in computer binary digits modes. For example, in 1-bit mode, each pixel can receive 2 levels of reflectance (0 and 1) and an 8-bit mode offers 256 possible values (0 to 255). These values are named Digital Number (DN) and have integer format. Most of the sensors have a pre-defined radiometric resolution, but the sensitivity of the ASTER and the Landsat ETM+ can be shifted up and down to adjust for the wide range of spectral reflectances on Earth (Huggel, 2004). For normal, the setting is low gain over ice and snow and high gain over other land. This parameter needs to be taken into account when sensors sensitivity is saturated by snow or is close to 0 over shadow. In cast shadow for example, few details can be seen with low gain setting but better contrast in the ASTER 3N/3B over snow for DEM generation can be expected.

3.3 Glacier mapping

Glacier area is one of the most important parameters to be monitored from satellites. The high altitude of platforms allows for an extensive field of view (170 x 185 km in case of Landsat) which permits covering large regions or even entire mountain ranges. If weather conditions allow (cloud and free of seasonal snow), it is possible to map glacier extents by automatic delineation (i.e. band ratioing, see § 3.3.1C). The methodology used to create the inventory is described in the following in more detail.

3.3.1 Methodology

The method uses optical satellite data in a semi-automatic way and takes advantage of the spectral reflectance properties of ice and snow to map glaciers and ice caps (Paul and Kääb 2005)..Steps A to H are visualized in Figure 3.2 and are explained in detail here:

A) Selection of satellite scenes

In some maritime regions like in Alaska, where cloudy conditions prevail, it is often difficult to find cloud free images. Therefore, merging two or more images from different years can be required to cover the complete region (see Quicklooks in Appendix A1). The snow conditions are also a key parameter when selecting images. Satellite scenes acquired at the end of the ablation period are the most suitable also regarding solar elevation as they offer a good trade-off between shadow and contrast. (See web link (http://academic.emporia.edu/aberjame/gage/glacier7.htm) for optimal dates for each region in the world).

B) Co-registration and georeferencing

To be digitally overlaid in a GIS, all data need to have a projection that can be transformed to the projection of choice. This implies mathematical transformations of the datasets and the use of projection and coordinate systems. Landsat scenes used in this study have been orthorectified with a DEM and were downloaded as the standard terrain correction (Level 1T) product. After downloading all scenes were re-projected to the Universal Transverse Mercator (UTM) zone 5. DEMs were mosaicked and also re-projected to this UTM zone using a bilinear interpolation and 30 m cell size.

C) Main processing - Band ratioing

This processing step uses the multi-spectral capability of Landsat sensors to map glaciers and ice caps. With the respectively high and low reflectance of glacier ice and snow in TM3 (red) and TM5 (shortwave) bands (e.g. Dozier 1989), a simple band ratio (RedA6-9') offers the possibility to efficiently discriminate clean ice from the surrounding terrain with a threshold in a reproducible and consistent manner (e.g. Albert 2002; Paul 2002) (Fig. 3.1). The band ratios TM4/TM5 or the Normalized Difference Snow Index (NDSI) were applied as well for glacier mapping (e.g. Sidjak and Wheate 1999), but here preference is given to the TM3/TM5 ratio (see D).

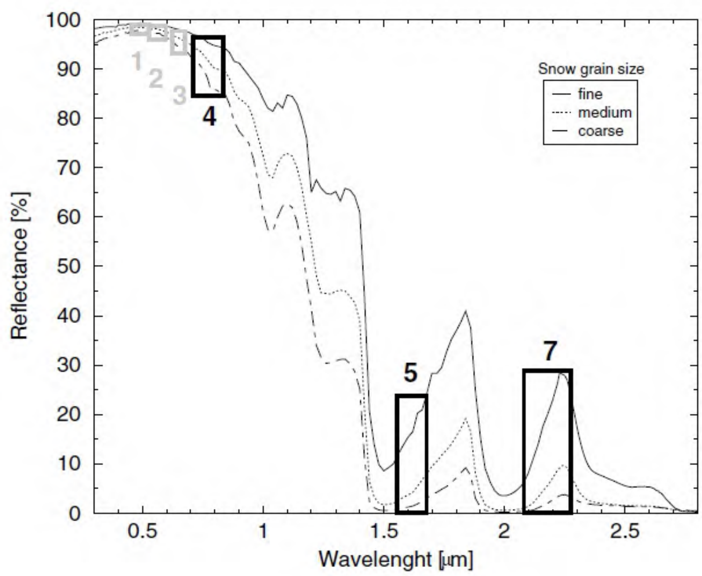

Figure 3.1: *Spectral reflectance curves of snow with varying grain sizes (from Paul, 2007)*

D) Classification – Threshold selection

The classification step is basically a selection of the threshold values on the raw ratio image (Rott 1994; e.g. Bayr *et al.* 1994; Dozier and Painter 2004). Several tests are made to find the most convenient results. In most of the cases values are set between 1.8 and 2.2. An additional threshold is applied on the blue band (TM1) to enhance the classification of glaciers in cast shadow regions. A low pass median filter (3x3) is finally used to remove isolated pixels (often snow patches). Even if the TM3/TM5 ratio also maps water bodies (which are easily recognized and removed in post-processing), it is still preferred over the TM4/TM5 ratio as this ratio failed to map glaciers in cast shadow (e.g. Andreassen *et al.*

2008). The choice of the band ratio depends on the study region and its haze conditions. For example, in one region of Alaska it was not possible to map the lower parts of the glaciers due to fog originating from fires. A second scene was used to map these parts (see Appendix A1-I-J).

E) Vector – Raster conversion

The raw classified map is converted from raster to vector format within the GIS or remote sensing software to obtain vector outlines and allow manual editing.

F) Post-processing (Manual corrections)

Misclassifications resulting from the band ratio technique need to be manually corrected in post-processing steps. Commissions errors (clouds, water bodies (lakes and/or rivers), snow patches) and omissions errors (debris-cover part of glacier, region in shadow) can be easily identified by visual interpretation of false colour composite (FCC) images in the background and manual digitizing. In this regard, band combinations normally used for visual identification are (i) 3-2-1, (ii) 4-3-2 and (iii) 5-4-3 as red, green and blue (RGB) respectively. The first combination (i) shows feature in natural colours while (ii) enhance vegetation (appearing in reddish colours) and water bodies (blue colours) and (iii) is the most appropriate combination to recognize glacier and cloud features (see Appendix A2).

G) Creation of drainage divides

The primary use of drainage divides is to separate contiguous ice masses into individual glaciers. The technique used to create them follows a method developed by Bolch *et al.*7 (2010) (see § 5.2.2). The first step is to define a buffer zone (usually between 1000 to 1500 m) around each glacier and then apply hydrological watershed analysis using a DEM. Even if DEM accuracy influences the quality of the resulting drainage divides, this approach is recommended as it is more consistent and faster than a complete manual digitizing. However, manual corrections remain to obtain a high quality product.

H) Glacier parameters

Glacier specific topographic parameters (e.g. area, minimum and maximum elevations, slope, and aspect) are calculated within the GIS using zonal statistics tools (Paul *et al.* 233C for details). These tools use a value grid (a DEM) to compute statistics over a defined digital polygon zone (i.e. the glacier boundary in vector format). Further details are given in the GIS section. Tabulated attributes are stored along with shapefiles to complete the inventory which is finally uploaded into existing glacier databases (GLIMS).

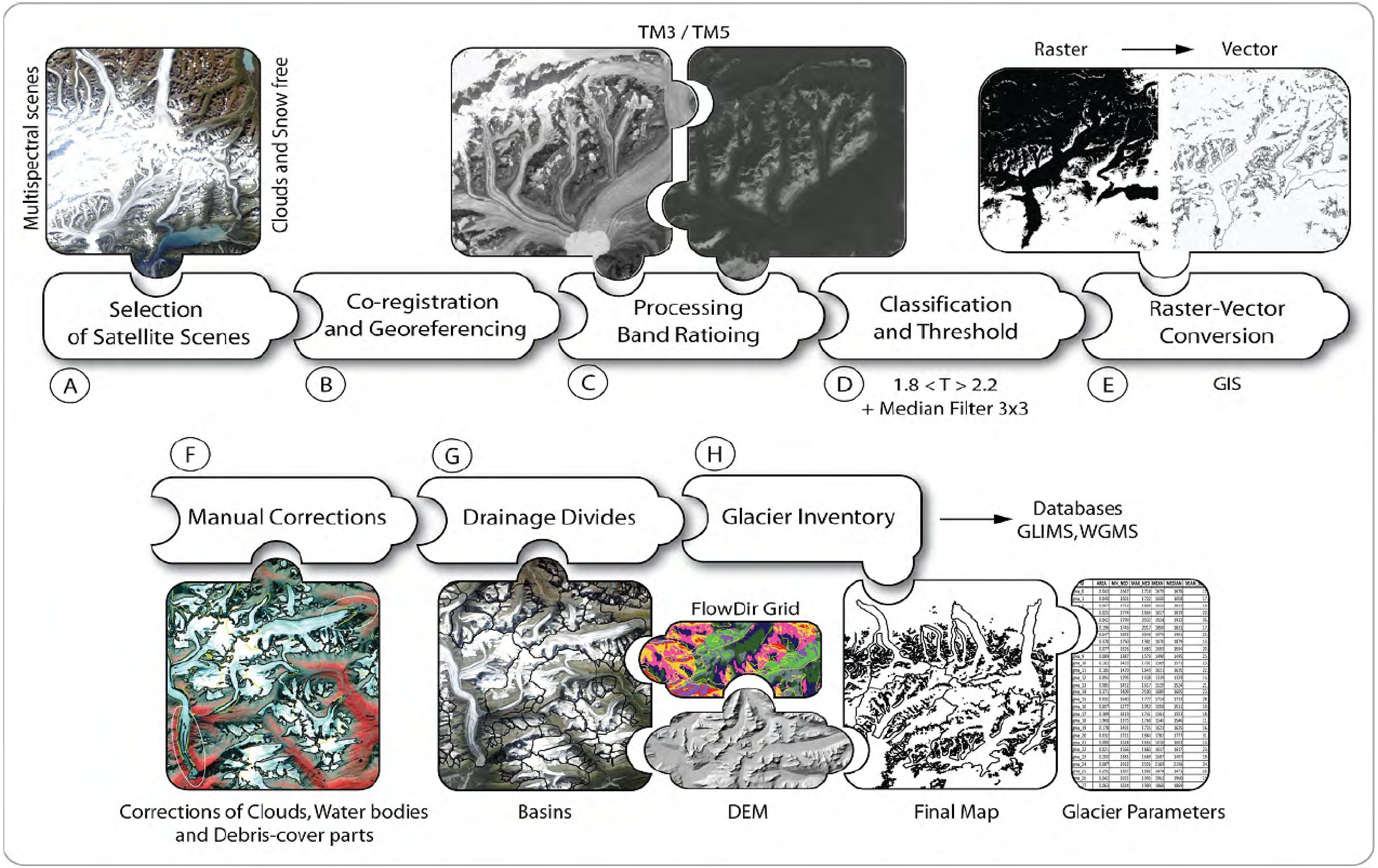

Figure 3.2: Flowchart of the glacier mapping process