CASE STUDY – AIR TRAFFIC MANAGEMENT SYSTEMS

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Contents

Summary

The National Airspace System (NAS) is a large scale, hybrid, dynamic system, with an Air Traffic Control (ATC) authority which is organized hierarchically. In this chapter, certain subsystems within the current ATC system are presented as case studies for analysis and full or partial automation through hybrid control design. A brief history of ATC is first presented; and its organization and structure are described. Then, some case studies of hybrid modeling and control for prototype automation are presented. In particular, a control theoretic model of sector-based air traffic flow using hybrid automata theory is detailed. This model is Lagrangian, meaning that it models the properties of the system along its trajectories. A subset of this model is used to generate analytic predictions of air traffic congestion. A *dynamic sector capacity* which is used to predict the time it takes to overload a given portion of airspace is described. The design and validation of an air traffic flow simulator, used to assess the accuracy of these predictions, is presented. Some existing automation tools are then described, and

analysis results based on optimization and game theory for hybrid systems are used to derive results in congestion control, routing and sequencing, and collision avoidance.

1. Introduction

The U.S. *National Airspace System* (NAS) is a large scale, nonlinear dynamic system, with a control authority which is organized hierarchically. A single *Air Traffic Control System Command Center* (ATCSCC), in Herndon VA, supervises the overall traffic flow, and this is supported by 22 (20 in the continental US or CONUS) *Air Route Traffic Control Centers* (ARTCCs, or simply, Centers) organized by geographical region and controlling the airspace up to 60,000 feet. Each Center is sub-divided into about 20 sectors, with at least one air traffic controller responsible for each sector. Each sector air traffic controller (ATC) may talk to 20-25 aircraft at a given time (the maximum allowed number of aircraft per sector depends on the sector itself). The controller guides the aircraft through the sector using a set of standard commands (over voice channels). In general, the controller has access to the aircraft's flight plan and may revise the altitude and provide temporary heading assignments, amend the route, speed, or profile, in order to attempt to optimize the flow and to keep aircraft *separated*.

The history of U.S. ATC dates back to the 1920's, when congestion and safety issues made an organization of aircraft flow necessary. Since then, the major updates to ATC have been in the addition of new technologies and an overall structure incorporating each geographical region. Throughout its history, it has been critical to maintain ATC as a human-controlled system with exacting levels of safety. Recently, the system is experiencing a new phenomenon: airspace saturation – there are too many aircraft for the NAS and ATC to handle without forcing backups and resulting delays. In addition, new safety challenges have arisen in the past year and a half. One major question that has received much recent research attention is: can the problems of airspace saturation be alleviated by automation or partial automation of some of ATC functionality, while still maintaining, or improving, the levels of safety in the system.

One of the most important, and time consuming, controller tasks is to prevent *losses of separation* (LOS), between aircraft; for high altitude sectors (above 29,000 ft), this means that the controller must keep each pair of aircraft in the sector separated by more than 5 nautical miles horizontally, and 2000 feet vertically. The terminology *protected zone* is used to represent the 5 nautical miles radius, 2000 foot height cylinder around an aircraft that another aircraft must not penetrate. For any pair of aircraft, their relative configuration or *state* (relative position and orientation), is referred to as *unsafe* if there is a *rational* process of actions which leads one aircraft to penetrate the protected zone of another.

This chapter presents some recent research results which could lead to partial automation of ATC functionality. Portions of the NAS and ATC are modeled as a hybrid dynamical system, and analysis results based on optimization and game theory for hybrid systems are used to derive results in congestion control, routing and sequencing, and collision avoidance. For some of these results, the models and methods pertain to the hybrid system verification methodology presented in this volume. First, a brief history of ATC is presented, and its organization is overviewed. The chapter then presents a mathematical model for a controlled sector, based on a hybrid system model for each aircraft which encodes simple aircraft dynamics under the discrete action of the controller. It is observed that the set of commands used by controllers, while large, is finite, and consists of simple actions such as: “turn to heading of x degrees”, “hold current heading”, “fly direct to jetway y”, “increase speed to z knots”. The model is then analyzed and the concept of sector dynamic capacity is defined, combined with analysis to predict the time it takes to overload given sectors of airspace, and thus predict delays, assuming controllers use a subset of their available control actions. These results are validated using a simulator of the system, which is implemented in c++ interfaced with Matlab, and uses data from the *Enhanced Traffic Management System* (ETMS), which is a set of time stamped data for all aircraft in the NAS, at intervals of a few minutes between time stamps.

The data presented in this chapter pertains to several sectors within the Oakland ARTCC, located in Fremont, CA.

2. A Short History of Air Traffic Control

Air Traffic Control in the United States began in the late 1920s, pioneered by airport employees using red and green flags, and lights to signal their instructions to pilots. The Air Commerce Act of May 20, 1926, was the first step of the Federal government towards regulation of civil aviation. This legislation was pushed by the leaders of the aviation industry, who were convinced that the airplane could not reach its full commercial potential without Federal action to define, improve and maintain safety standards. The Air Commerce Act defined several tasks, including issuing and enforcing air traffic rules, licensing pilots, certifying aircraft, establishing airways, and operating and maintaining aids to air navigation. The first city to have a radio-equipped control tower was Cleveland (1930). The first three centers for ATC were established by an airline consortium, encouraged by the Federal government, between 1935 and 1936. Maps, blackboards, and mental calculations were the first tools used by early Air Traffic Controllers to ensure the safe separation of aircraft traveling between cities along designated routes.

In 1938, the Civil Aeronautics Act transferred the Federal civil aviation responsibilities from the Department of Commerce to a new independent agency, the Civil Aeronautics Authority. The legislation also expanded the government’s role by giving the Authority the power to regulate airline fares and to determine the routes that airlines would serve. The Authority was split in 1940, giving birth to the Civil Aeronautics Administration (CAA) and the Civil Aeronautics Board (CAB) placed under the Department of Commerce. The CAA was responsible for ATC, airman and aircraft certification, safety enforcement, and airway development. The CAB’s task was safety rulemaking, accident investigation, and economic regulation of the airlines.

The increasing airspace congestion triggered by the growing traffic in the 1940s, the introduction of jet airliners and a series of midair collisions motivated passage of the Federal Aviation Act of 1958, which generated a new agency: Federal Aviation Agency. Even though a special committee had already recommended the use of radar in 1947, it was not until the late 1950s that a civilian radar system was installed by the CAA. The

Federal Aviation Agency was given sole responsibility to develop and maintain a common civil-military system of air navigation and ATC. The Act also transferred safety rulemaking from the CAB to the Federal Aviation Agency. On April 1, 1967, the Federal Aviation Agency became one of several organizations within the Department of Transportation (DOT) and became the Federal Aviation Administration (FAA).

In the mid-1970s, the FAA achieved a semi-automated ATC system based on a combination of radar and computer technology. By automating certain functionalities of ATC, the system allowed controllers to concentrate more efficiently on the vital task of aircraft separation, which is still not automated today. The controller graphical display encompassed technology able to visualize numerous aspects information about aircraft (identity, altitude, and ground speed of aircraft carrying radar beacons), while controlling the airspace. Despite its effectiveness, this system was not able to keep up with the growth of traffic and increasing congestion. The NAS Plan, created in January 1982 by FAA aimed at finding solutions to the congestion problem, defined more advanced systems for En Route and Terminal ATC, modernized flight service stations, and improved in ground-to-air surveillance and communication. Several other levels of automation were introduced until the events of September 11, 2001. Shortly after, Congress created the Transportation Security Administration (TSA), whose principal responsibility is civil aviation security.

Despite the negative impact of September 11 and the concurrent economic recession, which made passenger demand fall initially by more than 20%, airspace congestion continues to be a problem. Recent studies have shown that the overall impact of September 11 on air traffic congestion was just a two year delay in previous estimates. In 40 years, the delays have increased by 50% in the United States. From 1995 to 1999, the average delay grew from 42 minutes to 50 minutes. Flight cancellations increased by 68% between 1995 and 1999. Annual traffic growth is still 2.3% and airlines have increased their flight times on 80% of all busy routes, up to 27 minutes. Such a list of alarming numbers could be extended almost endlessly. It vehemently speaks for automation and optimization of the current ATC system, in order to satisfy the ever-increasing amount of traffic.

3. Organization of Air Traffic Control

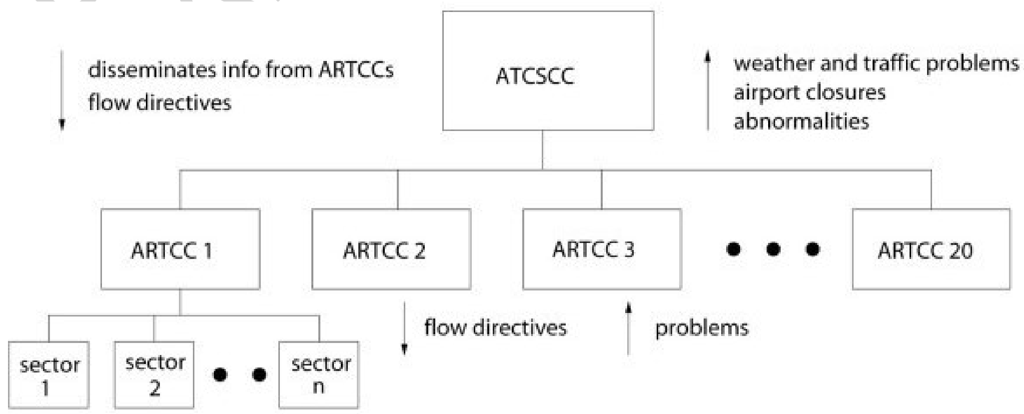

Figure 1: Control hierarchy in the current structure of NAS.

This section explains how the airspace is currently divided geographically, and how it is organized hierarchically. Then, the onboard and ground navigation infrastructure is briefly presented. Finally, the communications between all agents in the network is presented. The information enclosed in this section pertains for the US airspace. We mention the European airspace at the end and highlight some specificities of this airspace.

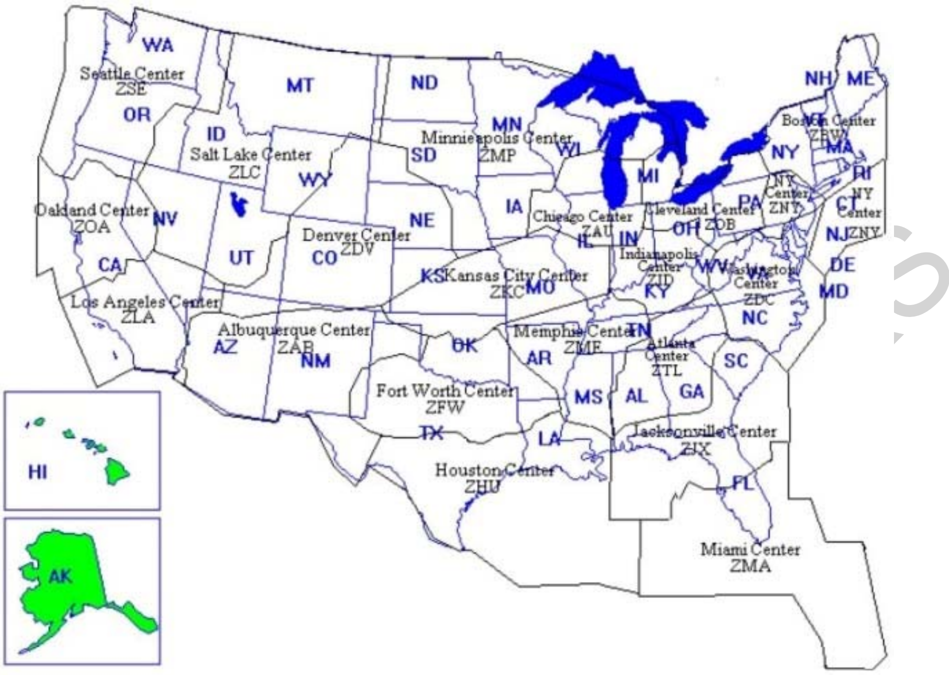

Figure 2: Map of the 22 ARTCCs in the U.S. (Map courtesy of www.seaartcc.org)

3.1. Airspace Structure

The airspace is divided in different *classes*, which correspond to regions under different regulations and use. An exhaustive classification of airspace is available (see bibliography) and is only briefly summarized here.

Class A airspace exists from 18,000 to 60,000 feet. All operations in this airspace must be under *instrument flight rules* (IFR) (pilots must be rated to fly according to the rules governing the procedures for conducting instrument flight) and are subject to air traffic control clearances and instructions. *Class B airspace* surrounds "busy" airports in the US. Each Class B area is individually tailored and consists of a surface area and two or more surrounding layers (see Figure 3) (most Class B airspace would look like an inverted wedding cake if viewed in profile). Again, pilots must receive an ATC clearance to enter class B airspace. *Class C airspace* generally surrounds "smaller" airports with an operating control tower, a radar approach control facility, and a certain number of IFR operations. The area encompassed by this airspace is delimited by two circles with the inner circle extending 5 nautical miles from the airport starting at the surface and extending up to 4000 feet above airport elevation. The outer circle extends to 10 nautical miles from the airport and consists of a shelf from 1200 feet to 4000 feet above airport elevation. The rest of civilian airspace is divided in further categories

(*Classes D*, *E*, *G*), not relevant for the description in this chapter. Airspace also includes *special use airspace*, which encompasses prohibited areas, restricted areas, warning areas and military operations area, which will not be detailed here.

The *National Airspace System* (NAS) is a large scale, layered, hybrid dynamic system: its control authority is currently organized hierarchically with a single *Air Traffic Control System Command Center* (ATCSCC), in Herndon VA, supervising the overall traffic flow. This is supported by 22 (20 in the continental US or CONUS) *Air Route Traffic Control Centers* (ARTCCs, or simply, Centers) organized by geographical region up to 60,000 feet. Each Center is sub-divided into about 20 sectors, with at least one air traffic controller responsible for each sector. Each sector controller may talk to 25-30 aircraft at a given time (the maximum allowed number of aircraft per sector depends on the sector itself). The controller is in charge of preventing *losses of separation* between aircraft, keeping them separated by more than 5 nautical miles horizontally, and 2000 feet vertically. In general, the controller has access to the aircraft's flight plan and may revise the altitude and provide temporary heading assignments, amend the route, speed, or profile, in order to attempt to optimize the flow and to keep aircraft separated, as well as to provide weather reports and winds. An illustration of the current control structure is presented in Figure 1.

There are about 17,000 controllers in the NAS infrastructure, each controlling a zone with rough diameter from 20 to 200 miles. There are about 19,000 landing facilities, with about 400 of these major airports with ATC towers. The acceptance rate of each airport is usually 1 aircraft/minute per runway in normal operations (if the runway is used for both take off and landing); this capacity is doubled if the runway is used for landing only.

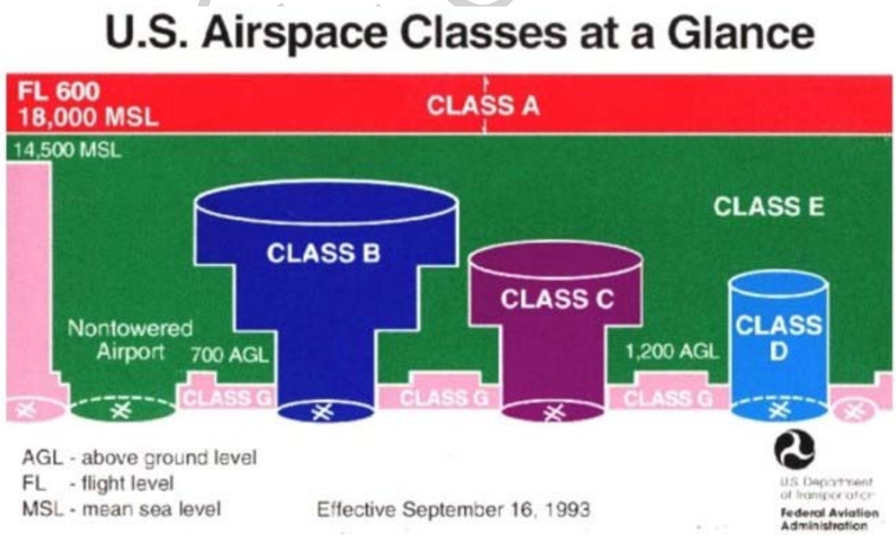

Figure 3: Airspace Classes (Courtesy of U.S. Department of Transportation)

Within the Center airspace, the low traffic density region away from airports is known as the *en route airspace* and is under jurisdiction of the ARTCC. The high traffic density regions around urban airports are delegated to *Terminal Radar Approach Control* (TRACON) facilities. The TRACONs generally control this airspace up to

15,000 feet. There are more than 150 TRACONS in the United States: one may serve several airports. For example, the San Francisco Bay Area TRACON includes the San Francisco, Oakland, and San Jose airports along with smaller airfields at Moffett Field, San Carlos, and Fremont. The regions of airspace directly around an airport as well as the runway and ground operations at the airport are controlled by the familiar *Air Traffic Control Towers*.

3.2. Navigation and Surveillance

Surveillance is performed by ATC through the use of radar: a primary radar system which processes reflected signals from the aircraft skin, and a secondary radar system, which triggers a transmitter in the aircraft to automatically emit an identification signal. The range of the radars depends on the type of airspace being served: in the En Route airspace the long-range *Air Route Surveillance Radar* (ARSR) is used, while in the TRACON the shorter range *Automated Radar Terminal System* (ARTS) is used. The accuracy of the radars, and their slow (12 second) update rates (6 seconds in TRACON, 12 seconds in En Route airspace), contribute to the FAA standards for aircraft separation, which are 5 nautical miles horizontal separation, 1000 feet (2000 feet above 29,000 feet) vertical separation in the Center airspace, and 3 nautical miles horizontal separation, 1000 feet vertical separation in the TRACON. Each ATC facility is equipped with a computer system which takes the radar signals as input and provides a very limited amount of flight data processing, including a rudimentary conflict alert function. This information is displayed to controllers in two-dimensions on the black and green *plan view displays* (PVDs). Controllers issue directives to pilots using two-way voice (radio) channels.

ATC currently directs air traffic along predefined *victor airways* (low altitude <18,000 feet) and jetways (high altitude), which are "freeways in the sky", or straight line segments connecting a system of *beacons* (*non-directional beacons* (NDBs), *very high frequency omni-range receivers* (VORs), and *distance measuring equipment* (DME)). These beacons are used by pilots (and autopilots) as navigational aids, to update and correct the current position information provided by the *inertial navigation systems* (INS) on board each aircraft.

New systems for navigation and surveillance are currently in the process of certification for use in the NAS.

The *Global Positioning System* (GPS) and its *Wide Area* and *Local Area Augmentation Systems* (WAAS and LAAS) provide 3D position information worldwide using signal information from a constellation of 24 satellites. A single GPS receiver can determine its position to an accuracy of a few meters, using signals from at least 4 out of these 24 satellites; if this information is augmented with differential corrections from another receiver (*differential GPS* or DGPS), this accuracy can be increased to a few centimeters. Many factors make the use of GPS in the cockpit a desirable alternative to the current ATM navigation methods: the accuracy is uniform from aircraft to aircraft whereas with the currently used INS, the accuracy decreases in time due to sensor drift rates; each GPS receiver acts like an atomic-accurate clock, thus making it possible for many aircraft to coordinate among each other over a communication link; a GPS receiver is much cheaper than an INS system, and orders of magnitude cheaper than a VOR beacon. Fueled by the success of GPS and its augmentations, the EU started a European Satellite Navigation system, called Galileo. Galileo will be built around 30 satellites (27 operational and 3 reserve craft), and will offer features similar to the GPS. Aside from the evident industrial benefits of such a system (industry will now provide the same type of equipment for GPS and Galileo), the advent of such a system is also very important for the ATC community, since it will enable the use a redundant guidance system relying on both technologies.

Automatic Dependent Surveillance (ADS) is a communication protocol by which aircraft would transmit over digital satellite communication their GPS position information, velocity, as well as information about their intended trajectory, to the ground ATC. ADS-B (for broadcast) is a protocol for broadcasting this information to neighboring aircraft. Its major advantage over the current ATM surveillance methods is its ability to provide very accurate information for trajectory prediction, without relying on the radar system. Two immediate benefits of such a communication link are a huge improvement in surveillance over oceanic airspace, which is not covered by radar, and the possibility of reducing the separation standards between aircraft in all airspace.

Traffic Alert and Collision Avoidance System (TCAS) is an instrument integrated into an aircraft cockpit, which consists of hardware and software providing the pilot with information about traffic in its direct vicinity. In case of a potential upcoming collision with another aircraft, TCAS will sound an alarm and will provide the pilot with an escape maneuver to follow, coordinated with the other involved aircraft.

User Request Evaluation Tool (URET) is a tool which automatically predicts upcoming conflicts between the aircraft and notifies the Air Traffic Controllers. It is currently in use in six Centers in the US, and is in the process of being implemented in 14 Centers. URET also works as an advisory, resulting in greater efficiency in airspace use, in particular regarding direct routing and restrictions at sector boundaries. URET has also the potential of helping guidance of free through its advisory capability.

3.3. Communication and Procedures

All IFR pilots must file a *flight plan* at least 30 minutes before pushing back from the gate. The pilot reviews the weather along the intended route, maps the route and files the plan. The flight plan includes: flight number (which includes the airline identification), the aircraft type, the intended airspeed and cruising altitude, the route of flight (departure airport, Centers that will be crossed and destination airport). It also includes additional information, such as *waypoints*, *navaids*, or *fixes*, which will be used by the aircraft to navigate through sectors of airspace. The flight plan also contains the *arrival*, which is a set of closely spaced waypoints, navaids or fixes leading to an airport. An example of arrivals into the Oakland airport (in California) is shown in Figure 4, with corresponding infrastructure. The pilot transmits the desired flight plan information to ATC, where a controller called a *flight data person* reviews the weather and flight plan information and enters the flight plan into the FAA main, or “host” computer. The computer generates a set of flight progress *strips* that are sent electronically from sector controller to controller across the flight plan; these strips, and flight plans, may be updated by each controller throughout the flight. The flight progress strip contains all of the necessary data for tracking the aircraft. After the pilot has filed the flight plan, ATC may modify the flight plan according to constraints of the NAS and other aircraft (information which is available to each controller from conversations with the ARTCC and ATCSCC controllers), and issues a clearance to the pilot. After take-off, the control of the aircraft is passed through the Tower, TRACON, and possibly several Center facilities until the destination TRACON is reached.

Each sector controller may talk to 25-30 aircraft at a given time. When an aircraft crosses the boundary from one sector to the next, there is a “hand-off” in which the communication is transferred from one controller to the next. Potential conflicts must be resolved before hand-off occurs. The controller directs the aircraft according to a set of simple *control directives*, voiced sequentially. One of the most important, and time consuming, controller tasks is to prevent LOS, between aircraft.

Radio communications are a critical link in the ATC system. The most important aspect in pilot-controller communications is mutual understanding of the command and response. Therefore, pilots acknowledge each radio communication with ATC by using the appropriate aircraft call sign; contacts are kept as brief as possible. For example, a contact procedure is codified as follows: name of facility being called, full aircraft identification as filed in the flight plan, and eventually, the request or type of message to follow. Each procedure is codified in a similar way. Each sector is handled by one key controller and each controller has his own radio frequency over which the communication with pilots in his sector takes place. As a flight progresses from one sector to another, the pilot is requested to change to the appropriate frequency. The *International Civil Aviation Organization* (ICAO) phonetic alphabet is used by FAA personnel when communications conditions are such that the information cannot be readily received without their use. The grammar and phraseology used in the current system is available and has been the focus of recent studies. In general, the commands given to the aircraft by ATC are very precise and can be easily categorized in a discrete set of functions, parameterized by real numbers indicating speed, heading, or other flight variables. This very procedural command environment facilitates the task of modeling human ATC action, communication and aircraft behavior, as will be shown in this chapter. A sample command given by a human ATC to an aircraft might be: “*achieve flight level* 290, *turn to a heading of* 130, *reduce airspeed to* 120 *knots* …”. In addition, the procedures differ from TRACON to Center control: in the TRACON, the controller is responsible for taking the aircraft from *Climbout* $\rightarrow$ *En Route* (the control actions must meet impromptu flow restrictions, hand-off to En Route control, clear to join filed route); in the Center, the controller may revise the altitude and provide temporary heading assignments, amend the route, speed, profile, and provide weather reports and winds.

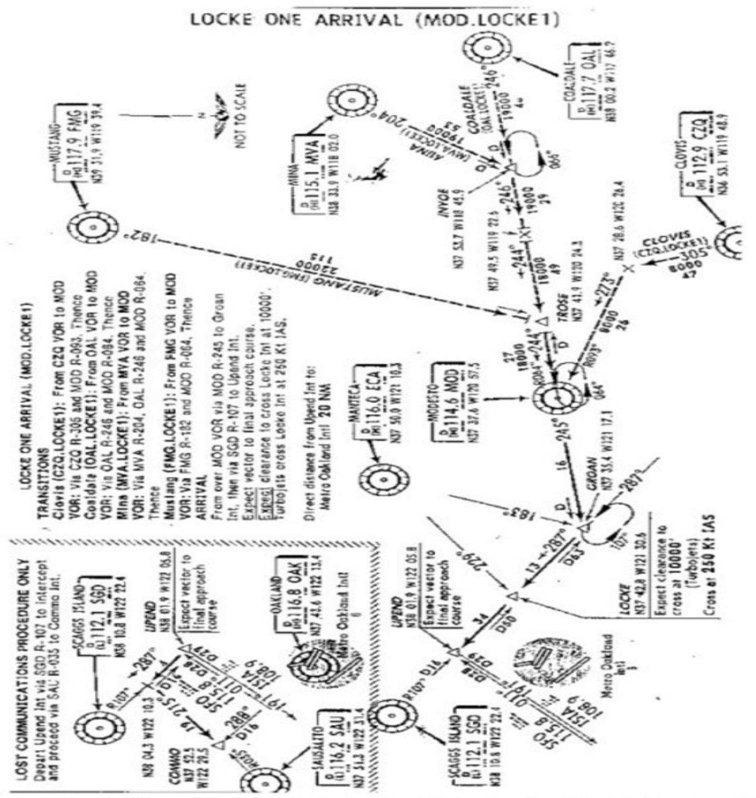

Figure 4: Example of arrivals into the Oakland (oak) airport: locke 1 (mod.locke1). Aircraft enter this airspace through the waypoints: MUSTANG, MINA, COALDALE, CLOVIS, whose acronyms are FMG, MVA, OAL, CZQ. Note the tracks for holding patterns (shown as loops at various merge points).

In this way, the control is *distributed*, since it is applied locally in each sector. There is loose *coupling* within the ATC hierarchy: the ATCSCC controllers talk to the ARTCC controllers several times a day to provide updates and receive feedback about the flow control in each Center/sector. In the case of bad weather, airport closures, or other large disturbances, this feedback tightens, and the directives and updates among the levels of the hierarchy become more frequent. Air Traffic Control regulations and infrastructure in other parts of the world differ from the US airspace. In particular, in Europe, unlike other large countries such as Russia or China, the skies are not unified, despite a similar size infrastructure. Eurocontrol, a European agency unifies the different national entities participating in ATC under a single organization, but the different sovereign States remain responsible for their airspace, which sometimes are of small geographical dimensions, leading to several handover procedures for short flights. The European skies include 75 centers in charge of En-Route traffic, with around 18,000 Air Traffic Controllers (13,000 for the 15 states of the EU). Even if regulations differ from airspace to airspace, a Regulatory Committee and an accompanying Regulatory Unit have been created within Eurocontrol to ensure that regulations are properly observed by member states. An example of differences in standards with the US is vertical separation. Since January 2002, the *Reduced Vertical Separation Minimum* (RVSM) standards have provided six additional flight levels between 29,000ft and 41,000ft in the airspace of 41 European and North African countries, by reducing the separation minima from 2,000ft to 1,000ft. The midair crash above Überlingen mentioned above

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