Macdonald, M. and Hughes, Gareth W. (2004) *Solar sailing.* In: Proceedings of Summer Workshop on Advanced Topics in Astrodynamics, 2004-07-01, Barcelona, Spain.

Solar Sailing

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Lecture 1: Introduction

An introduction to solar sailing is presented. The physical principles are briefly reviewed along with an introduction to the historical context of solar sailing. Potential solar sail configurations are briefly introduced, while placing these in the context of the current hardware development programmes. Following the introduction to solar sailing we progress onto a discussion of solar sail orbital dynamics in a planet-centred environment. The development of solar sail trajectory generation is presented, from Earth escape trajectories through to lunar fly-by trajectories and more accurate Earth escape methods. Much of this work relies on assumptions to generate near-optimal solutions rather than true globally optimal solutions, which are computationally difficult to determine for multiple revolution trajectories. Many of these traditional planet-centred solar sail applications, such as Earth escape, also require rapid attitude slew manoeuvres to achieve. This first lecture is based on theory development and application with a view towards future missions, such as planetary sample return.

Lecture 2: Planet-Centred Orbital Dynamics

Once again a focus is placed on planet-centred solar sail applications. However, this lecture will analyse solar sail orbital dynamics in the context of realistic near- and mid-term missions. These missions require the removal of the many rapid slew manoeuvres required in historically popular mission applications, such as Earth escape. The theory towards realisation of such missions is developed. It will be shown through analytical methods that many of the most promising planet-centred mission applications for solar sailing require astute use of basic orbital dynamics, rather than development of ever more complex methods, while also placing fewer and more realistic demands on the sail technology. This lecture will finish with an introduction to non-Keplerian orbits and their potential future applications for Earth-centred missions.

Lecture 3: Heliocentric Orbital Dynamics

We move on to discuss solar sail orbital dynamics and trajectory optimisation methods in a general Sun-centred frame. The heliocentric equations of motion and sail force vector will be detailed, and the effects of imperfect reflectivity and billowing of the sail will be mentioned. Conic section orbits that can be achieved with a fixed sail pitch will be briefly discussed. We will then proceed to investigate simple interplanetary orbit transfers such as the logarithmic spiral approach. The heliocentric orbital element perturbations that can be achieved using locally optimal analytical control laws to maximise the rate of change of a particular orbital element will be outlined, as was discussed in Lectures 1 and 2 for planet centred manoeuvring strategies. The remainder of this lecture will be devoted to methods of optimising the thrust vector direction to accomplish minimum-time heliocentric transfers. A range of local and global optimisation methods will be presented and their relative merits and demerits summarised.

The approaches to control representation will be assessed. Finally, the heliocentric trajectory optimisation code developed at the University of Glasgow will be presented as a prelude to the trajectory applications in Lecture 4.

Lecture 4: Mission Applications

In this lecture, a range of mission applications for solar sails will be presented, with particular emphasis on the trajectory aspect each of the interplanetary missions. Trajectories to the inner planets, Mars, Venus and Mercury will be discussed along with sample return trajectories. Mercury is very difficult to reach with conventional propulsion, but solar sailing performs well here due to the inverse square increase in the available solar radiation pressure. Short Period Comet rendezvous and Long Period Comet flybys are also presented. For solar sailing, propellant mass is not an issue and so multiple Main-Belt Asteroid rendezvous trajectories can be realised and will be detailed. The unique features of using a close solar swing-by to generate large heliocentric velocities will be discussed, and it will be shown how these 'eccentricity pumping' strategies can be utilised to reach Jupiter, Pluto and the outer solar system. Exotic Non-Keplerian Orbits, unique to solar sailing will also be investigated. A discussion of the nature of these displaced orbits, in a Sun-centred 2-body context, and examples of optimised transfers to them will be shown. Finally, 3-body Non-Keplerian orbits will be briefly described. Applications of these are the so-called Pole-Sitter concept, where a solar sail can levitate over the Earth's poles, and the Geostorm mission, whereby a solar sail can be placed Sunward of the L_1 libration point to provide advanced warning of solar storms.