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There (70°S @ 10,177 m) and Back Again, An Umbraphile's Tale

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Abstract. Until 23 Nov 2003, no total solar eclipse (TSE) had ever been observed from the Antarctic. Yet, interest in securing observations of that event, visible only from the Antarctic, was extremely high and provided the impetus for breaking that paradigm of elusivity in the historical record of science and exploration. The execution of a lunar shadow intercept and the conduction of an observing program from a Boeing 747-400 ER aircraft over the Antarctic interior permitted the previously unobtainable to be accomplished. The unique computational and navigational requirements for this flight are discussed from the enabling perspective of control and data acquisition S/W specifically developed for this task.

1. Introduction

In recent years the astronomical lexicon has expanded to include the term **Umbraphile**: (*n.*) 1. shadow lover (2). one who is addicted to the glory and majesty of total solar eclipses. Those who have basked in the Moon's shadow will grasp (2) without further explanation. Those who have not may have difficulty in understanding that umbraphillia is not only an addiction, but an affliction, and a way of life. The real raison d'etre for many umbraphiles. The more common and prolific term "solar eclipse chaser" is nearly synonymous, but fails to convey the depth of commitment to this lifelong endeavor. Whenever the lunar umbra gracefully brushes the Earth's surface umbraphiles drop whatever they are doing and trek by plane, ship, train, foot, or elephant-back, to gather along a narrow strip in some remote corner of the globe defined by the inexorable laws of celestial mechanics. Newtonian physics heeds no national boundaries, and neither do umbraphiles. Wherever the solar photosphere is extincted, enshrouded by the ashen lunar disk, umbraphiles revel in the fleeting, quasi-twilight, darkness.

Occasionally, the path of totality (the region where a total solar eclipse may be viewed), is so elusive that an airborne observation of such an eclipse is the only viable option. Such was the case on 03 October 1986 (Schneider 1987), and again on 30 June 1992. The fortuitous astrodynamical circumstances associated with the 21 June 2001 TSE could have given rise to an hour long airborne totality if fate had not tragically intervened with the horrific loss of Air France 4590 and the subsequent, then, grounding of the Concorde fleet.

On the long-term average, a TSE is visible somewhere in the world about once every sixteen months. However, the overlap between the cycles (saros, titros, innex) of solar eclipses is complex. The most recent TSE, with a maximum duration of only 42 s occurred on 08 April 2005 (mid-Pacific). Its immediate predecessor, TSE 2003 on 23 Nov 2003, occurred 354 days earlier. Also on average, any given spot on the Earth will see a TSE about once every 360 years. However, eclipse paths can cross specific locations more frequently (e.g., the 2001 and 2002 TSE paths crossed in South Africa, and those living in the right location saw both of them). Prior to 23 Nov 2003, the most recent TSE in the Antarctic occurred on 12 November 1985, but was unobserved.

2. TSE 2003

TSE 2003 was visible only from a small portion of the eastern Antarctic. The path of totality began off the coast in the Antarctic Ocean. The Moon's umbral shadow first touched the Earth at 22h 24m UT with the total phase of the eclipse visible at sunrise at 52.5°S latitude, southeast of Heard Island and the Kerguelen archipelago. The lunar shadow then moved southward toward Antarctica and traversed an arc-like sector of the continent, from approximately longitudes 95°E to 15°E, where it then lifted off into space only 51 minutes later at 23h 15m UT.

TSEs in the polar regions have unusual geometries, and TSE 2003 was no exception. The Moon's shadow passed "over the pole" before reaching the Earth, so, the path of totality advanced across Antarctica opposite the common direction of the Earth's rotation and the lunar orbit. The eclipse occurred in the hemisphere of the Earth which, except at southern polar latitudes, was then experiencing nighttime. Hence, mid-totality occurred very close to local midnight. Antarctic TSEs are infrequent, but not particularly rare. TSE 1985 (the Saros 152 predecessor to TSE 2003) grazed the coast of Antarctica at Halley Bay, but proved beyond the logistical reach of proposed observing expeditions.

Until the advent of TSE 2003, Antarctic TSEs had remained elusive, and never-observed, phenomena. Accessibility to, and mobility in, TSE 2003's path of totality was severely limited. As anticipated, coastal locations were hampered with less-than cooperative weather, and inland regions within the path of totality were, for all practical purposes, unreachable. A Russian icebreaker, challenged by off-coastal weather that is often cloudy and accompanied by high winds and ice fog, made its way to the path of totality finding observing conditions for the eclipse marginal, at best. A ground-based expedition to the Russian Antarctic station at Novolazarevskaya, located very close to the end of the eclipse path at sunset, persevered through hours-earlier threats of blowing snow and white-out conditions, and observed the totally eclipsed Sun partially obscured by the horizon. If ever there was a clear-cut case for the necessity of using an airborne platform to observe a total solar eclipse, TSE 2003 was it.

3. The Genesis of EFLIGHT

Intercepting the Moon's shadow from a high speed aircraft (AC) is conceptually not too complex a problem. However, to do so successfully with high precision while optimizing a flight intercept to simultaneously maximize duration, observability, and minimize cost within the operational constraint envelope of a given AC, is a task which must be be approached with rigor and care. The circumstances of the 03 October 1986 eclipse were so tightly constrained[1] that virtually no deviation from the, then, laboriously pre-constructed flight intercept could be tolerated. By 1992, however, the availability and capabilities of "laptop" computers had so rapidly evolved, that eclipse flight re-planning in reaction to *in situ* conditions became possible. As a result, EFLIGHT[2], an integrated eclipse flight planning and navigation S/W package, was engineered for the fledgling Macintosh PowerBook (100 series) laptop computers. Subsequently, augmented versions of EFLIGHT have been used to: (a) navigate a DC-10 through the path of, and optimally intercept, TSE 1992, (b) plan a supersonic intercept using an AF Concorde for TSE 2001, (c) plan and execute TSE 2003 airborne missions over the Antarctic.

EFLIGHT's core algorithms have a long history. The computation of astronomical ephemeredes and eclipse circumstances performed by EFLIGHT were originally implemented in 1974 on a Xerox Sigma 9 computer under the UTS operating system in APL. These core algorithms have been used for planning ground-based, ship-board and/or airborne observations every TSE since. Early in its history, the software was migrated to other mainframe computers and operating systems (including the IBM/360, Ahmdahl/470VM and Harris 500). By 1979 the software had also been implemented in a combination of BASIC and 6502 assembly code and "packaged" for use on an APPLE II computer. The eclipse prediction and planning software was integrated into a end-user oriented system called CENTERLINE and migrated to the microAPL desktop environment of the Waterloo Language System on the Commodore SuperPet SP9000 in 1982. By 1985 CENTERLINE had again moved, to a VAX/VMS environment, implemented in APL11 under RSX. CENTERLINE was then augmented with some rather special purpose algorithms to aid in the planning of the airborne eclipse observation of the exceptionally challenging 23 Oct 1986 eclipse over the north Atlantic near Iceland. By 1988, CENTERLINE was transformed to the paradigm of the graphical user interface under MacOS 6, implemented first on a Macintosh SE in APL/68000. Contemporaneously, following TSE 1988, a real-time automated camera controller called ROSE (the Reprogrammable Observer for Solar Eclipses) was developed for the Rockwell AIM-65 (6502 μP) as a machine/assembly language program, which relied on computationally derived inputs from CENTERLINE. ROSE, supported computationally by CENTERLINE, was used successfully during the exceptionally long TSE 1991. With the Macintosh Powerbook, in 1992, ROSE and CENTERLINE were symbiotically merged into a single APL/68000 application running under MacOS 7, the first prototype of UMBRAPHILE. But UMBRAPHILE would not be field-tested (quite successfully) until TSE 1995 in Ghanoli, India.

In parallel with the early development of UMBRAPHILE, a separate MacOS APL/68000 application, EFLIGHT (predicated on the same core algorithms), was born to plan and assist in the real-time navigation of a VASP airlines DC-10 to observe TSE 1992 over the South Atlantic. UMBRAPHILE evolved in the late 1990's to a user friendly MacOS application (Schneider, 2004;

[1] http://nicmosis.as.arizona.edu:8000/ECLIPSE_WEB/ECLIPSE_86/ECLIPSE_86.html

[2] http://nicmosis.as.arizona.edu:8000/ECLIPSE_WEB/EFLIGHT/EFLIGHT.html

see Fig 1) and was subsequently used as an eclipse calculator/instrument controller for TSE 1997 (Siberia) and TSE 1999 (Black Sea). EFLIGHT was upgraded and modified for MacOS 9 nativity as an APL Level II for Power Macintosh application in 2000, in preparation for a planned nearly one-hour airborne observation of TSE 2001 with an Air France Concorde. The tragic crash of AF 4590 on 25 June 2000, which lead to the subsequent grounding of the Concorde fleet, resulted in the upgraded EFLIGHT being put "on the shelf". Observing instead from the ground in Zambia, TSE 2001 was imaged with UMBRAPHILE, for the first time, by multiple eclipse users and at different locations along the path of totality. UMBRAPHILE was used again for TSE 2002 (Australia), with Macintosh Powerbooks spanning 10 years of technology (68K to G4 processors).

In preparation for TSE 2003, later observed from two AC over Antarctica, EFLIGHT underwent additional modifications and a port to run natively under MacOS X (Fig 2). The current version of EFLIGHT (2003 X version 2.0.0), described here, is written in from mciroAPL Ltd's. APLX for Macintosh.

4. QANTAS Flight 2901

TSE 2003 presented the first opportunity in the history of science, and indeed of humanity, to conduct high-altitude airborne observations of a TSE over Antarctica. Until that day no TSE had ever been witnessed from the Antarctic. To fill this previous void in the experience base of humankind, while enabling compelling and otherwise unobtainable observations furthering a wide variety of astronomical, solar dynamical, and aeronomic studies, a truly unique QANTAS B747-400 ER flight, designated QF 2901, departed Melbourne, Australia on 23 November 2003 to intercept the lunar umbra. After a poleward journey to a latitude of $\sim$70°S, the flight centrally rendezvoused with the Moon's shadow at 22:44:00 UT at an altitude 11 km above the Earth's surface as the shadow rapidly and obliquely swept over the eastern end of the White Continent. The requirements levied upon QF 2901, to meet the goals of its umbral intercept in the specific context of the TSE 2003, are discussed in §5.

5. EFLIGHT Computational Considerations

Time in totality is a highly precious commodity. TSE 2003 was characterized by a relatively short maximum duration of totality and very limited opportunities to position observers within its umbral path. Extreme care was taken in the planning and execution of an airborne shadow intercept, as codified in the EFLIGHT ephemeris generation and constraint optimization algorithms, to avoid unnecessarily shortening the achievable in-flight totality duration.

5.1. Shadow Dynamics, AC Velocity Vector, Duration of Totality

The dynamics of solar eclipses are driven by the laws of Newtonian celestial mechanics, as naturally applied to the orbital configurations of the Earth/Moon/Sun system. As computed by EFLIGHT, the long slender conic of the TSE 2003 lunar umbral shadow, 1/2° in angular extent at the distance of the moon, was only 34 nautical miles in radius at 11 km above the Earth's surface and tapered to a geometrical point below. The umbral shadow sliced through the Earth's atmosphere at very high speed, decelerating to its slowest instantaneously velocity of 2109 nautical miles per hour with respect to the rotating surface of the Earth at 22:49:17 UT. At that instant, the instant of "greatest eclipse", a ground-based observer concentrically located along the shadow axis would have experienced 1m 59s of totality, the maximum possible for this eclipse. Elsewhere within the path of totality the achievable ground-based duration was reduced.

As is typical for any TSE, the duration of totality w.r.t. maximum declines slowly (except near sunrise and sunset) along centerline but reduces significantly and non-linearly (to zero) across the direction of the shadow's velocity vector at the extrema of the shadow. For a ground-based observer, the duration of totality as seen at some particular location within the umbral shadow declines, to first order, as $(1\text{-}[1\text{-abs}(x/R)]^2)^{1/2}/D$; where R is the radius of the umbral shadow where it intersects a surface of constant elevation, x is the distance of the observer from the shadow axis perpendicular to its instantaneous direction of motion, and D is the duration of totality on centerline at the same Universal Time of mid-eclipse. The duration of totality achievable by an observer with three degrees of positioning freedom (ΔX, ΔY, ΔZ [or Δlongitude, Δlatitude and altitude]) depends upon the $(\Delta X^2+\Delta Y^2+\Delta Z^2)^{1/2}$ perpendicular displacement from the shadow axis normalized to the topocentric shadow width. These "off centerline" scaling relations, however, do not consider the effect of an AC's velocity vector on the absolute achievable duration of totality, and are directly applicable only for a stationary observer. For any AC trajectory the maximum duration of totality declines both with an AC-to-shadow axis centration error and as additionally modified by the AC's motion relative to the lunar shadow.

The nominal at-altitude air speed of a B747-400 ER is 470 Nm/hr. TSE 2003's umbra moved across the Earth with a minimum speed (near the point of greatest eclipse) $\sim$ 4-1/2 times faster than the AC's speed. Hence, with the AC properly positioned at the critical time, and with the heading adopted for QF 2901's mid-eclipse intercept, the lunar shadow overtook the AC more slowly than for a stationary observer. An increase in the duration of totality is realized for an AC with a net velocity component in the direction of motion of the lunar shadow axis. Without the necessary consideration of other constraining factors, a maximum theoretical gain of 37 s was possible for TSE 2003 using an AC with a ground speed of 470 Nm/hr following the trajectory of the lunar shadow axis and precisely co-aligned with axis at the instant of greatest eclipse. Such a fully duration-optimized AC trajectory may not be tenable, as the goal of maximizing the duration of totality cannot be taken in isolation.

5.2. Primary Factors for Simultaneous Optimization

A) AXIAL CONCENTRICITY: At the selected instant of mid-eclipse, QF 2901 was required to be concentrically located along the lunar shadow axis. To the requisite degree of targeting precision (discussed below), this is complicated because the photocentric location (i.e., the "enter of figure") of the Moon's shadow is not coincident with its dynamical center (i.e., its "center of mass") due to irregular selenographic features along the lunar limb. It is these features that give rise to the "diamond ring" and Baily's Beads phenomena at second and third contacts of the eclipse. The lunar limb profile, (e.g., see Figure 4 of Espenak & Anderson 2002), changes with topocentric physical and optical librations and will differ with an observer's latitude, longitude, and altitude along and across the path of totality, and hence, must be applied dynamically (and differentially) with changes in AC position and targeting.

B) MID-ECLIPSE APPROACH/DEPARTURE SYMMETRY: Observation and analyses of the spectrally decomposed brightness and color gradients of the sky, illuminated by light scattered into the umbral shadow by upper atmospheric particulates (as planned to be executed on QF 2901), can provide unique insights into the bulk aerosol content over the Antarctic. In-situ measures by Antarctic ground stations rely on back-scattered LIDARs, whereas aerosol scattering of sunlight into the lunar shadow is uniquely front-scattered and can be used to break degeneracies in particle scattering models applied to the upper atmosphere. Quantitative calibration of aeronometric studies of the bulk physical properties of the upper atmosphere, particularly due to airborne contaminants, require sampling the scattering properties of the atmosphere in a symmetrical manner with respect to concentric shadow illumination, and hence immersion and emersion of the ACs penetration through the umbral shadow.

(A) and (B), above, defined a temporal shadow concentricity/symmetry requirement for the AC trajectory, i.e., how close to the geometrical shadow axis the AC must be at the instant of mid-eclipse and where it must be positioned as it transitioned through the umbral boundary at second and third contacts. An offset in time would produce a time and position error not only reducing the duration of totality but causing a temporal shift in the expected absolute (UT) contact times of the eclipse which is counter to the needs of planned imaging and photographic experiments executed on QF 2901.

C) MID-ECLIPSE HEADING ALIGNMENT: The line-of-sight to the Sun (observed through the Sun-side AC windows) was constrained to be in a plane very close to perpendicular to the AC heading throughout the "totality run" to provide an unimpeded, stable, and nearly optimal viewing angle and FOV. The AC heading alignment and totality duration must be simultaneously optimized as such time-variable orientations will differ from the umbral velocity yielding centerline-crossing flight trajectories.

D) MINIMIZE TOTALITY RUN HEADING RE-ALIGNMENTS. The azimuth of the Sun varies continuously depending upon UT and the AC position. To fully optimize (C) would require near-continuous differential course corrections, which cannot be accommodated at high temporal cadence due to CDU/FMS command input granularity and operational procedures constraints. Large and/or ill-timed discrete corrections during totality would cause a sudden displacement in the positioning of the Sun with respect to the line-of-sight, which were contraindicated and constrained to be avoided.

5.3. Navigation Requirements & Error Tolerance

Taken together, the primary factors for simultaneous optimization (A – D, above) applied to the topocentric circumstances of the eclipse, give rise to a defining set of navigational precision requirements that are summarized in Table 1. Adherence to these requirements was of fundamental necessity to assure the success of the time-critical in-flight eclipse observation programs and the realization of the goals of those programs.

Table 1.

NAVIGATION REQUIREMENTS & ERROR TOLERENCE
1) Absolute Position Error Tolerance:
a) Maximum Aircraft lateral (cross track) position error:
±1 km at mid-eclipse, contact II, and contact III
b) Maximum Aircraft vertical position error ±100 meters.
2) Absolute Timing Error Tolerance: ±6s from UT predictions* @ CII & CIII.
3) Heading Constraint: Portside Orthogonality:
a) Absolute: ±1.5° from mid-eclipse ±5 minutes.
b) Differential: ±0.5° from mid-eclipse ±5 minutes.
4) CDU/FMS Way Point Input Updates:
a) Granularity: Specifiable to 1s minimum cadence.
b) Precluded: within 2 minutes of mid-eclipse, except for mid-eclipse update.
c) Preferentially avoided within 5 minutes of mid-eclipse.
5) Aircraft Altitude: Maximum possible for least air-mass along LOS to Sun.

*Exclusive of IERS delta-T updates.

Table 2.

FLIGHT DEFINITION VARIABLES, CONSTRAINTS & RESTRICTIONS
A) ATMOSPHERICS: METEROROGICAL CONDITIONS:
Local obscuration by cloud: monolithic & multi-layer along LOS to Sun.
Wind speed and direction and vector gradients.
Atmospheric turbidity along the line-of-sight to the Sun.
B) ASTRO-DYNAMICS (Time/Position Dependent Fundamental Geometry):
Non-linear motions (absolute & relative) of Earth, Moon & Sun.
Shadow Velocity and instantaneous acceleration profile.
Shadow axis (X,Y,Z) position loci as functions of altitude above geodial surface (MSL), differentially corrected through atmospheric refraction models based upon temperature/pressure scale-height profiles.
Shadow boundary loci as functions of topocentric lunar limb profile and atmospheric refraction corrections.
Conic shadow projection on the elevated oblate geoidal surface.
Flight-level turbulence (platform stability).
C) AIRCRAFT PERFORMANCE CONSIDERATIONS:
Take-off or In-flight delay (contingency compensation).
Maximum service ceiling for predicated gross weight at eclipse intercept.
D) AIRCRAFT OPERATIONS CONSIDERATIONS:
Minimum desired/Maximum Allowed airspeed.
FMS Targeting Compliance (CDU input granularity and precision).

5.4. Navigation Requirements: Constraints and Restrictions

Earlier QANTAS Antarctic overflights, confined to coastal regions, were driven by the more casual needs to provide a suitable downward looking venue for sight-seeing. Those flights were unconcerned with the specific and highly demanding external constraints imposed by the unique needs of a TSE intercept (see Table 2). For the TSE 2003 flight the necessary responsiveness to uncontrollable, but anticipated, atmospheric variables (Table 2, §A) were fettered and constrained by the defining astrodynamical geometry of the eclipse (§B) and coupled to the performance restrictions and characteristics of the B747-400 ER (§C and §D).

6. The Success of QF 2901

The Boeing 747-400 ER was exceptionally well suited to the QF 2901 mission given the operational capabilities and characteristics of the AC. The experience of QANTAS flight crews in conducting previous Antarctic overflights, though less demanding in navigational specificity and compliance than the TSE 2003 flight, remains unparalleled in commercial aviation. The triad of Boeing, QANTAS, and EFLIGHT capabilities resulted in a perfectly executed flight profile with the AC transitioning through the umbral center of figure within 1 second of the planned and optimal intercept. The technical success of the QF 2901 umbral intercept translated directly into the success of the on-board imaging and observation programs (e.g., Fig 3). As a result, QF 2901 provided, for the first time, a TSE observation venue above 80% of the Earth's atmosphere in the near particulate-free and exceptionally dry and pristine skies over inland Antarctica.

7. Summary

The success of QF 2901, realized as it was plunged into darkness and concentrically enveloped by the lunar shadow at 22:44 UT, was not assured by reliance on pre-planned flight trajectories. Detailed pre-planning, while essential, was predicated upon the inherently unrealistic simplification of presumptively static, but in actuality highly dynamic, input variables. While the likely states of those variables were probabilistically bounded, their values could not be a priori ascertained. Such foreknowledge with the requisite degree of specificity was, in fact, unobtainable and unpredictable. The real-time evolutionary development of an optimal flight plan, built *in situ* on the AC flight deck based upon changing in-flight conditions, was absolutely essential. The accomplishment of the QF 2901 mission objectives, while computationally extensive and algorithmically complex, was enabled by EFLIGHT. This highly specialized software application facilitated an optimal and executable solution to this practical problem in astrodynamical navigation. Developed and tested over many years, EFLIGHT has emerged in its current incarnation to provide the requisite computational resources, codified and integrated into its infrastructure, to solve the highly complex and multiply constrained optimization problem at hand.

With QF 2901 and TSE 2003, EFLIGHT has (again) proven itself as an invaluable tool by enabling an optimized umbral intercept over, perhaps, the most extreme and logistically-challenging region of the Earth. EFLIGHT now awaits a future opportunity to serve umbraphiles again at the next TSE over otherwise climatologically hostile or virtually inaccessible terrain. Got an airplane?

Acknowledgments. The many contributions of QANTAS flight operations, technical, management, security, and support personnel are most gratefully acknowledged. The author is indebted to Captain John Dennis for his staunch support and unparalleled professionalism in executing the QF 2901 mission as Pilot in Command. Without the work of Phil Asker of Croyden Travel, symbiotically merging the needs of umbraphiles and Antarctic "site-seers", QF 2901 would have remained purely an intellectual exercize in flight planning.

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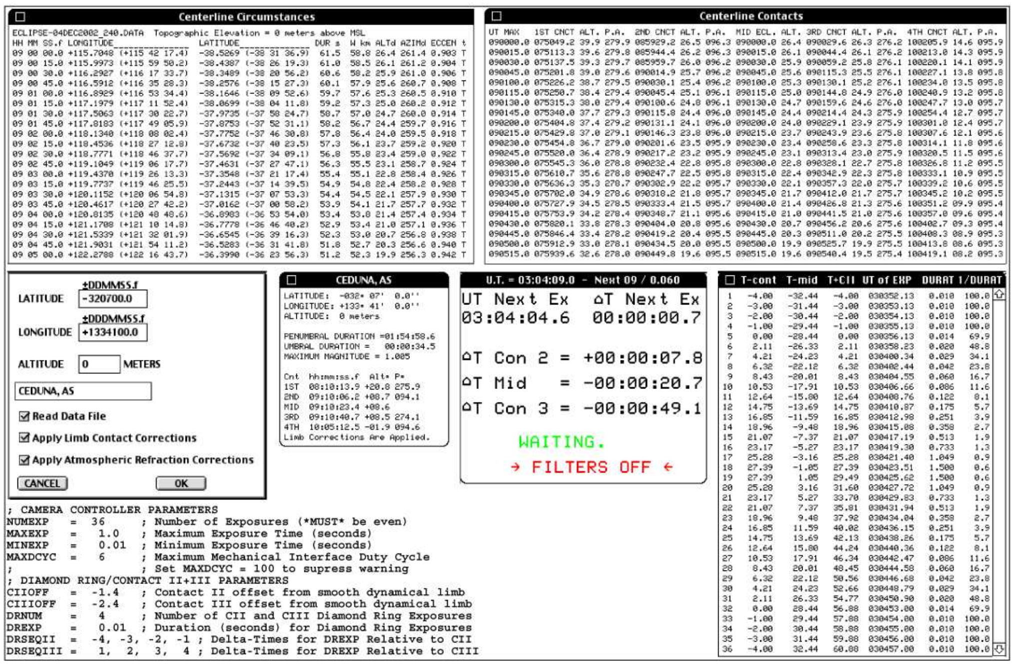

Figure 1. UMBRAPHILE high precision eclipse calculator & instrument controller. Top: UT-dependent topocentric centerline circumstances and contacts are computed along the path of totality. Bottom: For any specified location (left), refraction and limb-profile corrected circumstances are computed, from which an optimized camera-controller exposure sequence table (and dynamical timer status display) is built predicated on user-tunable operational parameters.

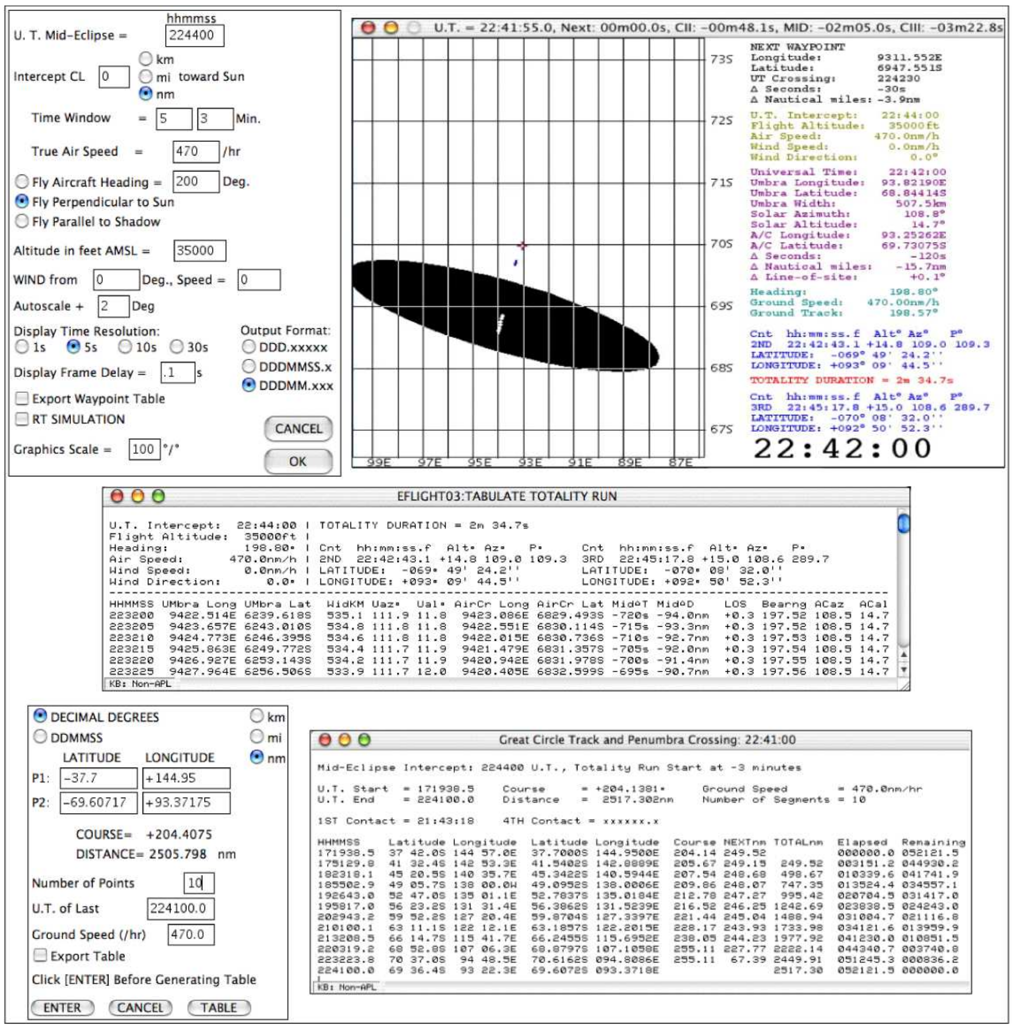

Figure 2. EFLIGHT flight definition specifications, real-time graphical display, event timer, and CDU (Command & Data Unit)/FMS (Flight Management System) compliant tabular outputs.

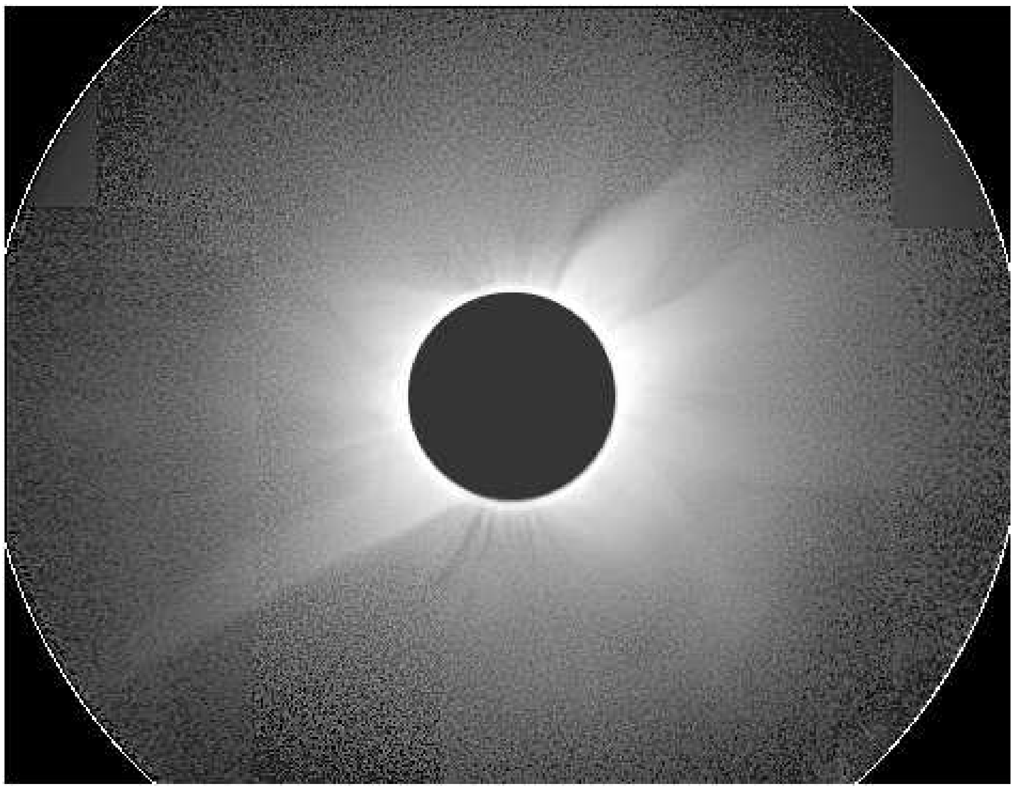

Figure 3. Representative imagery from one of four instruments on a 3-axis gyro stabilized mount autonomously operated (two by UMBRAPHILE) on the QF 2901 flight deck over Antarctica. Mosaic of 5 x 40ms offset-pointed exposures with an SBIG ST-2000 XM 1200 x 1600 pixel CCD camera and 530.3 nm filter (centrally between the LASCO/C2 "Blue" and "Orange" bands; Brueckner et al. 1995.)