Chapter 1
Introduction

On 7 March 2014 at 16:42,[1] Malaysian Airlines flight MH370 departed from Kuala Lumpur (KL) International Airport bound for Beijing. There was a total of 239 persons on board (227 passengers and 12 crew). The aircraft was a Boeing 777-200ER registered as 9M-MRO. The aircraft lost contact with Air Traffic Control (ATC) during a transition between Malaysian and Vietnamese airspace. The last recorded radio transmission from MH370 was at 17:19. Over the following days, an intensive air and sea rescue search was made around the last reported position of the aircraft in the Gulf of Thailand without success. It then became clear that satellite communication messages between the aircraft and one member of Inmarsat's constellation of geosynchronous satellites were crucial to defining the search zone for the aircraft. Satellite communication systems involve transmissions between multiple terminals using a satellite. The aircraft 9M-MRO communicated with the Inmarsat ground station in Perth, Western Australia, via the Indian Ocean Region satellite Inmarsat-3F1. The data available for MH370 is mostly comprised of approximately hourly "handshake" transmissions initiated by the ground station for aircraft that have not communicated in the preceding hour. No explicit information relating to the aircraft terminal location is contained in the messages; however, the messages contain metadata which can be processed to produce estimates of the flight path and final location.

Inmarsat conducted a rapid and innovative analysis of the data which placed the aircraft in the Australian search and rescue zone on an arc in the Southern part of the Indian Ocean. On 17 March 2014, the Australian Maritime Safety Authority took responsibility of the search and rescue operation. Subsequently the Joint Agency Coordination Centre (JACC) was established on 30 March 2014 to coordinate the Australian Government's support for the search and over the following weeks an intensive aerial and surface search was conducted by an international team.

[1] All times are given in Coordinated Universal Time (UTC) in format hh:mm:ss. Local time in Malaysia and Western Australia is 8 h ahead of UTC and local time in West Indonesia is 7 h ahead of UTC.

S. Davey et al., *Bayesian Methods in the Search for MH370*, SpringerBriefs in Electrical and Computer Engineering, DOI 10.1007/978-981-10-0379-0_1

On 28 April 2014, the aerial search concluded and the search moved to an underwater phase. The Australian Transport Safety Bureau (ATSB) took responsibility for defining the underwater search area. The ATSB convened a flight path prediction working group in order to bring together experts in satellite communication systems and statistical data processing and apply novel data analysis techniques to estimate the most likely final location of MH370. This working group consisted of representatives from the following organisations: Air Accidents Investigation Branch (UK); Boeing (US); Inmarsat (UK); National Transportation Safety Board (US); Thales (UK); and the Defence Science and Technology (DST) Group (Australia). The working group developed new methods to analyse the Inmarsat data and validated those methods. The ATSB released a report summarising the findings of the working group in August 2014 [3] and have subsequently released updates in October 2014 [4] and December 2015 [5].

In this book we detail the statistical approach adopted by the DST Group team to analyse the available data and produce a probability density function (pdf) of the accident aircraft's final location. In Chap. 2, we start by detailing a summary of the events and listing of the available data. In Chap. 3, we describe the Bayesian framework, upon which our method is formulated. This approach requires several ingredients. The first of these is a prior distribution; this is built on the primary radar data described in Chap. 4. The second ingredient consists of a set of likelihood functions detailing how the available measurements are linked to the aircraft state; the measurement models and error statistics are characterised in Chap. 5. The final ingredient is a stochastic model describing the possible dynamic trajectories of the aircraft. Chapters 6 and 7 describe our models for aircraft dynamics during cruise and manoeuvre respectively. The resulting set of (prior, likelihood, dynamics) enables us to calculate the probability distribution of aircraft trajectories. However since the models are nonlinear and non-Gaussian we are required to use numerical methods for the calculation; our particle filtering approach is described in Chap. 8. The Bayesian method that was developed has been validated against a number of earlier flights of the accident aircraft 9M-MRO, where accurate measurements of the aircraft location were available from the aircraft's logging system. These results are detailed in Chap. 9. The method has also been applied to the data available for the accident flight; the resulting probability distribution, which defines the search zone, is described in Chap. 10. The search zone is defined by combining our pdf from the analysis of the satellite data with a kernel describing the distribution of aircraft motion during descent, which was defined by expert accident investigators from the ATSB. Thus, any adjustment to the assumptions made about the descent (and hence the kernel describing its distribution) yields a change to the search region. Finally, in Chap. 11, we discuss on-going work including the impact of the flaperon wreckage discovery on Reunion Island.

Being statistical in nature, this book seeks to identify aircraft paths that are most likely, given models which incorporate sensor measurements, commonly observed commercial aircraft motion, and air transport safety investigator and manufacturer expert advice and assessments. The goal is not to identify the complete and exhaustive set of all possible aircraft paths, but rather the subset of those trajectories that are most probable. The area covered by the set of end-points of all possible paths is prohibitively large and the overwhelming majority of this area contains vanishingly small probability. In determining how to allocate finite search resources, priority is directed to the area containing the highest probability trajectories. The proposed method incorporates a rich variety of possible paths, and calculates a probability distribution based on the well-established, rigorous Bayesian toolkit, which automatically trades the complexity of the model against the match to the observed measurements.

The ATSB maintains a website http://www.atsb.gov.au/mh370.aspx with comprehensive information about the ongoing search and we refer readers to this resource for the latest news, data, maps, videos, reports and operational updates. Any comments or information related to the search or the analysis in this book should be sent to atsbinfo@atsb.gov.au. Feedback related to the analysis in this book can also be sent to MH370@dsto.defence.gov.au.

1.1 Summary of Results

The key outcome of this book is a probability distribution of the final aircraft location based on a Bayesian analysis, using models constructed through detailed study of the measurement noise statistics and commercial aircraft motion, incorporating assessments of likely operating parameters from expert accident investigators. The distribution is shown in Fig. 1.1, illustrated as a contour plot, where the colour

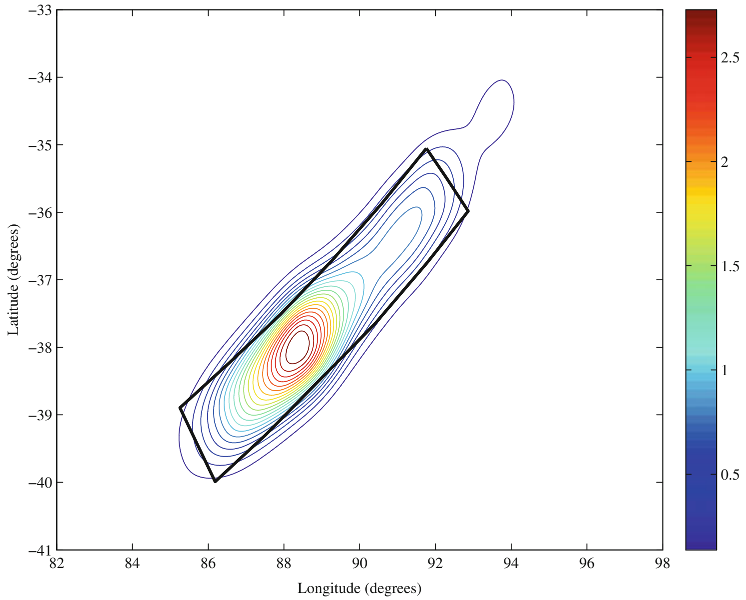

Fig. 1.1 Probability density function of final location of MH370. Indicative search area (as of November 2015) marked with *solid black line*

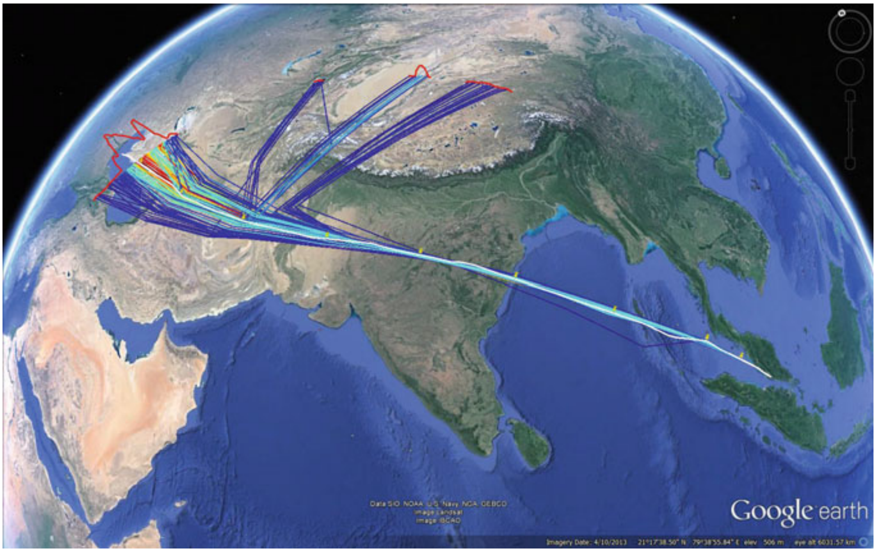

Fig. 1.2 Result of validation analysis applied to the 9M-MRO flight from KL to Amsterdam on 26 February 2014

indicates the likelihood, with red being most likely, and blue being least likely. The black rectangle shows the indicative search area as at November 2015. Full details can be found in Chap. 10. In order to orient the scale of the search being undertaken, the area of the indicative search region shown in Fig. 1.1 is 100,000 km^2. In contrast, the bounding region considered in the search for Air France flight 447[2] was a disc with radius 40 nm [40], corresponding to an area of 17,000 km^2.

The procedure used to generate the result in Fig. 1.1 was validated by applying the identical process to other flights for which the location was known. The flights examined included four flights for the same aircraft (9M-MRO) involved in the accident, as well as two others that were in flight at the same time as the accident. The communications logs for these flights were down-sampled to emulate the information available on the accident flight. An example of the result is shown in Fig. 1.2. The white line shows the true path taken by the aircraft, while other coloured lines show potential trajectories, coloured by their probability, again with red indicating the most likely paths and blue indicating the least likely. The probability distribution at the time of the final measurement is shown as a red line, with the likelihood encoded through the height above the earth.

Ten different subsets of measurements were used from each of the six flights to make a total of 60 validation experiments. In all cases, the true final aircraft

[2]Air France Flight 447 disappeared over the South Atlantic Ocean on 1 June 2009. The initial underwater search consisted of three phases over approximately one year. After the third phase of the search, US company Metron conducted a Bayesian analysis of the available data. Debris was found in April 2011 close to the final reported location of the aircraft.

location was contained within the 85 % probability region. This indicates that the probability distribution produced by the method is slightly conservative, otherwise only around 50 of the 60 experiments should be in the 85 % region. This is because the dynamics model allows for a wider range of aircraft manoeuvres than are actually experienced by typical commercial flights. Such a model is appropriate because the accident flight was not a typical commercial flight. Full details of the validation experiments can be found in Chap. 9.