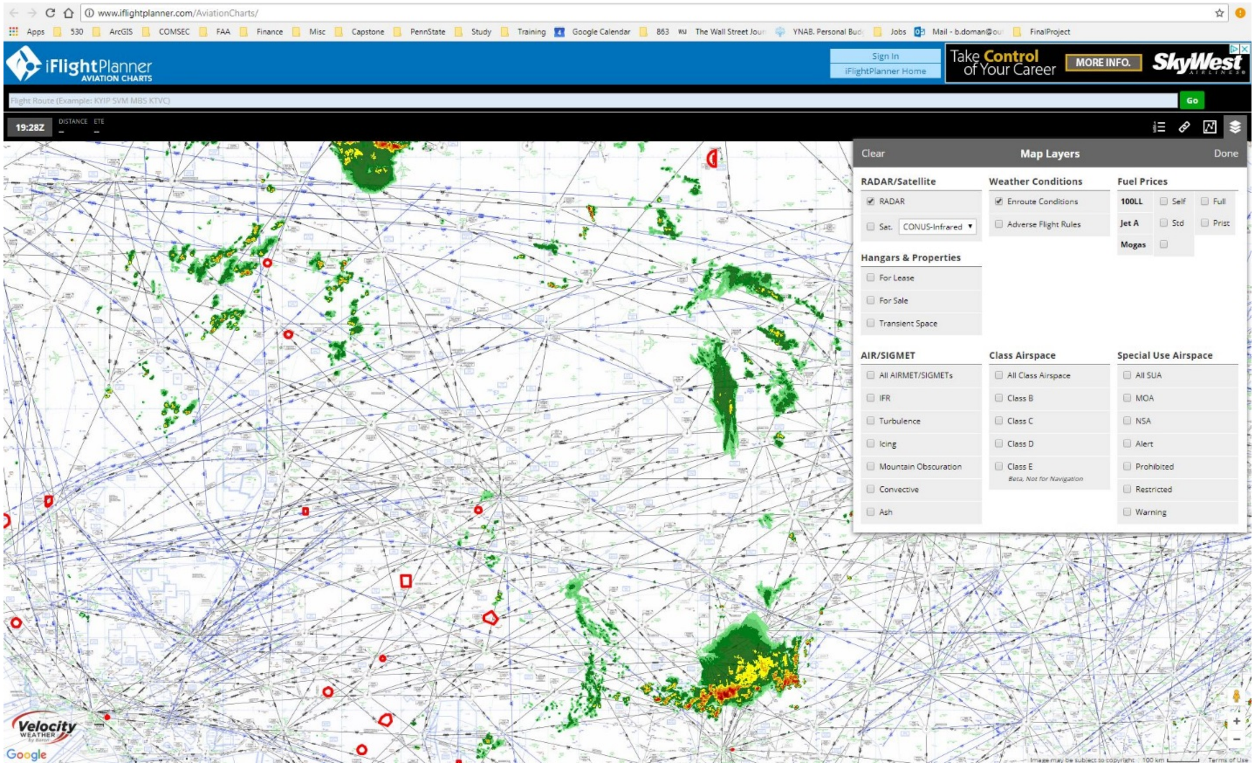


Figure 9. iFlightPlanner Aviation Charts with high altitude airways, live weather feed, and various map layer options (iFlightPlanner, n.d.).

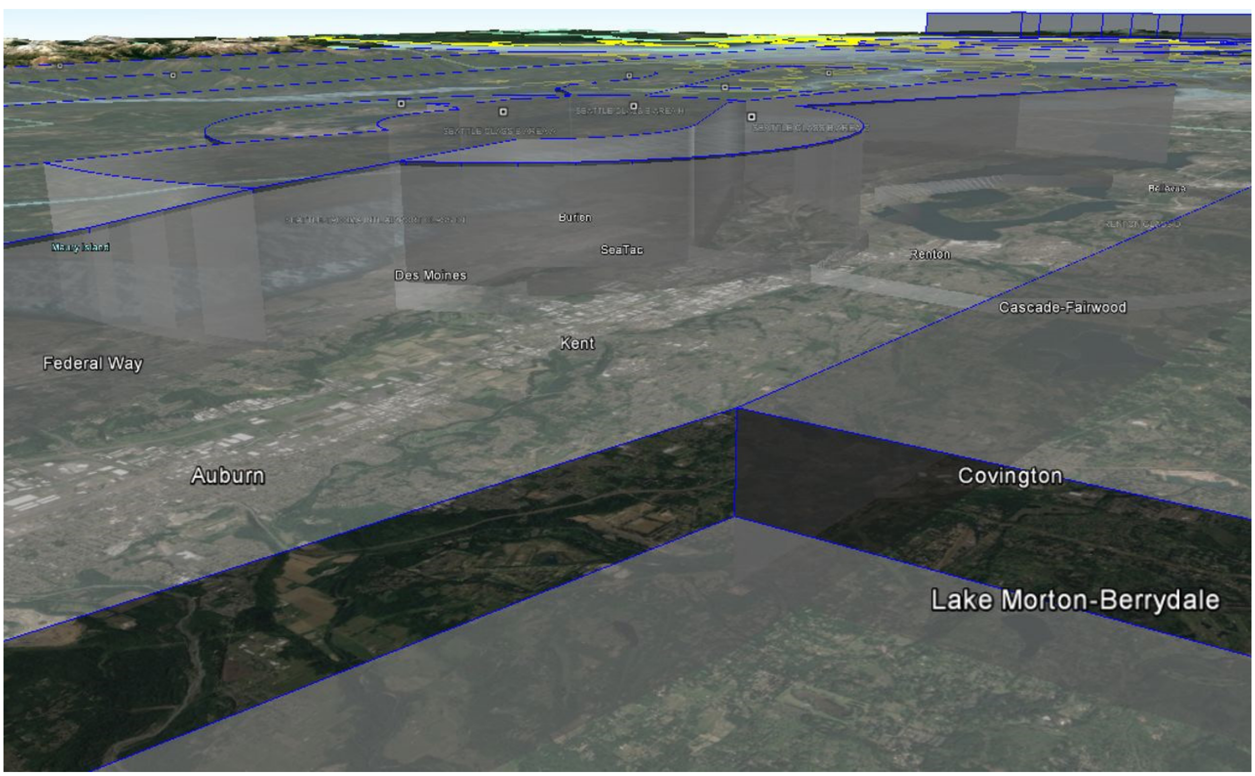


Figure 10. 3D rendering of Seattle Class B airspace in Google Earth (Gentile, 2017).

Bruce Frank, Esri's ArcGIS for Aviation program manager indicates that "GIS is used across all sectors of aviation, but each sector has unique requirements" (Esri, 2013). Denver's Center's unique aviation requirements include the ability to visualize and analyze en route traffic control components in 3D. The FAA provides several products to en route centers to address these needs.

SDAT (Sector Design & Analysis Tool, n.d.), PDARS (Performance Data and Reporting System, n.d.), and TARGETS (Terminal Area Route Generation and Traffic Simulation, 2018b) are three major software programs that Denver Center utilizes for GIS work. A review of each platform is provided, highlighting capabilities and limitations of each product.

SDAT is a web-based, SaaS (software as a service) platform owned by the FAA for calculating Center MIAs (Minimum IFR Altitude) and designing air traffic control sectors (Figure 11). It includes various base maps, aeronautical chart overlays, basic topographical features such as state and county boundaries, and obstacles (FAA, n.d.-b). It provides the capability to depict aeronautical reference data, such as NAVAIDS, fixes, airports, and certain radar locations. It also includes the capability to render sectors in 3D, through an external Cesium viewer.

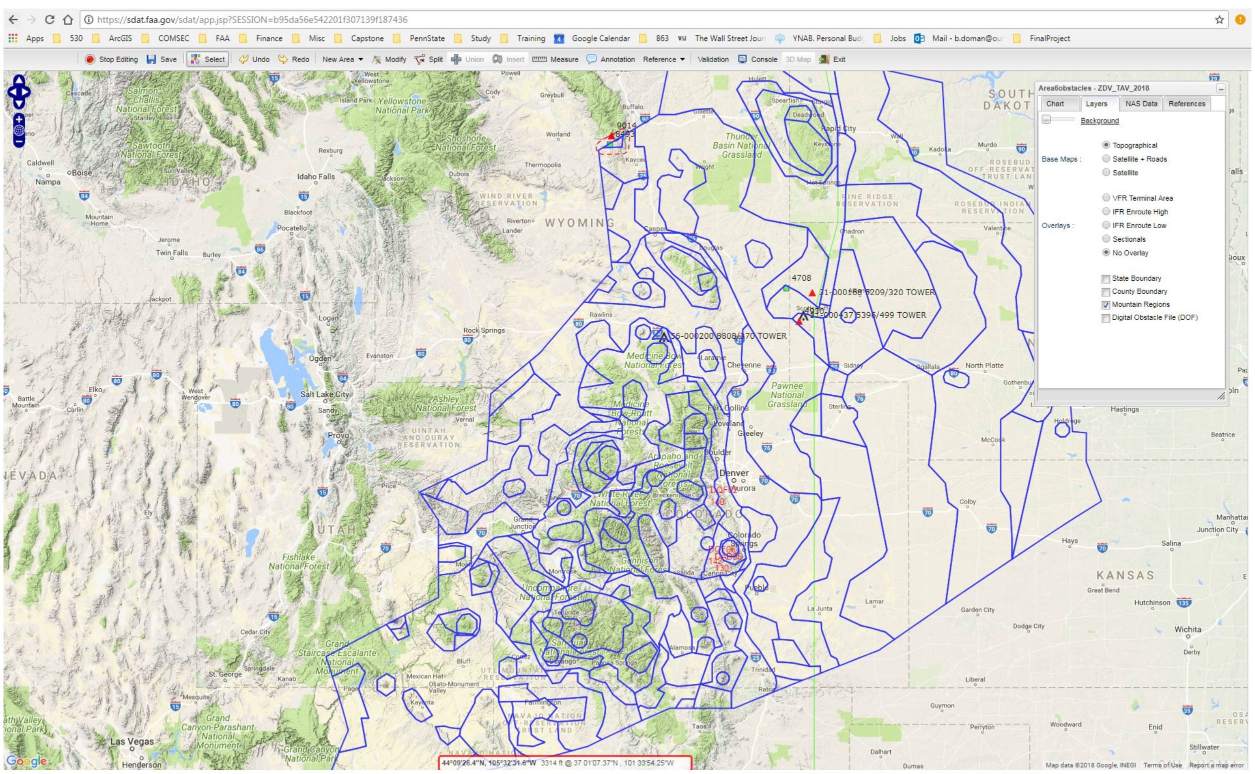


Figure 11. SDAT (2D only) ZDV MIA polygons with layering menu (SDAT, n.d.).

SDAT is a powerful design and analysis tool for creating minimum safe altitude and air traffic control sectors. However, it does not allow external user data to be imported or support direct printout capability. While a Cesium add-on is accessible via a pop-up window for 3D viewing of sectors (Figure 12), SDAT is not a native 3D application. 3D visualization is also limited to ATC sectors only (not MIA sectors).

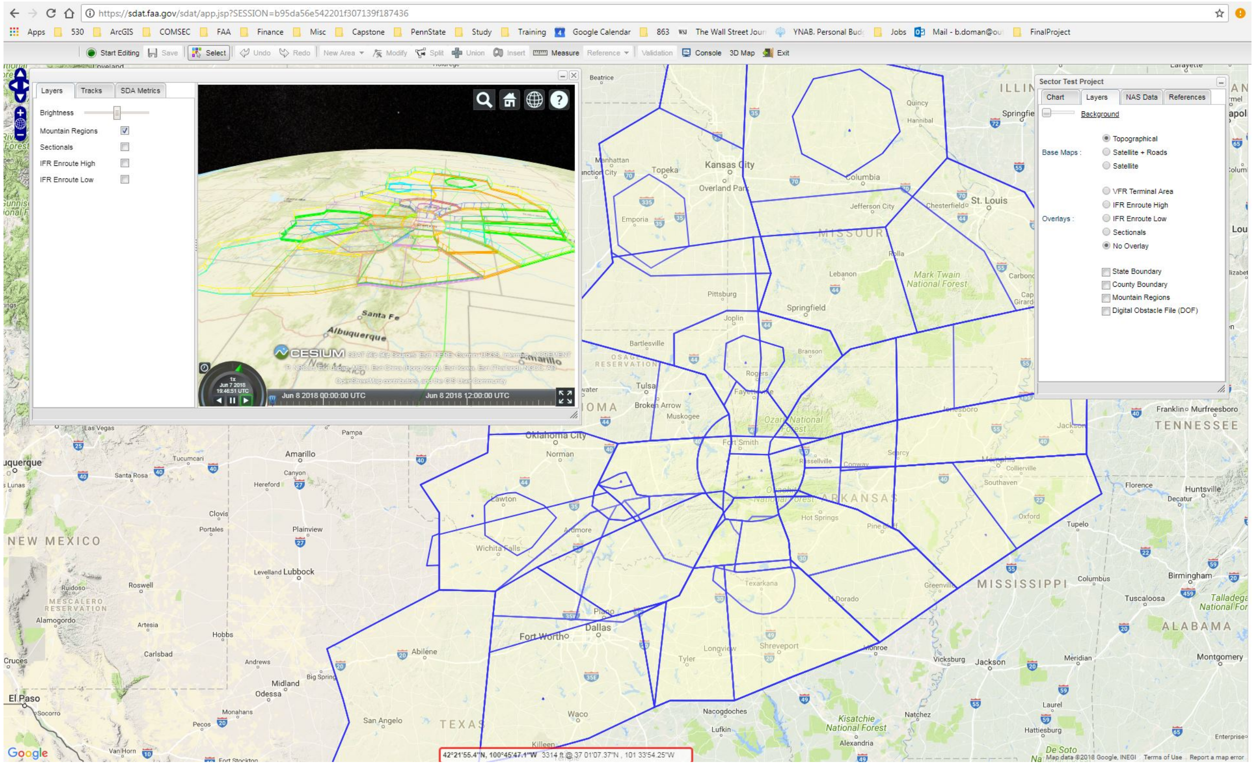


Figure 12. SDAT ZDV ATC sectors (2D) with Cesium pop-up 3D viewer (SDAT, n.d.).

PDARS is an FAA Software program designed primarily for air traffic analysis including basic air traffic control sector and airspace modeling. PDARS also provides traffic replay animation capability. Many different types of aeronautical data are available within the program including weather, airspace, airports and navigation objects (FAA, 2015). The currency of this data is updated every chart cycle by ATAC, the FAA contract service provider.

PDARS operates in a native 3D architecture as depicted in Figure 13. It also features visualization and animation capability including "replays of historical data using 3D and 4D visualization for operational analysis, and flight data filtering" (FAA, 2015).

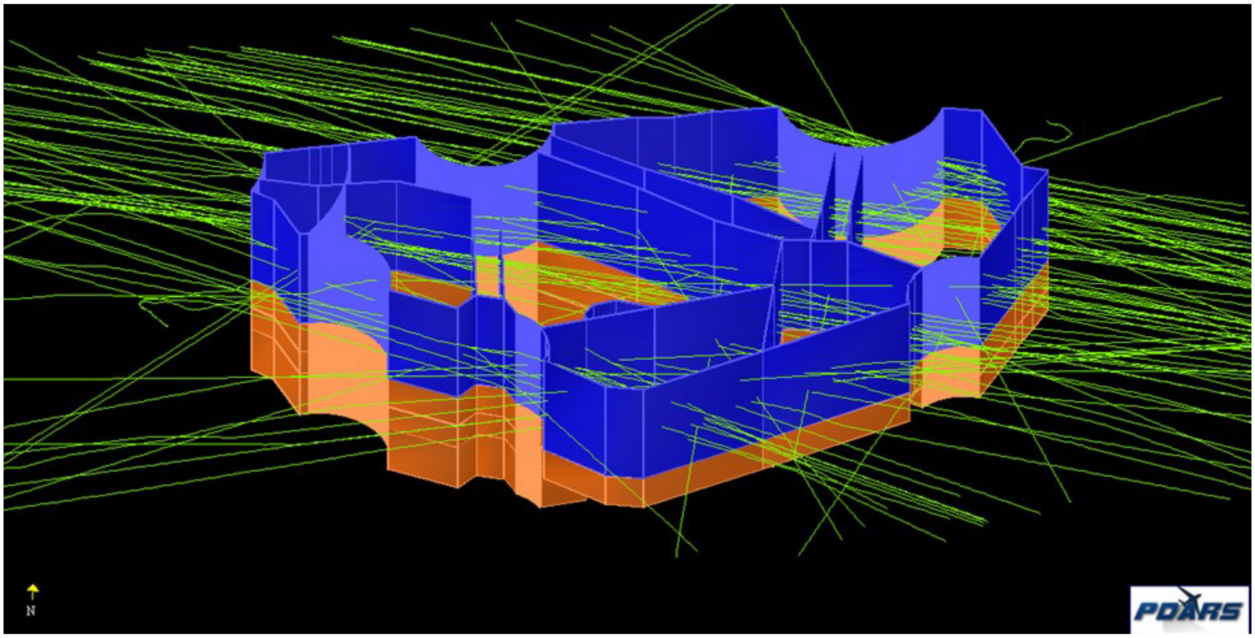


Figure 13. PDARS 3D depiction military airspace complex and impacted flights. Created in PDARS (2012).

PDARS works on a closed network connected to ATAC. While it does provide limited data import/export capability, file format compatibility options are few. Because of the closed system, all file transfers on and off of the PDARS workstation must be accomplished with removable storage media.

Even though PDARS is one of the only FAA products which provides true 3D visualization and analysis capability, the overall graphics rendering quality is dated by today's standards. Options for customizing symbols and labels are also quite limited.

Terminal Area Route Generation Evaluation & Traffic Simulation (TARGETS) is the third major GIS platform used at Denver Center (Figure 14). It is developed by the MITRE Corporation for the FAA. It is primarily designed for instrument procedure development. It also serves as a comprehensive airspace development and aeronautical data viewing tool. It benefits from an intuitive graphical user interface and offers powerful data import/export capability (including Esri shapefiles).

TARGETS serves as an excellent collaboration tool among stakeholders. It allows airlines, the FAA, chart makers, and other agencies a common platform and file format to share aeronautical files. It supports:

- Procedure design
- Flyability assessment
- Airspace/procedure surface generation
- Obstacle assessment
- Noise assessment
- Seamless data exchange

TARGETS also supports various image layer rendering including topography, terrain, and urban areas. It incorporates a vast amount of aeronautical information including:

- NAVAIDS
- Waypoints
- STARS

- SIDS
- SAAAR (Special Aircraft and Aircrew Authorization Required) procedures
- Airways
- Runways
- Airports
- Radars
- Radios
- ILS
- SUA
- Sector boundaries
- Terminal airspace
- Obstructions
- Holding patterns (TARGETS Brochure, 2018c)

TARGETS serves principally as a design tool. It does not provide as many custom symbology or label options as Esri software. However, due to its ease of use, it is often employed as a visualization medium for creating air traffic control graphics and animations. Its main drawback is the strictly-2D rendering engine. However, TARGETS exports can be visualized in 3D by other platforms such as Google Earth.

Figure 14. TARGETS depiction of ZDV (2D only). Created in TARGETS (2018a).

Although SDAT, PDARS, and TARGETS all adequately meet their intended area of specialization, none satisfy all of Denver Center's aeronautical visualization and analysis requirements. Fortunately, there are GIS software options from Esri that can help address these needs.

The FAA has been involved with Esri ArcGIS products for some time. At the Esri FedGIS Conference in 2017, national FAA officials demonstrated various applications of this powerful GIS suite including ArcMap, ArcGIS Pro, and ArcGIS Online (Figure 15). They have used it for aeronautical data management, both 2D and 3D visualization, as well as optimizing chart update procedures. They have implemented it as a collaboration tool with other federal agencies including the USGS for sharing map information. The have geocoded thousands of aeronautical features to streamline GIS integration and locator applications. They developed an open data website, facilitating public aeronautical data access in many formats including kml, shapefiles, and various APIs. Finally, they have incorporated Esri technology to help integrate UAS into the national airspace system, shown in Figure 16 (FAA, 2017).

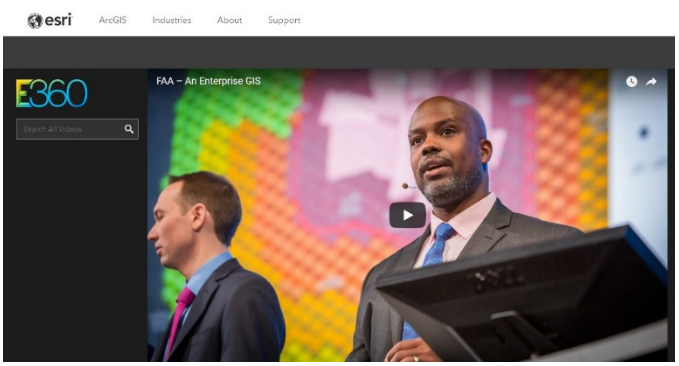


Figure 15. FAA officials presenting application of Esri technology at FedGIS Conference (FAA, 2017).

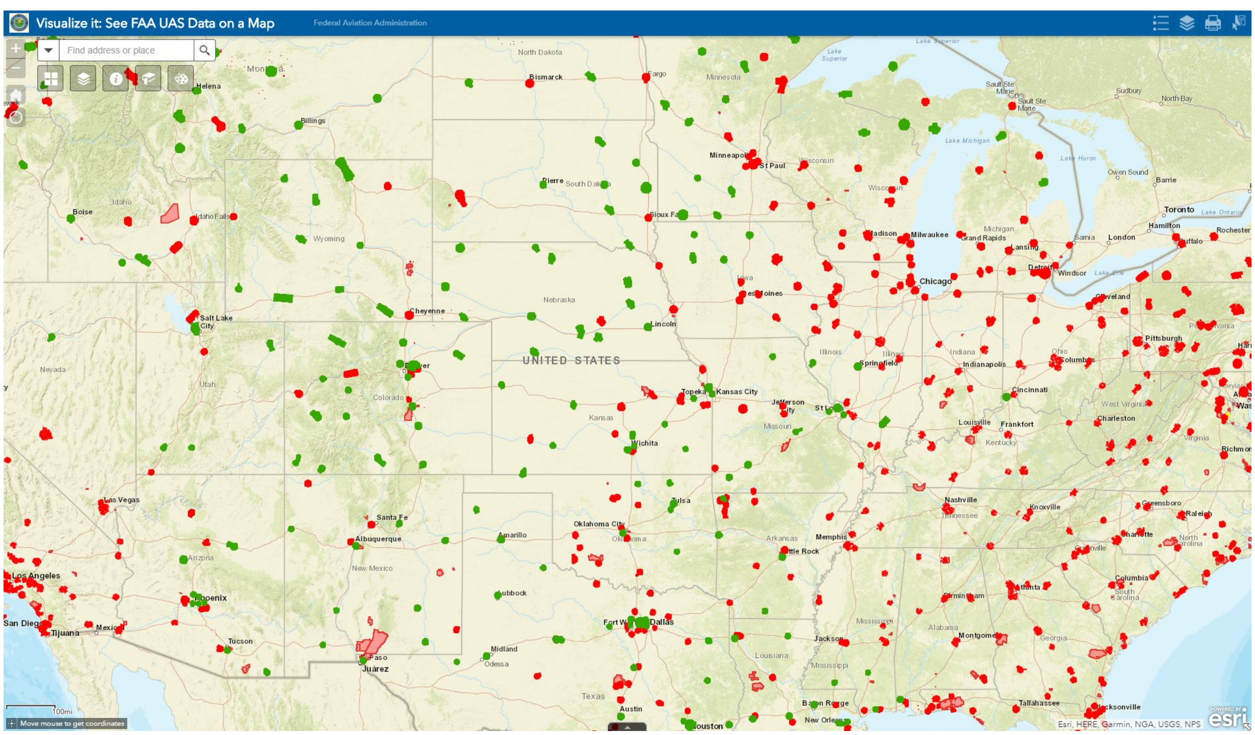


Figure 16. FAA's Esri web application depicting UAS (drones) airspace (FAA, n.d.-a).

Esri products are now available to en route traffic control facilities, such as Denver Center. ArcMap (or ArcGIS Desktop) was first introduced at Denver Center in 2013, as a CAD-replacement platform for producing controller charts. Although specialists from each center were provided with a basic ArcMap orientation course, the complexity of the GIS software was initially overwhelming. Despite the steep learning curve, the apparent universal data integration capability and potential for aeronautical analysis made a compelling case for adopting this software.

The products offered by ESRI include ArcMap, ArcGIS Pro, ArcGIS Online (AGOL), and ArcGIS Earth. One goal of ZDV-3D is to utilize ArcGIS products to improve upon existing tools while facilitating access to more Denver Center personnel, especially through AGOL and ArcGIS Earth.

The public and FAA software tools reviewed earlier are capable at achieving their respective software design goals. However, none meet Denver Center's present need for a modern GIS platform supporting native 3D visualization and analysis.

Figures 17-18 demonstrate scenarios where three-dimensional visualization would allow ATC support personnel to better understand complex airspace and procedural interrelationships. Figure 17 compares a multifaceted military operating airspace with its intricate system of altitude stratums and shelving in 2D versus 3D. Even though extensive altitude labeling is provided in the 2D depiction, the multi-tiered airspace is more easily discerned through the ArcGIS Pro 3D depiction.

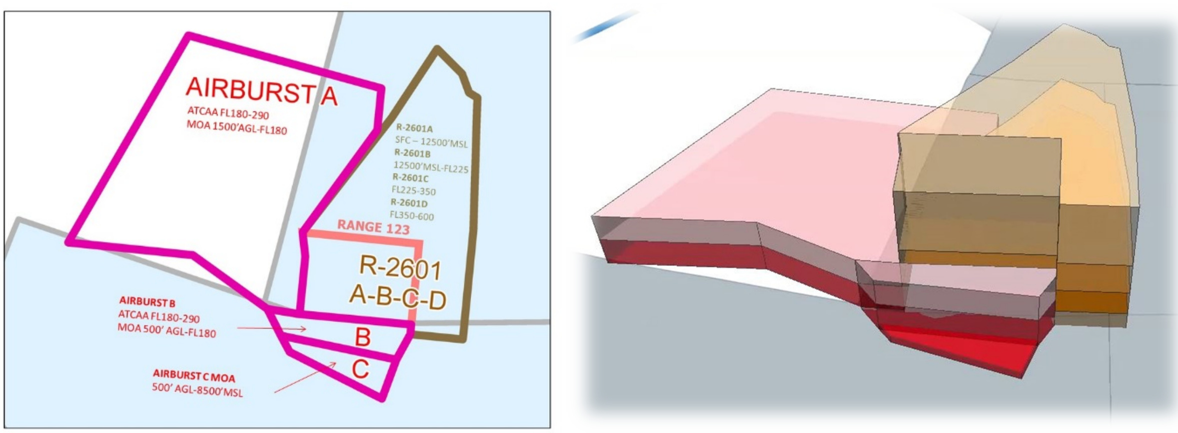


Figure 17. The power of 3D visualization. 2D rendering of military airspace on the left with 3D rendering of the same airspace on the right. Created in ArcGIS Pro (Esri, 2018).

Figure 18 illustrates the relative height of a spaceport trajectory near Denver terminal airports. The ability to visualize this hyperbolic flight profile in 3D allows air traffic analysts to determine conflicts with existing departure, arrival, and overflight traffic. It also serves as a powerful communication tool for conveying commercial spaceport operations' impact on the NAS. Deploying this 3D visualization and analysis tool could inspire aviation stakeholder collaboration, further supporting the successful integration of commercial space flight into our nation's busy airspace.

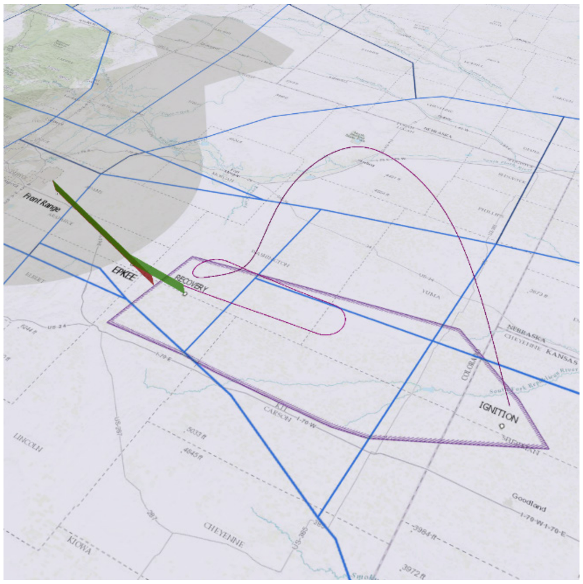


Figure 18. 3D flight profile of a hypothetical spaceport launch and recovery. Created in ArcGIS Pro (Esri, 2018).

2.4 Goals and Objectives

The evaluation of existing software described in Section 2.3 reveals a need for improved airspace and procedures analysis capability at Denver Center. Support personnel do not have access to a modern 3D visualization and analysis tool. The goal of ZDV-3D is to provide a comprehensive and easily accessible 3D representation of ZDV with associated aeronautical features.

A primary limitation of Denver Center's current platforms is inadequate 3D rendering. A secondary limitation is difficulty integrating aeronautical data from multiple sources into one interface. This section outlines ZDV-3D's specific objectives and requirements for overcoming these shortfalls.

This project uses existing FAA-funded software and hardware to remain within facility budgetary constraints. Current licensing to ArcGIS Pro, ArcGIS Online (AGOL), and ArcGIS Earth, allows ZDV-3D to be implemented through these highly-capable platforms. All three of these software titles support 3D rendering and the ability to integrate a host of aeronautical data. ZDV-3D is developed chiefly in ArcGIS Pro and deployed to other users via the AGOL and ArcGIS Earth simplified user interfaces. Constituents who do not have access to Esri software will still benefit from ZDV-3D's electronic and hard-copy outputs (.pdfs, .jpgs, paper charts, diagrams, briefings, reports, studies, etc.).

A primary objective of ZDV-3D is to create a 3D representation of Denver Center with its many components including areas and sectors, approach airspace, adjacent air traffic control sectors, SUAs, MIAs, temporary airspace, airspace proposals, STARS/SIDS, instrument approach procedures, and aviation reference data. Having all of these features incorporated into ZDV-3D enables powerful air traffic control visualization and analysis capability.

Many of these features are described in Section 2.2, Concepts. Explanations are expounded upon here to help identify benefits of rendering this data in 3D. Areas, sectors, and approach airspace make up the geographical structure and substructure of air traffic control. As a controller has jurisdiction over a defined portion of airspace, being able to visualize other aeronautical features in 3D with respect to this airspace is a major objective of this project. This is particularly beneficial when comprehending the impact of ATC airspace change proposals. The ability to visualize adjacent air traffic control sectors, with which controllers may not be as familiar, is also a major benefit. For this reason ZDV-3D models ATC airspace 30 nautical miles into each of its five adjacent centers.

Incorporating all of Denver Center's special use airspace (SUA) is a goal of ZDV-3D. It can be particularly difficult to coordinate procedures or work traffic in complex SUA. Further, military aviation activity associated with SUA occurs at a high tempo. New SUA proposals involving military exercises or even space launches need to be visualized and analyzed prior to implementation. For this reason, controllers and associated support personnel require an authentic three-dimensional representation of ZDV SUA.

Temporary flight restrictions, or TFRs, are implemented throughout Denver Center in real-time. These 3D volumes of airspace are created to keep non-participating aircraft away from hazardous events or law enforcement activities such as firefighting, presidential airlift, or airshows. ZDV-3D intends to provide 3D rendering of TFRs to controllers and support personnel.

MIAs provide the minimum safe altitude for vectoring aircraft over terrain or obstructions. Incorporating these volumes of airspace into ZDV-3D allows Denver Center personnel to analyze relationships between air traffic procedures and the obstacles that are driving these safe altitudes. For example, prototyping a proposed windmill in ZDV-3D can help determine whether the associated MIA sector needs to adjusted to accommodate the new obstacle. It can also be used to determine when flight tracks penetrate a MIA, and if so, the necessary adjustments to prevent further minimum safe altitude incursions. For these reasons, 3D rendering of MIAs is included as an objective for ZDV-3D.

STARs, SIDs, and instrument approach procedures (IAPs) are all integrated into ZDV-3D. Having these instrument procedures referenced in Denver Center's digital twin is necessary to reference arrival and departure procedures for ZDV's airports. Actual flight trajectories can also be imported into ZDV-3D to analyze procedural compliance and areas for optimization.

In order to create a comprehensive 3D representation of Denver Center, a whole host of aeronautical reference data is incorporated into this platform. This includes airports, airways, NAVAIDS, waypoints (fixes), communication sites, radar locations, RSC (radar sort cell) grids, obstacle data, FAA controlled airspace (Classes A-E), and UAS airspace (Part 107 grids near airports). Having each one of these components represented in 3D space provides a high-fidelity replica of Denver Center. This empowers controllers, support personnel, and managers with the ability to comprehend the impacts and interrelationships of all of these aeronautical features.

A secondary objective of ZDV-3D is to integrate many different aeronautical data sources into one location. Three major source categories are incorporated: FAA distributed data, Department of Defense data, and locally generated data. Each of the features identified for inclusion originates from one of these major data sources. The first source is publicly available through the FAA's Aeronautical Data Delivery Service (http://ais-faa.opendata.arcgis.com/). The Department of Defense data is incorporated through a National Geospatial Agency (NGA) DVD subscription. The final data source is generated locally, based on facility directives and resident databases. In addition to these main data providers, supplementary sources are also incorporated into ZDV-3D, including 2D aeronautical basemaps draped over the 3D DEM (digital elevation model). All of these sources are required to provide a comprehensive interactive model of Denver Center.

3. Methodology

3.1 Data and Materials

The data for this project is obtained from three main providers: the FAA, NGA, and locally produced data. Figure 19 depicts each of the data layers implemented in ZDV-3D with its respective source category in parentheses: (FAA) for FAA distributed data, (NGA) for Department of Defense data, whereas no parentheses denotes Denver Center data.

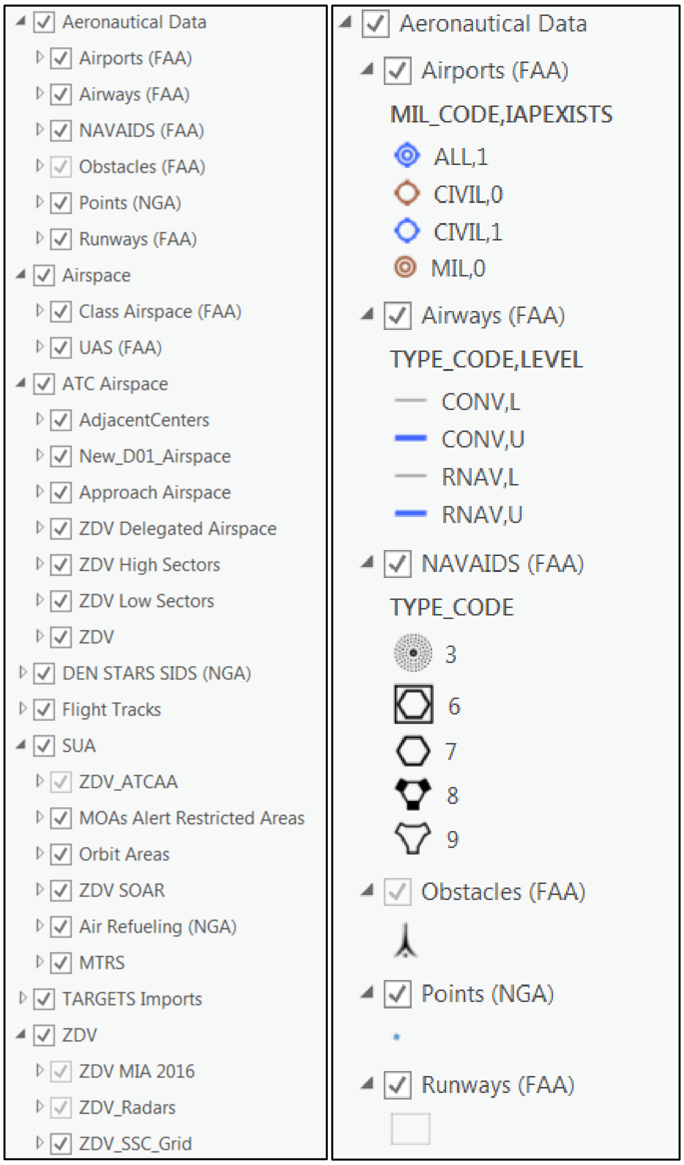


Figure 19. ZDV-3D contents with source data in parentheses. Items in the right column depict expanded Aeronautical Data subsection from the left column with associated symbols. Created in ArcGIS Pro (Esri, 2018).

The FAA data originates from two sources. The first is distributed data from the FAA's Aeronautical Data Delivery Service open data website (Figure 20). This comprehensive source of information includes airports, airways, NAVAIDs, waypoints, controlled airspace, and UAS airspace. "This Aeronautical Data Delivery Service is an FAA-enabled web service that makes data available in CSV, JSON, KML, [and] Shapefile formats…" (FAA, 2016). Much of this data includes 3D attributes used to portray vertical components of aeronautical features such as airspace floors or ceilings. This elevation information is critical for ZDV-3D to function as a 3D renderer. Streamlined access to current aeronautical data is ensured as latest editions, as well as new pending editions, are offered as a geoservice through this public website.

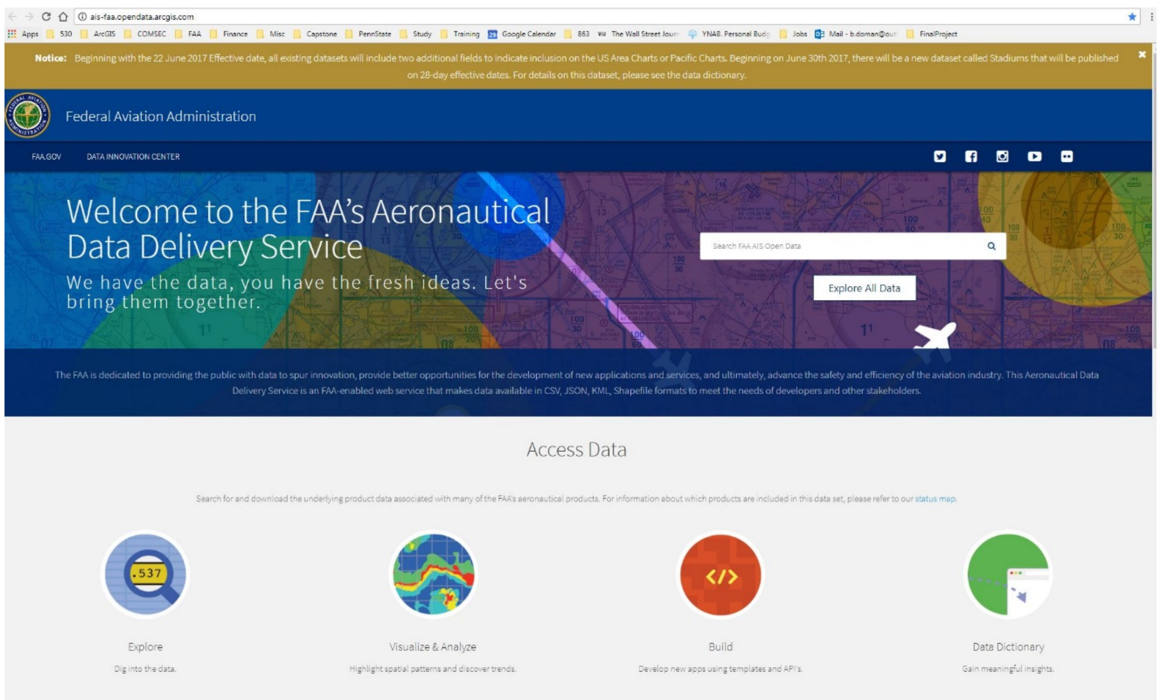


Figure 20. FAA's Aeronautical Data public website (FAA, 2016).

The second FAA data source comes from CMAP, or the Center Mapping Automation Program. These nationally-produced Microstation CAD files are used by air traffic control center cartographers to generate controller charts for their respective facilities (FAA, 2018). This digital data is obtained from an internal FAA website and is converted into a geodatabase for inclusion into ZDV-3D as basemaps or as supplemental reference layers.

The NGA produces Department of Defense (DoD) aeronautical data including aerial refueling tracks, low level training routes, other special use airspace used by the military. It also replicates some FAA aeronautical distributed data including waypoints, airports, and NAVAIDs (NGA, 2018). The latest DoD information is mailed to Denver Center every 28 days on an unclassified DVD. It comes available in shapefile format and serves primarily as military airspace source data for ZDV-3D.

Denver Center is the final major data provider for ZDV-3D. This information includes air traffic control areas and sectors, approach airspace, delegated airspace, reference controller points, MIAs, communication frequencies and locations, radar locations, soaring areas, orbit areas, and other SUA. It originates from local facility documents, LOAs, and ATC computer adaptation files (ERAM).

Supplementary resources are obtained through Web Map Services (WMS) and the ArcGIS Pro Portal including DEM and aeronautical chart layers. ZDV-3D includes Airbus WorldDEM4Ortho global aviation data, incorporated into ArcGIS Pro and AGOL from the ArcGIS Living Atlas of the World (Pratt, 2018). Various FAA aeronautical chart basemaps, including IFR High/Low En route and VFR Sectional Charts are draped over the top of the DEM and are accessed via an FAA WMS (FAA, n.d.-c). These 2D basemaps are accessed via WMS in order to minimize local data storage requirements and ensure the currency of this information.

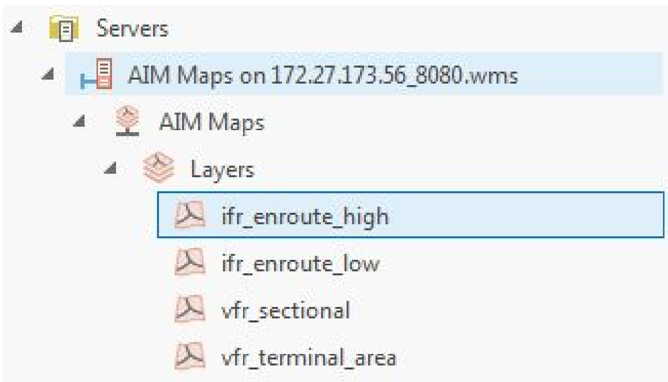


Figure 21. FAA WMS AIM (Aeronautical Information Management) maps used for basemap implementation into ZDV-3D (FAA, n.d.-c).

3.2 Technology

ZDV-3D is accomplished with ArcGIS products including ArcGIS Pro, ArcGIS Online, and ArcGIS Earth. ArcGIS Pro serves as the primary development platform, currently using version 2.2.2 (2018). ZDV-3D outputs are designed for accessibility in ArcGIS Online (2018) and ArcGIS Earth (n.d.).

Each of these Esri platforms plays a role for ZDV-3D, even though there is some functionality overlap. Denver Center only currently has one license to ArcGIS Pro which is the most powerful 3D GIS platform of the three. As most Denver Center employees do not have access to ArcGIS Pro, ArcGIS Online and ArcGIS Earth are deployed as ZDV-3D portals. Center personnel may access ZDV-3D via ArcGIS Online or ArcGIS Earth. ArcGIS Online also provides an intuitive app development platform to further simplify the ZDV-3D user interface (see Figure 34). A performance comparison for achieving ZDV-3D's design objectives through these ArcGIS products is provided in Section 4, Results.

Cloud computing technology is incorporated using Esri's secure cloud integrated into ArcGIS Online. Hosting ZDV-3D on the cloud facilitates access to personnel FAA-wide. As some of this aeronautical data can be sensitive, the account and user group features of AGOL limits access to individuals with a need to know.

3.3 Analysis and Methods

ZDV-3D is developed as a 3D ATC visualization platform with substantial aeronautical analysis potential relative to existing options. An overview of the development process is depicted if Figure 22.

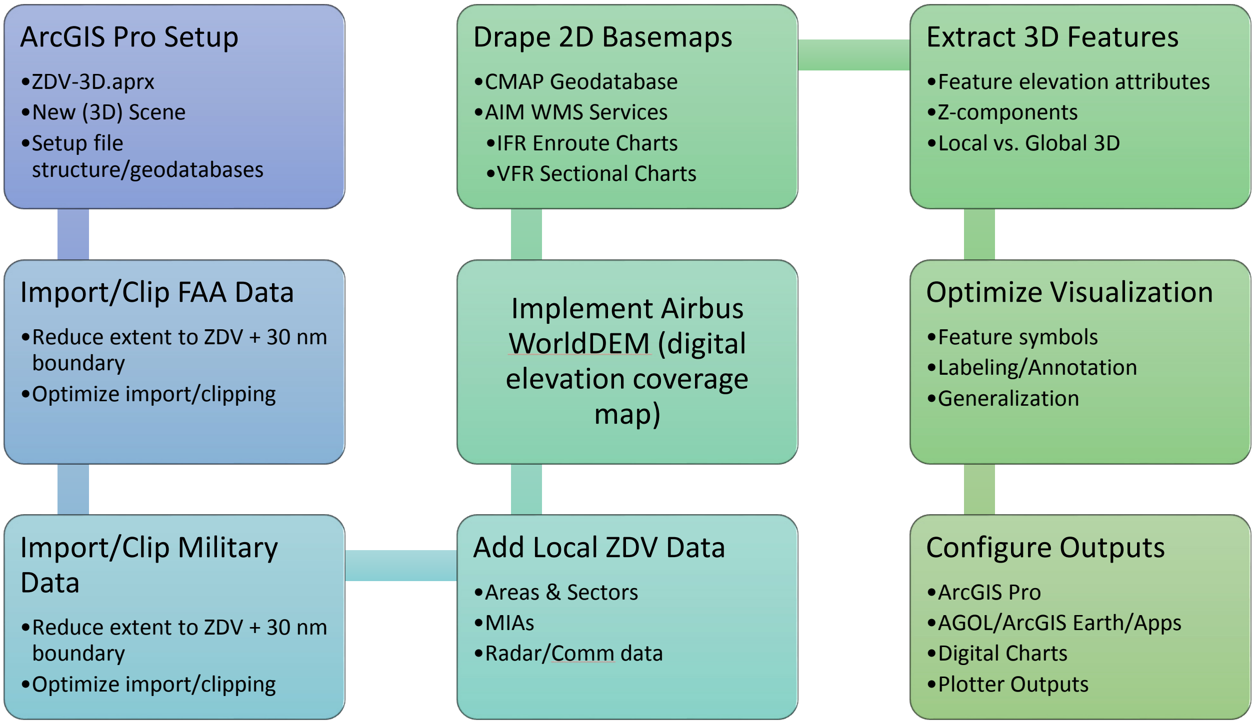


Figure 22. ZDV-3D development overview.

The first block of ZDV-3D's development process is the initial ArcGIS Pro setup and configuration. This involves creating the ZDV-3D.aprx project file and inserting a new (3D) scene. File structure and geodatabase configuration comes next. A main ZDV-3D folder and associated geodatabase (.gdb) is created for ZDV-3D with supporting subfolders and geodatabases (see Figure 23). WMS and additional folder connections are added to ZDV-3D's catalog for quick access to a host of aeronautical data.

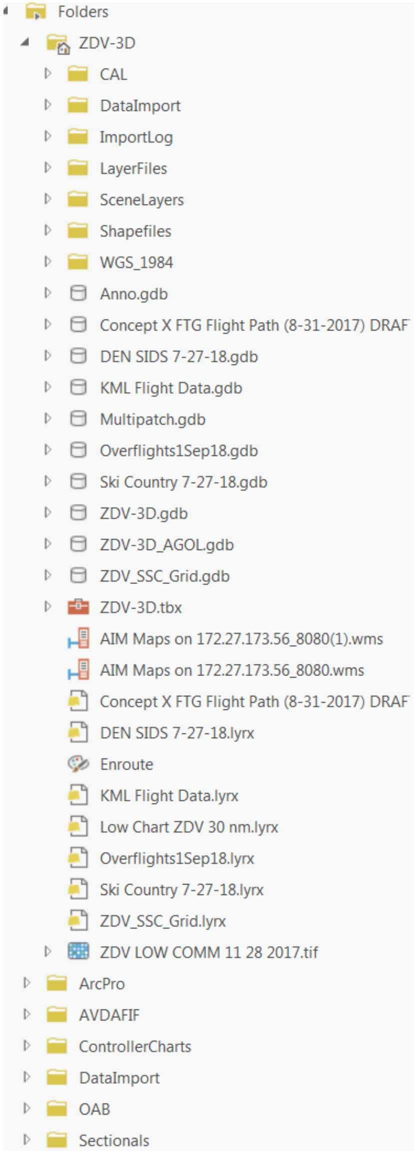


Figure 23. ZDV-3D file and geodatabase configuration. Created in ArcGIS Pro (Esri, 2018).

The next two steps involve importing and clipping FAA and military data to Denver Center's boundary plus 30 nautical miles. Using the ArcGIS Pro Clipping tool to reduce the extent of this data decreases file storage requirements and optimizes 3D GIS performance. ArcGIS Pro tasks are developed to help import this data and clip it to size. Figure 24 illustrates how Tasks not only streamline import and clipping procedures, but also support subsequent data processing and rendering. This is particularly helpful for newcomers to ZDV-3D or for any other air traffic facility wanting to adapt its methods.

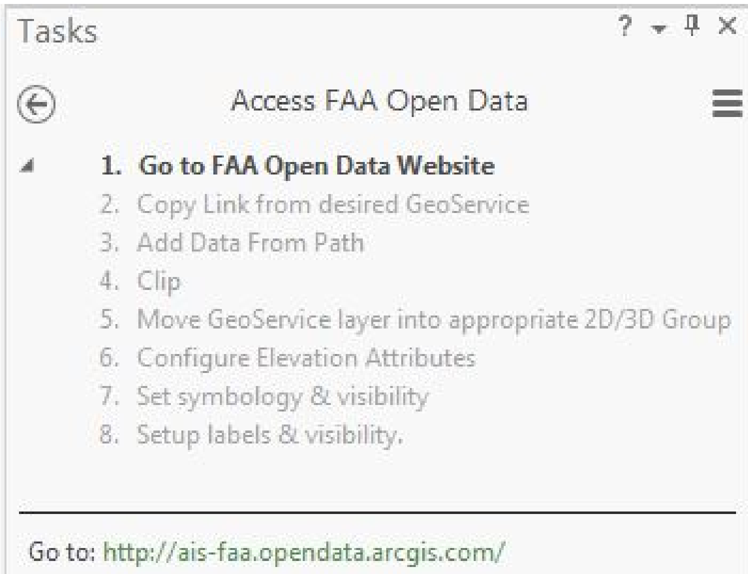


Figure 24. ArcGIS Tasks facilitate import and processing procedures for ZDV-3D data. Created in ArcGIS Pro (Esri, 2018).

Local Denver Center data is added in the next step. This includes air traffic control areas, sectors, MIAs, as well as radar and communication information. For the most part, these items already exist as feature classes or shapefiles in local geodatabases or folders and are brought into ArcGIS Pro initially as 2D features. The majority of these features will be extracted into 3D in a subsequent step.

The fifth major step is to implement a 3D DEM of the terrain underneath Denver Center. As mentioned in Section 3.1, Airbus's WorldDEM is already incorporated into ArcGIS Pro. As "the most consistent and accurate satellite-based elevation model on a global scale" (Pratt, 2018, p. 6), this DEM provides an excellent foundation for building Denver Center three-dimensionally.

2D aeronautical basemaps are draped next over the top of the ArcGIS Pro's DEM. These include CMAP CAD controller chart files. They also include WMS of the FAA's aeronautical information services IFR High/Low and VFR Sectional charts. These basemaps come to life accentuated by ZDV's Rocky Mountains which dominate much of the underlying terrain.

Perhaps the most significant step in this process involves extracting features into 3D. Because none of the aeronautical data used in ZDV-3D includes native Z elevation components, 3D extraction is performed using elevation attributes instead. Attribute tables are scrubbed for elevation data and are used for setting the base and height of each feature. The base is set using the feature elevation menu of the layer properties. The height of the feature is extracted through the Feature Extrusion portion of the Feature Layer Appearance dialogue. Arcade expressions are necessary in some cases to achieve desired elevation rendering results, such as for accommodating differences in elevation datums. One aviation phenomenon is that height is sometimes measure above ground, other times above sea level, and often according to a flight level based on barometric pressure. Figure 25 shows examples of the elevation menus with a corresponding Arcade expression in Figure 26 accounting for these variations.

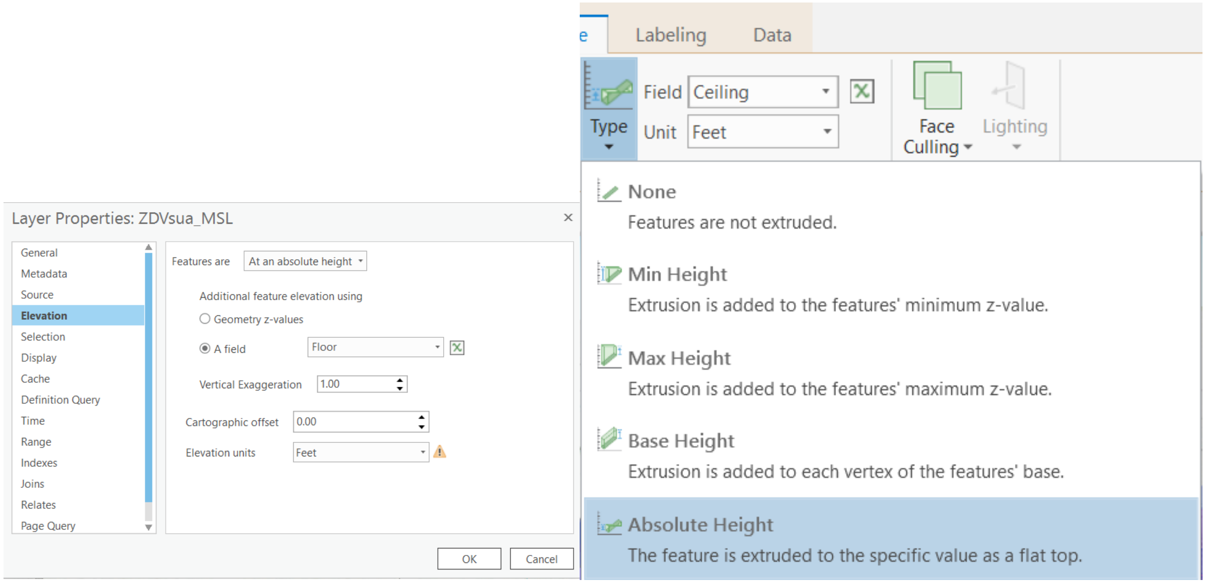


Figure 25. ArcGIS Pro menus for setting up elevation properties and associated 3D extrusions. Images from ArcGIS Pro (Esri, 2018).

```
if ($feature.UPPER_UOM == "FL"){
 return $feature.UPPER_VAL * 100;
}
 else if ($feature.UPPER_CODE == "UNLTD"){
 return 60000;
}
 else {
 return $feature.UPPER_VAL;
}
```

Figure 26. Sample Arcade expression for rendering airspace with different elevation datums in 3D.

This step includes another consideration whether to view the extracted 3D features in ArcGIS Pro's Local or Global view. The Global view is preferred because of Denver Center's large geographic footprint. However, certain smaller extent outputs may warrant switching to the Local view instead.

Optimizing visualization, feature symbols, and labeling is the most rewarding, and perhaps time-consuming step. An iterative process is often required to arrive at the right visual solution for representing a particular aeronautical feature. This involves setting up the rendering properties of each entity including color and layer transparency. Implementing layer transparency is particularly important in order to visualize underlying features in 3D. Configuring labels and annotation is also a substantial portion of this step. As with 3D rendering, Arcade expressions are implemented in order to label features based on varying altitude references (see Figure 26).

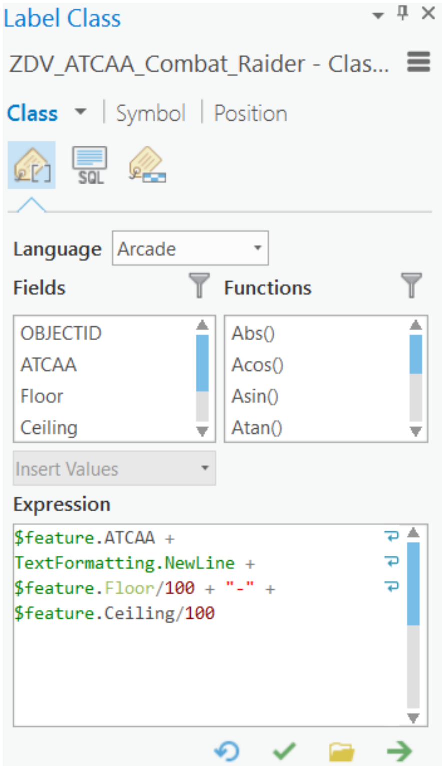


Figure 26. Arcade expression for labeling altitudes based on barometric pressure or flight levels. Image from ArcGIS Pro (Esri, 2018).

The final step in ZDV-3D's development process is configuring outputs. This comprises setting up ArcGIS Online and ArcGIS Earth as simplified user interfaces for accessing ZDV-3D data as well as AGOL apps. It also includes digital and hardcopy output support, primarily from ArcGIS Pro as AGOL and ArcGIS Earth are relatively limited in this area (reference Section 4, Results).

3.4 Challenges

Several challenges were encountered with ZDV-3D, ranging from minor to significant. Minor challenges include avoiding project creep and reducing chart clutter. Major challenges include rendering and labeling 3D features and optimizing map interface performance.

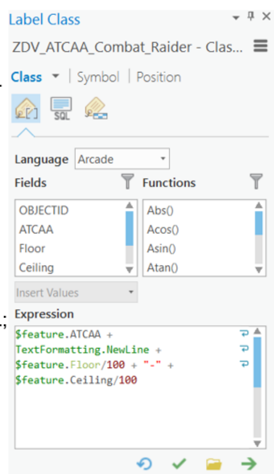
Because of the limitless potential of this visualization and analysis platform, project creep threatened ZDV-3D from the onset. This was mitigated by establishing concise project objectives within a clear scope. Applications beyond the project scope were tabled for further development. Project creep was also kept in check by adhering to an aggressive implementation timeline.

Chart clutter is a challenge for 2D aeronautical charts, particularly in dense terminal air traffic areas. ZDV-3D cluttering was even more pronounced in 3D due to 3D objects' tendency to mask other features. Chart clutter was primarily addressed by adjusting the transparency of 3D features, thus allowing visibility of underlying or masked features. It was also managed by minimizing the number of 3D features being displayed at any given time.

Rendering and labeling aeronautical data in 3D proved be to the most significant challenge. One cause was the lack of innate Z-attribute elevation data associated with the source data. Even though most of the FAA REST services directory features contain the statement “HasZ: true,” the Z values which should have represented altitude were not available. Consequently, the distributed FAA aeronautical data would not display natively in 3D without further manipulation. In order to render and label features in 3D, attribute table fields were used as base elevation values and extruded to an associated top altitude field or calculation.

However, variations in elevation datums introduced additional challenges. Some of the elevations were measured above the surface of the earth, above sea level, or were based on barometric flight levels (truncated altitudes above 18,000 ft. MSL). These variations were accounted for by sorting and extracting features with common elevation references, then rendering and labeling the features using Arcade expressions (see Figure 27).

```
if ($feature.UPPER_UOM ==
    "FL"){
 return $feature.UPPER_VAL
    * 100;
}
 else if
    ($feature.UPPER_CODE
    == "UNLTD"){
 return 60000;
}
 else {
 return $feature.UPPER_VAL;
}
```




```
If ($feature.Ceiling==-9998){
 return $feature.NAME +
    TextFormatting.NewLine +
$feature.Floor + "-18000";
}
else
    if($feature.UPPER_CODE=="ST
    D"){
 return $feature.NAME +
    TextFormatting.NewLine +
$feature.Floor + "-FL"
    +$feature.Ceiling;
}
else{
 return $feature.NAME +
    TextFormatting.NewLine +
$feature.Floor + "-"
    +$feature.Ceiling;
}
```

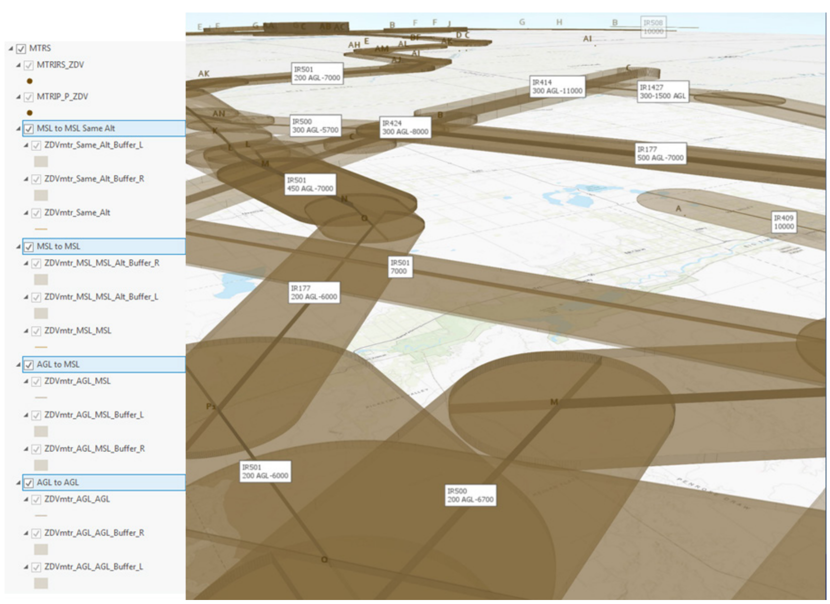


Figure 27. Arcade 3D rendering/labeling expressions and associated rendering examples. Created in ArcGIS Pro (Esri, 2018).

Another challenge is the inability of ArcGIS Online and ArcGIS Earth to extract volumetric 3D items the way ArcGIS Pro does. In fact, the only way to render ZDV-3D's features in 3D is as scene layers. The process for converting an extruded 2D feature from ArcGIS Pro into an AGOL/Earth scene layer is provided in Figure 28. However, scene layer labeling is not supported so this presents the challenge of not being able to label 3D features in AGOL or ArcGIS Earth. A workaround is to import a 2D web map or tiles with annotation for the corresponding scene layer. However, this only works if the overlying 3D features are transparent so that the underlying annotation can be read. Since ArcGIS Earth does not currently support transparency for scene layers, 3D labeling or annotation is not an option.

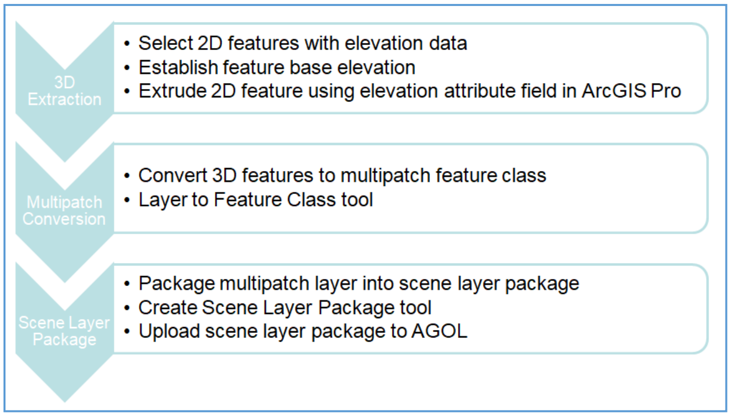


Figure 28. ArcGIS Online 3D rendering process (Esri, 2016).

A final significant challenge was optimizing the performance of ZDV-3D based on the massive geological area and amount of data involved. This was achieved, in many cases, by downloading data to local hard drives in lieu of network or web-based streaming. Additionally, national data was clipped near Denver Center's boundary to reduce the amount of information consumed by ZDV-3D. The cost of keeping data current is the associated multi-step process of downloading, clipping, and otherwise preparing the aeronautical data for inclusion into ZDV-3D every time it changes, usually every 56 days.

4. Results

ZDV-3D matured into a powerful tool for achieving Denver Center's 3D visualization and analysis needs. It is accessible through several Esri platforms to serve both the development and deployment objectives of this project. This section includes ranking of these platforms, output comparisons, recent implementation examples, further development potential, and emphasizes the overall achievement of ZDV-3D.

ZDV-3D is created in ArcGIS Pro to be accessible by the majority of Denver Center users via ArcGIS Online and ArcGIS Earth. As expected, ArcGIS Pro proves to be the premier platform for visualizing and analyzing Denver Center airspace in three dimensions. ArcGIS Online is a better platform for ZDV-3D than ArcGIS Earth in most cases, but not quite as good as Pro. A main reason for ArcGIS Pro's dominance is its superior 3D rendering and labeling capabilities.

ArcGIS Pro provides adjustable transparency control over 3D features which allows many more underlying features to be visible. While ArcGIS Online also provides variable transparency, it exhibits a tendency to indiscriminately mask underlying features. ArcGIS Earth (version 1.6) does not provide any transparency controls for associated scene layers, which significantly limits the number of viewable 3D features (see Figure 29).

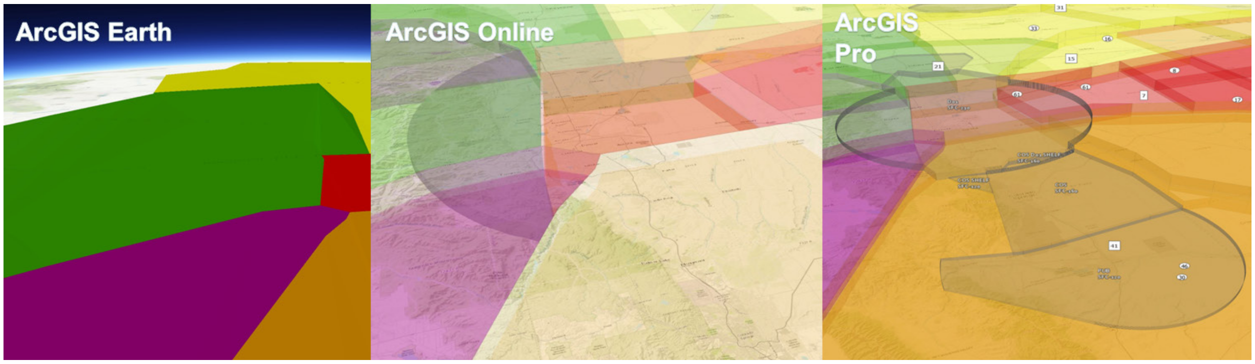


Figure 29. Comparison of Esri 3D outputs. Created in ArcGIS Earth (n.d.), ArcGIS Online (2018), and ArcGIS Pro (Esri, 2018).

3D labeling capability varies greatly between platforms. Because 3D rendering is limited to scene layers in AGOL and ArcGIS Earth, 3D labeling is not supported. ArcGIS Pro is the only platform that fully supports 3D labeling. Workarounds for AGOL and Earth include enabling pop-ups (to actively obtain individual feature attribute information) or adding 2D annotation layers (web tiles).

While the ability to render and label in 3D are major considerations for determining the best platform for accessing ZDV-3D, Figure 30 provides additional ranking factors. These components help determine between the good, better, and best platform for visualizing and analyzing Denver Center in 3D.

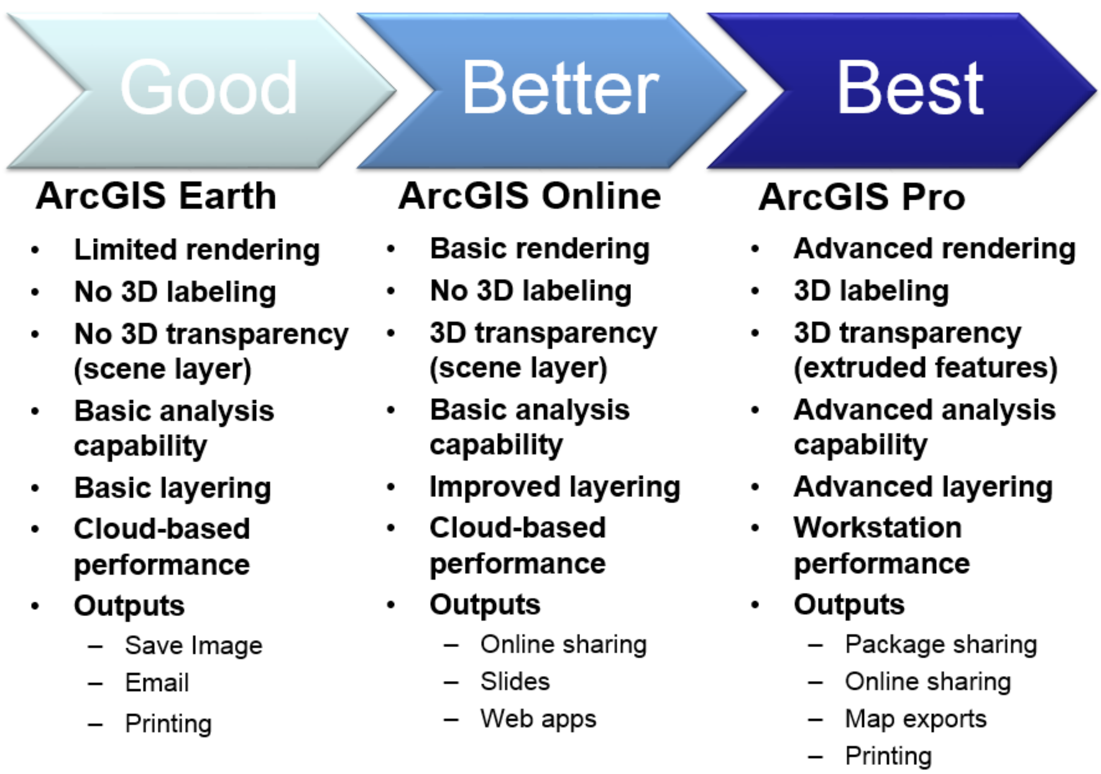


Figure 30. Esri 3D platform rankings based on ZDV-3D development process.

The success of ZDV-3D is determined largely by comparing 2D and 3D renditions of the same aeronautical components. Figure 31 provides several of these comparisons. ZDV-3D is particularly effective at portraying complex airspace with tiered altitude stratums. It is also a great tool for visualizing both lateral and vertical interrelationships between distinct aeronautical features which are in close proximity to each other, such as the windmill proposal and associated MIA sector example referenced earlier.

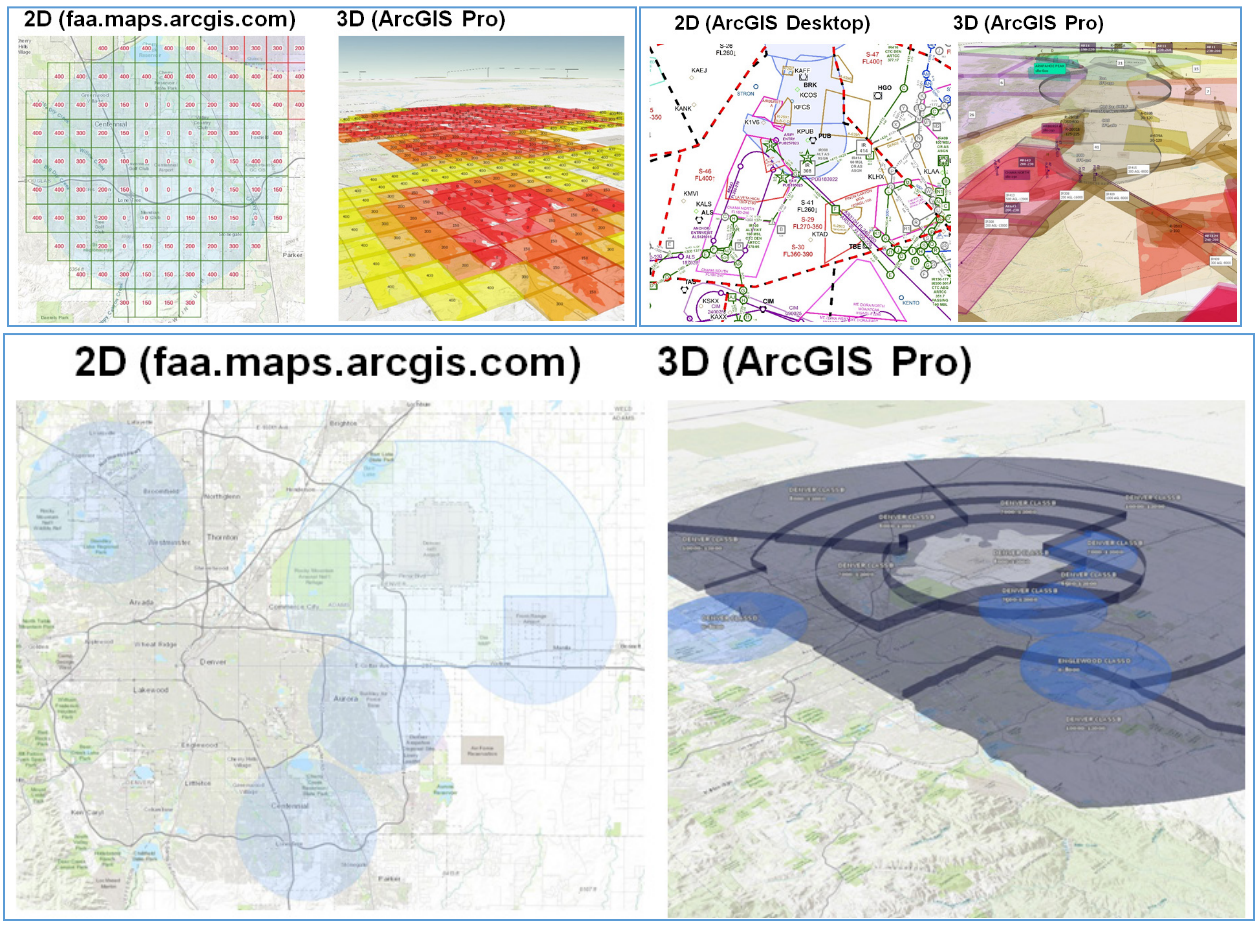


Figure 31. 2D vs 3D output comparisons. UAS airspace (upper left), SUA airspace (upper right), FAA airspace (bottom). Created in ArcGIS Pro (Esri, 2018), Desktop (Esri, 2017).

Even though ZDV-3D has only been operational for several weeks, it has already made an impact. Here are just a few examples of how it has recently provided significant benefit to Denver Center personnel. An operational manager inquired whether a TFR supporting firefighting operations would impact instrument approaches into the airport at Montrose, Colorado. Analysis performed with ZDV-3D indicated that this particular TFR would restrict usage of the ILS to Runway 17, while other approach options would remain clear of the temporary flight restriction and still be usable (see Figure 32). In another instance, a controller providing training to a newer controller asked to use ZDV-3D to help visualize the complexities and interrelationships of Denver Center airspace in 3D. Finally, during a safety risk management panel supporting a large force military exercise, ZDV-3D was used to communicate the overall impact of the proposed airspace expansion from 26,000 up to 51,000 ft. (see Figure 33). These are only a few examples of the many ZDV-3D applications that have been deployed since its inauguration.

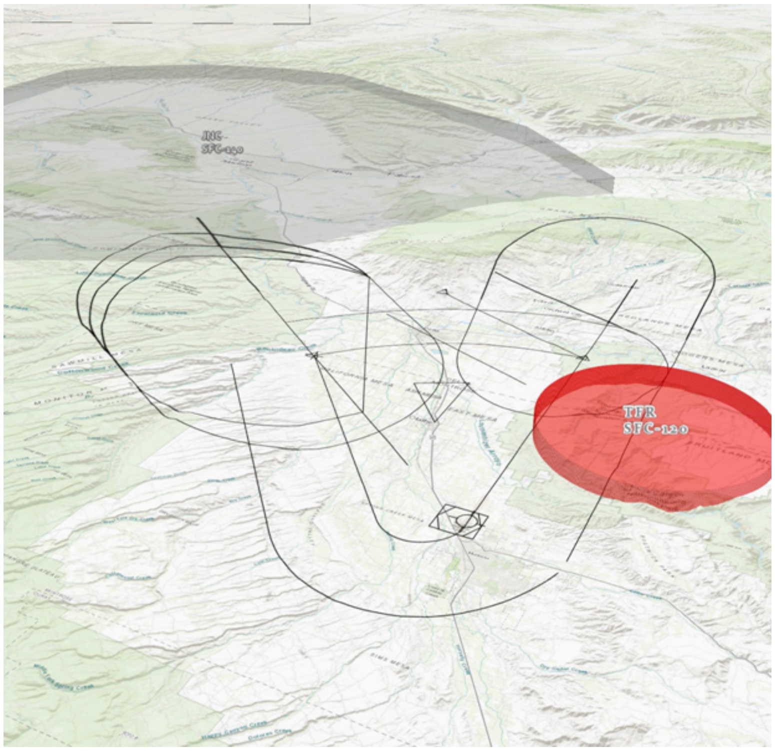


Figure 32. TFR impact on instrument procedure at Montrose, CO. Created in ArcGIS Pro (Esri, 2018).

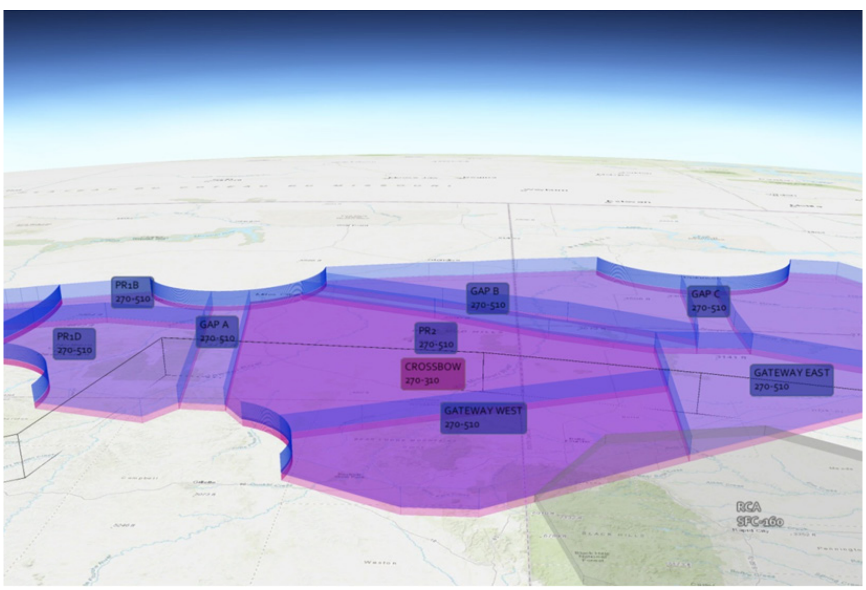


Figure 33. Military airspace expansion proposal visualization in ZDV-3D. Created in ArcGIS Pro (Esri, 2018).

The sky is the limit when it comes to further development potential for ZDV-3D. Some areas for future work include:

- Depicting instrument procedures in 3D for overlapping airspace analysis
- Model NAVAID/Communications/Radar service volumes
- Complement ZDV-3D with 2D Web map and/or app development (and associated suite of widgets)
- Refine ArcGIS Pro Tasks to automate data update routines
- Incorporate live flight traffic feeds
- Formalize cloud sharing with other En Route FAA facilities

ZDV-3D, as deployed today, is successful at achieving its objectives. These objectives include creating a 3D representation of ZDV airspace, incorporating data from various sources, and providing an intuitive GUI for Denver Center personnel to visualize and analyze aeronautical information. It also has strong potential for establishing a best practice capability for other FAA facilities, especially at en route centers.

5. Conclusion

Denver Center needed a modern GIS platform to efficiently manage the numerous aeronautical features, system interrelationships, and complexities involved in this massive volume of en route airspace. ZDV-3D has become this invaluable tool for visualizing and analyzing ATC airspace in 3D.

ZDV-3D pioneers the development of an aviation-based GIS platform that is portable and reproducible at other air traffic control facilities. The ArcGIS Pro Tasks and scripts implemented into this project are efficient mediums for transferring product knowledge and platform sustainment procedures to others. The author intends to expand ZDV-3D into a tool that can be deployed at other centers.

Extending access to FAA support personnel and management officials through intuitive applications, such as ArcGIS Online, will continue to improve the safe and efficient use of airspace for the flying public.

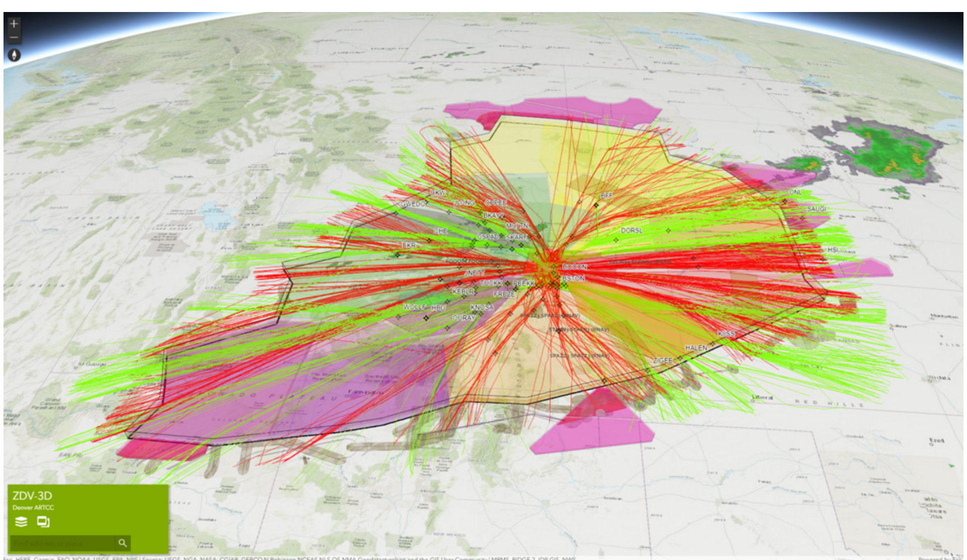


Figure 34. ZDV-3D app. Created in ArcGIS Online (Esri, 2018).

6. Acknowledgments

- FAA, Denver Center, Airspace & Procedures personnel
- Ryan Baxter, Advisor, Penn State University

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