Review of current radiometer technology with suggestions for future South African satellites

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science at the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

Signature of Author..

Cape Town
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Abstract

Given that South Africa is an emerging space nation, in a continent of emerging space nations and economies, several technologies need to be developed to progress the space program into a viable and sustainable endeavour. The three main areas of space technology are communications, navigation and remote sensing. Earth science is strongly reliant on the third of these areas for obtaining global scientific data, on a suitable temporal/spatial scale. One of the forms of electro-magnetic remote sensing is microwave radiometry. This dissertation presents a short review of currently available space-faring radiometer technologies and applications, which are then discussed in the context of today's South Africa. For instance Passive Microwave Radiometers (PMR) in the L-Band have huge implications in Soil Moisture (SM) and Sea Salinity (SSS), which in turn affect the global climate, and are being investigated by current and soon to launch missions such as Aquarius, SMOS and SMAP. Multi-frequency radiometers are used to classify various other aspects of Earth's surface-atmosphere system. The structure of this dissertation is to introduce the concepts of radiometry with a review of current and future radiometers from literature (up to November 2011). The user communities, current and possible, are also analysed. There is a discussion of South Africa's history, needs and presence in space, along with possible constraints on a future South African instrument going to space. A technology demonstrator passive microwave radiometer, for SM and Sea Surface Temperature (SST) along with some atmospheric correction channels, is presented. Synergy with data obtained from other instruments, such as an Infra-Red (IR) sounder, is also discussed. Finally, some recommendations for future research are made.

To those that dream,

because when they believe,

those dreams become a reality.

Thanks to all those who have believed in me and my dreams.

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B	—	Transmitted RF bandwidth
$NE\Delta T$	—	Noise equivalent temperature
T_A	—	Antenna temperature
T_r	—	System temperature
τ	—	Integration time
T(z)	—	Vertical temperature profile
q(z)	—	Vertical humidity profile

Chapter 1

Introduction

1.1 Motivation

In 2009 the South African National Space Agency (SANSA) was founded and it has a focus on possible future space missions [8]. However, within South Africa there are elements that prefer that space be a purely commercial endeavour leaving funding for more immediate concerns; this was voiced by the Democratic Alliance shadow minister Marianne Shinn and various parties at the recent IAC2011 [9, 10]. It is well known that science drives progress, but some scientific endeavours are costly in the short and medium term. This leads to the need for a national level effort to support scientific experiments with little or no direct economic benefit.

The South African national space strategy looks to build innovative and useful instruments for scientific purposes in space. Since the researchers that worked on the Greensat program are rapidly approaching retirement, there is a rush, by SANSA, to launch satellites to enable technology and information transfer before the skills are lost [8]. On a related note the instrument proposed, a passive microwave radiometer (PMR), could be a technology demonstrator developing skills for South Africa.

Given that space programmes are costly and that the budget in South Africa is limited, there are two routes to build a satellite either, collaborate in an international conglomeration and build a bigger more complex satellite or build a smaller one, for technology demonstration, completely home-grown. In the context of passive microwave radiometry this trade-off is particularly poignant; the larger the primary aperture, the better the spatial resolution, hence the better the scientific output and the more scientific fields the data becomes applicable to. While on the other hand the larger dish size leads to a huge cost increase as the launch vehicle increases in size due to the increased mass and size of the payload [11]. The smaller option will have limited impact on the scientific community but will build the skills and trust needed at all levels to participate in larger international projects thereafter.

SANSA is well placed to co-ordinate the sources of data from space programmes world-wide for a local market e.g. weather services. While the agency does not currently directly obtain PMR data from it's own satellites it can still play an integral role in the space technology cycle. However, South Africa does have its own specific needs and goals [8] that might not be met by current international satellite platforms. In order to have these criteria met, South Africa must step in and get involved in the designing, assembly, launch, validation and processing of a satellite fleet. South Africa already uses satellite remote sensing data in oceanography [12], Soil Moisture (SM) [13] and other fields. The South African weather service indirectly uses PMR remote sensing data via atmospheric state models imported from the UK Met office [14]. Building a space-borne PMR will serve to further develop and improve the South African ground segment for future space missions.

If an international cooperation route is chosen, to contribute to a global constellation network, this will serve to improve international relations and further enable mutually beneficial ties between the involved countries. Examples of such international collaborations can be found in Table 1.2.

This dissertation concisely presents the results of the survey of PMRs worldwide, to date (November 2011).

1.2 Passive Microwave Radiometry

Passive microwave radiometry is the detection of electromagnetic radiation emanating from the thermal black body emission of the Earth's surface and atmosphere [15, 16]. Several things need to be considered for a PMR including scientific applicability, calibration and validation, frequency spectrum allocation, international space law and current technological capability to name a few. The frequency range from 1 GHz - 10 THz is under consideration. Even though strictly speaking the THz is above the microwave (MW) range, the fact that small and useful instruments can be made to detect the THz led to the inclusion in the consideration.

The effects of the atmosphere, clouds and even rain are negligible at the L-Band [17], however RFI from commercial applications is increasing. That said, there are many PMR applications that take advantage of atmospheric properties and fall into three broad categories, surface imaging at frequencies with low atmospheric opacity, atmospheric sounding at frequencies with higher atmospheric opacity and limb sounding of the stratosphere at almost opaque sub-millimetre wavelengths.

Polarisation measurements can allow for extra information to be estimated, for instance surface roughness over the ocean and wind direction [18]. A relatively new concept in MW radiometry is the use of Interferometric Synthetic Aperture Radiometry (InSARad), instead of a real aperture (dish) [19, 20]. The InSARad concept is currently undergoing calibration and validation on the European Space Agency's (ESA) SMOS mission (Soil Moisture and Ocean Salinity). Another new development is the concept of hyper-spectral passive microwave radiometry [21].

Three types of resolution need to be considered for PMR remote sensing namely; spatial, temporal and temperature resolution. You can build an instrument that favours the one type of resolution but all three are needed for most applications. An example of spatio-temporal requirements for scientists using the SM data, according to Jackson, are a 10 km resolution and a three day repeat cycle [11]. In addition to the resolution, the orbit and scan type have to be considered, in

Table 1.1: Table of pros and cons of types of Remote Sensing from space as compared to PMRs [22, 19]

Instrument Type	Advantage	Disadvantage
Optical	High resolution GEO useful, Easy interpretation	No "invisible" information, Clouds and night, narrow swath, SM estimates unreliable
Infra-red	Moderate resolution, GEO, plant stress, Hyperspectral data	Clouds and aerosols, Detection of SSS and SM, Complex interpretation
Radar	Cloud penetrating, High resolution (SAR), Roughness estimates, Compact antenna	Power hungry, Complex, Narrow swath, More sensitive to vegetation, Frequency spectrum regulation
Passive microwave radiometry	Unique information (SSS), Power needs, Wide swath, Cloud/aerosol penetration, Vegetation penetration	Low resolution/Large antenna, Limited applications, GEO difficult, Complex interpretation, RFI issues Dependent on target roughness

terms of the mission specifications.

The relative advantages and weaknesses of a passive radiometer system over other systems are discussed in in Table 1.1. The instruments available are looked at in the light of the current space arena situation globally and in South Africa. Although in most likelihood the simplest system that is likely to succeed will be chosen for launch, leaving bigger and better systems for future endeavours.

There are several new techniques arising in signal processing including, digital beam sharpening, hyper-spectral sounding [21] and synergistic models using optical, IR and MW sensors in combination. The MTVZA-OK instrument went one step further and combined MW and IR onto one instrument [23]. Weather centres already consider IR and MW sounders complementary and one cannot be used alone and still achieve the same performance as in combination [24, 25]. Scatterometers and Radiometers also work well in combination to determine the target temperature of the scene. The ITU, International Telecommunication Union, is going to assign a large amount of bandwidth above 275 GHz to science in February 2012 [26], so instruments taking advantage of the new or existing allocation should be considered, principally limb sounders and astronomical instruments.

Airborne systems that can give more immediate results are considered as a test-bed for space-borne instruments, they are also fully capable instruments in their own right, for example the High Altitude Monolithic Scanning Radiometer (HAMSR) [27, 28, 29]. But investigation of spin-offs, military or otherwise, of airborne systems is limited in this dissertation as it is not inside the scope of the space-borne project. Several applications in security have arisen for the mm and THz range, including allowing detection of concealed metallic and non metallic objects, that are driving technology development [30, 31].

1.3 History

Although radiometry had its beginnings in astronomy with the observations of Jansky in 1931, it was not until later that the same technique was used to look at Earth. Space-borne passive microwave radiometry has been around for 50 years since the Mariner-2 mission [32], and for Earth remote sensing since 1968 on Cosmos 243, according to Staelin [7]. A great deal of research was done into the applications in the 60's and 70's [22]; instruments were developed for these purposes and the associated errors determined in relation to the requirements [33, 34, 35]. There was a twenty year gap during the 80's and 90's where few PMRs were developed for launch and focus on Infra-red (IR) sensors was carried out [36].

There is a survey of the past instruments outlined in Table 3.1, and an occupancy plot showing the utilisation of the various frequency bands over time is shown in Figure 3.1. An overview of the PMR instruments from various countries is given in Chapter 3 and Appendix B.

To demonstrate that PMRs are deemed useful, here are some examples of international agencies that have built them: ISRO, the Indian Space Research Organisation, have built OceanSAT with a PMR aboard, JAXA, the Japanese

Table 1.2: Table showing some international collaboration satellites involving PMRs [5]

Satellite/Mission	Satellite bus built by	Instrument name	Instrument built by
Aqua	NASA	HSB AMSR-E	INPE (Brazil) JAXA (Japan)
Aquarius/SAC-D	CONAE (Argentina)	Aquarius	NASA
Sich-1M	NSAU (Ukraine)	MTVZA-OK	Roshydromet
Metop	Eumetsat (Europe)	AMSU-A MHS	NASA EUMETSAT
NOAA*	NOAA (USA)	MHS AMSU-B	EUMETSAT UKMO
Jason	CNES (France)	JMR	NASA
Megha-Tropiques	ISRO (India)	Saphir	CNES

* refers to the fact that MHS and AMSU-B flew on different NOAA satellites

space exploration agency, currently operate the Advanced Microwave Scanning Radiometer - EOS (AMSR-E) on board Aqua, INPE built the Humidity Sounder of Brazil (HSB) on the Aqua satellite and CONAE in Argentina built the satellite bus and a MicroWave Radiometer (MWR) for the Aquarius/SAC-D spacecraft. These instruments and others are shown along with the partners in Table 1.2. The Chinese have a strong showing in the PMR data gathering [37] with the Feng Yun 3 series (FY-3) [38, 39, 40, 41, 42, 43, 44, 45] and the upcoming Geostationary Interferometric Microwave sounder (GIMS) [46]. The Russians have a strong series of PMRs in the MTVZA series [3, 23, 47, 48]. Some of these instruments are shown in Table 1.3.

The future upcoming missions include SMAP, JPSS, GCOM-W and GPM. These missions aim to address shortfalls in our knowledge of the Earth's hydrological cycle and increase the temporal resolution of such data.

1.4 User Communities

The resulting field of MW Radiometry, is quite diverse with applications such as: Numerical Weather Prediction (NWP) for rainfall monitoring and wind vector determination [49, 18], verification of climate change models via monitoring of SM [11], Sea Surface Temperature (SST) allows current monitoring and discovery in oceans [12] and climatology needs records over time of ice type distributions, in the polar regions, along with large scale distributions in the ocean composition, e.g. Sea Surface Salinity [SSS] [50]. Monitoring sea ice concentration in the high latitude regions also has applications in oceanography. There other applications needing data regarding snow cover and monitoring of atmospheric constituents in the upper atmosphere such as aerosols [6]. Due to the poor spatial resolution of PMRs these applications are limited to regional and global scales [51].

Although a great deal of the historical radiometers and ones currently in use focus on the atmospheric sensing, for use in NWP, there is more emphasis on surface sensing recently with several L-band instruments going up, for example SMOS and Aquarius. The increasing resolution as time goes by allows more

Table 1.3: Table showing recent and current key instruments [2, 3, 4]

Dates	Satellite/ Mission	Principal agency	Instrument acronym	Frequencies [GHz] (channels)	Swath Width/ pixel resolution [km]	Main parameters
1997	TRMM	NASA	TMI	10.7,19, 21, 37, 85.5	760/4-35	SST and precipitation
1999	Oceansat-1	ISRO	MSMR	6.6, 10.65, 18, 21	1360/40-120	SST, Sea-Wind speed
2001	Jason-1	NASA/CNES	JMR	18.7, 23.8, 34	30/22-42	Path Delay
2001	Odin	SNSB	SMR	118, 490-500, 540-580(3)	ls.14-100/1.5	Limb sounding, Astrophysics
2001	Meteor-3M	Roshydromet	MTVZA	18.7, 22.2, 33, 37, 42, 48, 52-57 (10), 91, 183(3)	2600/12-75	T(z), q(z), precipitation, CLW, TPW, SSWS
2002	Aqua	JAXA	AMSR-E	6.9,10.7, 18, 23, 37, 85	1400/3.5-43	SST, SM, windspeed
		NASA	AMSU-A	23.8, 31.4, 50-60(12), 89	1690/40	Atmos. profiling
		INPE	HSB	150, 183(3)	1650/13	Humidity profiling
2002	Enivisat	ESA	MWR	23.8, 36.5	20/20	Path Delay
2003	F-16	DMSP	SSMIS	19, 22.2, 37, 50-60(7), 60-63(6), 91.7, 150, 183 (3)	1700/10-55	T(z), q(z), SSWS, TPW, CLW, Sea ice, SM, land temp
2003	Coriolis	USA DoD	Windsat	6.8, 10.7, 18.7, 23.8, 37	950/8-39	Wind vector
2004	Sich-1M	Roscosmos	MTVZA-OK	6.9, 10.6, 18.7, 23.8, 31, 37, 42, 48, 52-58 (10), 89, 183 (3)	2000/8-112	T(z), q(z), Precipitation, CLW, TPW, SSWS, SST
2004	Aura	NASA	EOS-MLS	183,500,2500	ls.10-100/2-8	H_2O, Trace gasses
2006	Metop-A	EUMETSAT	MHS	89, 157, 183(2), 190	2000/16	Humidity profiling
		NASA	AMSU-A	23.8, 31.4, 50-60(12), 89	2000/50	Atmos. profiling
2008	Jason-2	CNES/NOAA	AMR	18.7, 23.8, 34	26/14-26	Path delay
2008	FY-3A	CAST/NSMC	MWRI	10.65, 18.7, 23.8, 36.5, 89.0	1400/10-70	SM, Rain rate, Atmos. water, Sea Ice
			MWTS	50.3, 53.6, 55, 57	2100/60	T(z)
			MWHS	150, 183.31(3)	2700/15	q(z)
2009	SMOS	ESA	MIRAS	1.4	2000/45	SM, SSS
2011	Megha-Tropiques	ISRO	MADRAS	19, 23, 37, 89, 157	1700/6-40	Rain, CLW, TPW, Cloud Ice
		CNES	SAPHIR	183(6)	1700/12	Atmospheric profiling
2011	SAC/D	NASA	Aquarius	1.4	380/75-96	SSS
		CONAE	MWR	23.8, 37	380/27	Rain, SSWS
2011	NPP	NASA	ATMS	23.8, 31.4, 50-58(13), 88, 166, 183(5)	2300/15-75	Atmospheric profiling

ls. refers to the fact that resolutions for for limb sounders are given in vertical direction
T(z) refers to vertical temperature profile, q(z) to vertical humidity profile

science to be done as more features can be resolved, e.g. surface currents from TMI data [12] and AMSR-E data. Some of the AMSR data products are shown in Figure 1.1 and Figure 1.2.

Currently the main uses for the PMR data are atmospheric monitoring, i.e. Cloud Liquid Water (CLW), Total Precipitable Water (TPW) and temperature/water vapour profiling for meteorological purposes and climatology, as well as global ocean monitoring for oceanography. The atmospheric sounding channels, for atmospheric monitoring, are usually centred near the oxygen lines at 60 and 118 GHz and the water lines at 23 and 183 GHz. A typical instrument that uses these frequencies is the Advanced Microwave Sounding Unit (AMSU-A) [52] and the recently launched Advanced Technology Microwave Sounder (ATMS) [53].

In addition to the many uses for atmospheric sounding (vertical profiling [27]), surface imaging as well as the newer field of microwave limb sounding (stratospheric chemistry [54]) that have arisen, there are other secondary functions that PMRs play. The atmospheric wet path delay on MW altimeters is calculated using a PMR, e.g. AMR on Jason-II [55]. Altimetry is used in oceanography to monitor the sea surface height anomaly which in turn helps to understand pressure gradients in the sea [56].

The penetrative effect of MW radiation at longer wavelengths also allows for analysis of the bulk properties of a surface, like in the case of SM [11, 57]. Some SM applications are complementary with radar imaging in characterising radar return. The use of polarisation measurements can help characterise surface roughness and RFI as well as other uses.

The end-users would include the weather service, navy, army, climate change research groups, agricultural policy makers, oceanographers [12], hydrologists, marine biologists and possibly the forestry commission. Since the instrument will naturally lend itself to one particular category not all the above end-users will be served by one instrument, unless the instrument is extremely complex and large in size. South African user needs are considered in the light of present and future capability. The usual clients of a passive microwave system are shown in Table 1.4.

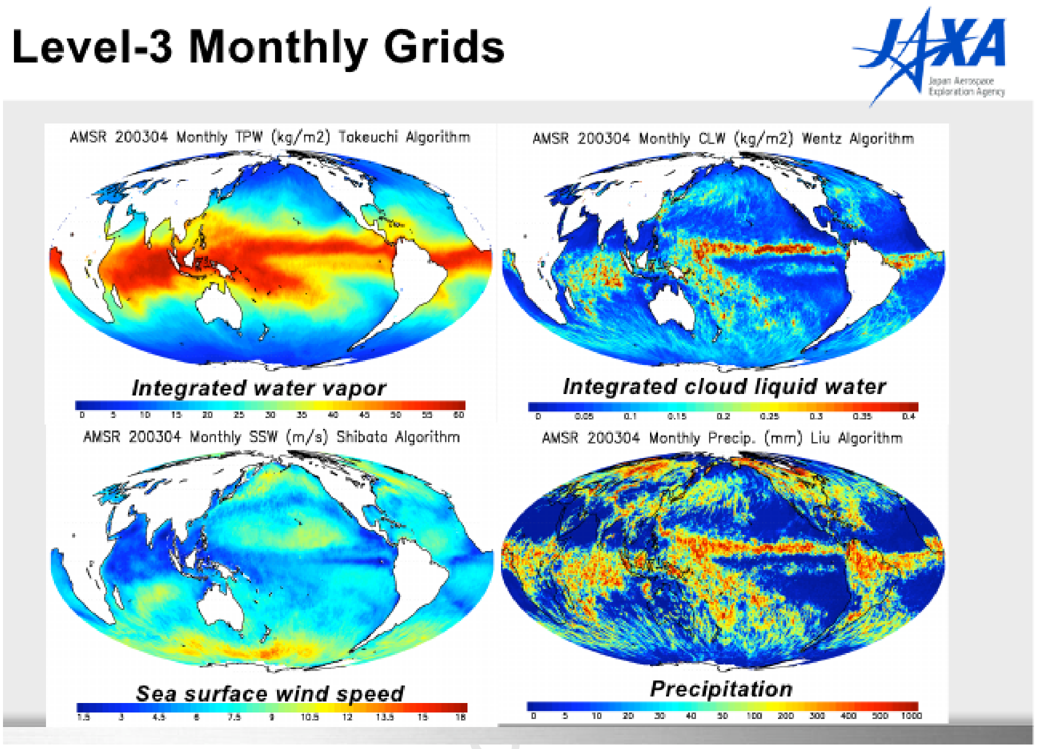


Figure 1.1: Figure of monthly products possible from AMSR-E [1]

Table 1.4: Table showing the data sets of interest for typical users of PMR EO data

User	Data sets of interest
Oceanography	SSS, SST, SSHA, Ice classification/monitoring
Climatology	SST, SM, IWV, CLW, precipitation
Weather centres	Temperature/humidity profiles, precipitation, wind vector
Scientists	Trace gases in stratosphere (Ozone)
Future user	Data sets of interest
Agriculture	SM, precipitation
Marine biology	SST, SSS
Forestry	Biomass estimates, NDVI
Radio astronomers	RFI sources (VLBI non earth observation)

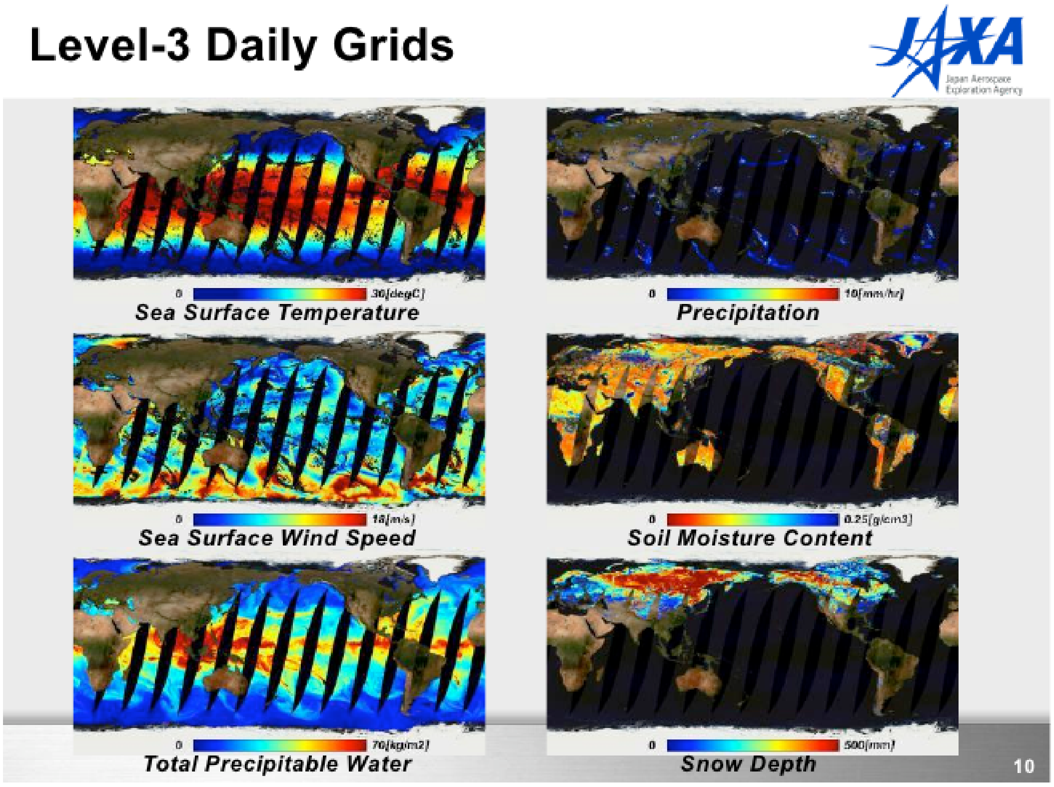


Figure 1.2: Figure of daily products possible from AMSR-E [1]

South Africa also has international commitments in space such as the African Resource Constellation which is designed to monitor the resources on the African continent, this means that the best and most useful instruments for monitoring Africa's resources will be built and launched. Such a resource management constellation would be well served by a MW instrument among its members. However, the capability of South Africa to produce such an instrument still needs to be validated.

The other up and coming area is synergistic models and data processing centres. As models become more complex and the number of instrument types contributing data increase, the stronger the need for dedicated data processing centres and the corresponding research to verify that the models are continually optimized. There are other options such as semi-passive instruments which include reflectometry and GNSS occultation which can give you information of the sea state and total electron content respectively, but these options are beyond the scope of this dissertation.

1.5 South African needs

South Africa has several pressing concerns in areas such as water monitoring, agricultural production, weather prediction and skills building. A Mckinsey report mentioned that there is a clear proportionality between the number of skilled and unskilled jobs. Hence, building a satellite creates skilled jobs which in turn implies an increase the number of unskilled jobs [58].

Given the international trade restrictions by various countries, such as ITAR by the US, the need for the local development of a space-borne instrument is stronger, since it is not easy to get an "off the shelf" space-borne radiometer from these countries. Given the relative scarcity of instruments in orbit, resulting in slow revisit times, has lead to the planned constellations to address this, providing an opportunity for South Africa to raise her international profile in the space arena by contributing an instrument or even a bus to these constellations.

Subandila Sat was a success and showed that South Africa does indeed possess the ability to make a functioning spacecraft. There is a plan to roll out spacecraft built by South Africa in the future. The aim of this dissertation is to lay out whether South Africa should be considering a PMR and what would be the optimum instrument or series of instruments to send up in the case that the go ahead is given. The technology driver in building the demonstrator instrument will proliferate into society improving the standards of locally produced products, which in turn will increase the marketability of South Africa to its international space partners and potential partners. The successfully launched and operated technology driver satellite will also serve as an advertisement to the greater South African population and research community of the capabilities of South Africa in the space arena. The Research community could very well come up with novel ways to use PMR data and in turn propose better and more complex follow up missions.

The field of MW radiometry is diverse and has implications in many other fields and therefore needs an established satellite applications centre to produce products for the end users. Such products would have been processed by discarding data affected by RFI or flagging areas where the scene temperature is affected by local conditions such as rain; in addition new product variations can be requested, for example RFI monitoring for the SKA project. Several capabilities of PMRs and the associated frequency allocations are described in a handbook on frequency allocations available online [59]. These capabilities require the ongoing maintenance and upgrading of the ground segment of South African and African Resource Management Constellation (ARMC) space missions. This ground segment capability can be advertised to local and international commercial space entities as well as to the research community in the context of future missions.

South Africa is already involved in the Earth Observation arena in the form of SAEON and SANSA Earth Observation and Space Science. We also use GEOSS data in climatology research. These pre-existing entities need funding for expansion in order to support the data that will come from the ARMC and South African space missions.

1.6 Recommendations

The various options include InSARad or real aperture radiometers in the collecting of atmospheric sounding, limb sounding or imaging data. All the applications shown in Table 1.4 need instruments that require a large amount of skills and expertise. Many of the national space agencies have started out with simple instruments, the Mariner-2 instrument in the case of the US, Cosmos 243 in the case of Russia and more recently the attempted launch of the DREAM instrument by Korea. It is important to build trust, in the manufacturing facilities of South Africa by international partners and the local scientific community, with a simple instrument with limited scientific potential before moving onto larger more complex projects later on. To this end many of the facilities will need to be maintained and upgraded.

We need to build up local capability to process data, case in point, the weather service in South Africa still buys preprocessed data products from the UK. While a demonstration mission is being sent up, ground testing for more complicated instruments as mentioned above should be in process for launches ten years from now, presently some such missions fall under the GCOM (Global Change Observation Mission) and GPM (Global Precipitation Mission) constellation missions. In preparation for international satellite constellations and instruments on international satellites, care should be taken to ensure interoperability of hardware, software and data formats with the international partners during development [60].

South Africa should bid to have instruments or possibly a satellite bus built by South Africa placed on the next cycle of decadal satellite instruments, from developed countries, which will be sent up to continue and improve the data gathering ability of the current satellites in orbit. That way we can avoid the risk of using a completely untried system, share the costs of the launch and have reasonable time to develop a space-worthy system to international standards. There should be standardised satellite bus designs developed by South Africa for South Africa in the various size and power categories. These buses should feature redundancies like extra momentum wheels (Subandila experience). A easy to read paper on imaging mission design considerations was published by L'Abbate et al. [61].

Also the technology demonstrator satellite can be built with complementary payloads such as an IR sounder or even small compact space weather experiments. By the nature of MW radiation the size of the satellite has a lower bound due to the need for a large aperture. This precludes the use of picosats and nanosats, at least until orbits can be determined precisely and a free drifting constellation InSARad concept can be developed. Given current technology the smallest satellite bus size we are looking at is micro-satellite size. However, if a reflector is used a concept taking advantage of the relatively small size of the feed-horns could be considered or alternatively of simply spinning the whole satellite (e.g. SAMIR) with novel calibration schemes. The calibration can be checked via vicarious methods as well as deep space view manoeuvres. Although, the maximum aperture size feasible must be a priority, 1 m together with a low orbit would be useful scientifically, TMI is 61 cm. The orbit should be selected carefully for scientific impact, orbit maintenance and battery cycle load (launch weight).

So given the following groups of key instruments, some described in Chapter 3 others in Appendix B: Aquarius/SMOS, MTVZA-OK/ATMS/MWTS, MLS, MSMR/Windsat/SSM/I and GeoSTAR/GIMS; the instrument was chosen for simplicity, heritage and use. The uses for the frequency selection of 6.8, 10.7, 23 and 37 GHz for the demonstrator include; SST, SM, atmospheric moisture content, precipitation and sea ice monitoring. The addition of a redundant 18 GHz channel would enable more accurate sea surface wind speeds, which can also be approximated by the 6.8/10.7 GHz channel pair, via the sea surface roughness estimate. The addition of an infra-red sounder would also increase the applicability of the mission to weather forecasting. Between the IR sounder and the higher frequency channels the atmospheric effect on the 10.7 GHz channel should be well estimated. Although, more channels means more power needed, in turn more weight due to batteries and solar panels. That said, the more frequency channels the better the scientific return.

Since South Africa is relatively lightly vegetated, the soil moisture measurements from the 6.8 and 10.7 GHz channel should be useful to some degree below 1.5 kg/m^3 vegetation water content [62], although in arid areas the moisture tends to be deeper underground than the ~1 cm skin depth at 6.8 GHz.

Although 2.7 GHz would be better for SM and introduces SSS, the lower frequency means the horn will be prohibitively big and the spatial resolution bad. A short focal length to a dish would relax the feed horn size requirement but cross-polarization effects, from the offset dish, could become significant. The horns for 6.8 and 10.7 GHz will present a challenge on a micro-satellite. Where there is a worry of RFI, like for the 6.8 GHz channel, another receiver centred at a nearby frequency such as 7.3 GHz (viz. AMSR-2 [63]) can be used to help filter out narrow band RFI.

Given the worldwide revolution in MW frequency devices, a PMR can be built using commercially available parts for a fraction of their real price in the 1970's. Space hardening the hardware to be launched will increase the odds of success but increase the price.

1.7 Structure of Dissertation

Before a new mission can be proposed the missions that came before must be studied and lessons from them considered when designing new instruments. To this end a survey of PMRs worldwide, to date (November 2011) is presented. Then considering all these instruments and their applications a series of recommendations are made.

In Chapter 2 a brief overview of passive microwave remote sensing from space is presented outlining some of the considerations for such a remote sensing mission, like viewing geometry. The theory behind Microwave radiometry itself, with regard to the scene observed and the uses of several frequency channels, is described. PMR theory is presented for an understanding of what they are, along with their calibration systems. The types of resolution are discussed, spatial, radiometric and temporal. The terms imager, sounder and limb-sounder are presented and each option is considered. The various trade-offs, both for PMRs and PMRs against other systems, are discussed. Finally some new techniques and airborne testing systems are covered.

For Chapter 3 the key findings of the literature survey is presented. The main past, present and future missions from various countries are described and presented in tables, with emphasis on the key instruments in the scientific community. Some of the key scientific instruments including imagers, sounders and limb-sounders are discussed. Since a technology demonstrator is being proposed a table of first missions from each country is presented, to gather a ballpark estimate for the complexity of a first instrument. Finally, the lessons learned from historical issues such as, scan motor failures, poor algorithms, calibration and RFI mitigation are mentioned. The rest of the survey including meteorological series of instruments, taking the major PMRs and PMR series, from each country in the survey and the future missions constellations, like GPM, are presented in Appendix B, including exciting new developments such as: geostationary sounders (GIMS and GeoSTAR) and an L-band active/passive instrument (SMAP), along with a section on astrophysics missions as an alternative use of a PMR instrument. The descriptions include both generic data on the instruments and specific information, such as weight, power and reason for failure, pertinent to the instrument in question.

Chapter 4 is a description of the various players that use PMR data. Each of the main uses are described and papers cited for further reading, for fields like oceanography, meteorology and climatology among others are included. The satellites and datasets the users are interested in are also described. The specific considerations in each case are mentioned like the effect of surface roughness and RFI on SM, heavy rain and coastal effects on SST. The motivations, capabilities, needs and potential areas of further research are discussed. The derived products are described, in order to see the end result after the data has been processed, like weather forecasts and flood warnings. The chapter rounds off with a description of various data processing centres around the world to model South African data processing centres on. Also the need for South Africa itself to have PMR data is analysed.

Finally in Chapter 5, the human resources, organisations, testing facilities and procedures that South Africa has are introduced, including the launch and production facilities. The considerations and options taken into account are described in terms of benefits to a developing nation. This leads to the description of the proposed instrument and motivations. Dual, triple and four frequency instruments are considered at various frequency ranges. A four frequency instrument at 6.8, 10.7, 23 and 37 GHz is favoured for simplicity and scientific return, with the option of two additional redundant frequencies (7.3 and 18 GHz) that would improve the data. The uses of the technology demonstrator (SM, SST, SSWS and TPW) are described. Then frequency selection, technical and academic considerations for the demonstrator are discussed. Afterwards, some of the next steps are proposed including, starting to process data from overseas missions to gain experience in developing and validating models. The possible missions after the favourable operation of the first mission are discussed like a radar altimeter or an instrument on a constellation member bus within a decadal plan, as well as missions that can be considered to go immediately such as a THz limb sounder on a space weather satellite. The current international commitments like the ARMC and CBERS constellations are considered in terms of whether a PMR would add value. The international nature of space technology is also analysed for motivations to send up a PMR instrument and as a source of technology transfer. The political landscape is briefly mentioned as the government will ultimately pay for scientific space missions.

The Conclusions of the proposed four or six frequency technology demonstrator are presented, along with concept areas for further research, like hyper-spectral sounders, InSARad (fixed and formation types) and GEO sounders. A glossary of acronyms is included due to their heavy use throughout the thesis.

Chapter 2

Theory of Radiometry and Background

Since Naledi Pandoor opened the South African National Space Agency in 2009, SANSA, there is a drive to put South Africa satellites and instruments in space, especially those that will positively impact the lives of South Africans [64]. The potential for growth from spin-offs in satellite development and from the use of satellite data is huge, thus investing in space science is investing in economic development, however within South Africa there are elements that prefer that space be a purely commercial endeavour leaving funding for more immediate concerns, as voiced by the DA shadow minister Marianne Shinn and various parties at the recent IAC2011 [9, 10]. Although given the expense of buying data from overseas is prohibitive, a locally produced satellite could give the data to local companies for free or for a subsidised amount. This would allow that money that would have been spent to be reinvested and the tax turnover would increase, thereby allowing further scientific projects. This would give a competitive edge to the local economy and reducing the cost of business allowing better investment margins.

There is a drive to launch a African Resource Management Constellation (ARMC) with three other African partners. A passive microwave radiometer (PMR) on that constellation will go some way into giving information needed for resource management, also the inter-institutional collaboration, both local and international, before and during the Earth observation space mission, will strengthen and enhance the academic environment in South Africa [65]. There are current plans to get into Earth observation missions including bidding to manage data for the CBERS-3 satellite launched by Brazil and China [64].

Other uses of PMRs are neglected in South Africa. This is most noticeable in numerical weather prediction (NWP), where the South African weather service buys their data pre-processed with PMR data from Europe instead of processing the raw data locally [14]. This is unfortunate given that South Africa could easily build the skills to do so.

The various target parameters, on the surface of Earth or in the atmosphere, as well as the frequencies used to detect them are presented in Table 2.1. A more complete description for the uses of the various frequencies can be found in a space frequency coordination group hand book, resolutions SFCG 21-2R3 and SFCG 29-1 [66, 67, 68]. Since there are several contributions to a signal, especially above the X-band (10 GHz), an extra channel (frequency or polarization) is needed for each contributing factor. For example, cloud liquid water (CLW), integrated atmospheric water vapour (IWV) and precipitation rate necessitate the use of three well placed frequency channels. This leads to the concept of primary and secondary uses for frequency bands.

Table 2.2 shows some of the limb sounding products that are used on Aura MLS [54] and Odin [72], the CII and NII lines are included since future missions may target them [4, 73]. There is also an atomic oxygen line at 4.76 THz which was not included in the table for the sake of space. At these higher frequencies spectroscopy is possible so that one receiving unit can resolve several frequencies of interest, within a passband width, 4 GHz in the case of Odin [74]. There is a proposal that the FY-4 series carry sub-mm instruments at 380 GHz and 424 GHz [37]. Another proposal for a GPM partner satellite involves channels at 243, 325, 448 and 664 GHz for ice cloud characterisation [75].

Table 2.1: Table showing the primary (p) and secondary (s) uses of PMR frequencies [69, 70, 6, 71]

Application	1.4GHz	6-7GHz	9-11GHz	18GHz	21-23GHz	37GHz	50-60GHz	89GHz	118GHz	183 GHz	175GHz+
Sea Surface Salinity	p										
Soil Moisture	p	p	p	s	s	s		s			
Sea surface Temperature		p	s	s	s	s					
Sea ice		s		p	s	p		p			
Ice type classification			s	p		s		p			
Cloud liquid water				s	s	p		s			
Water vapour				s	p	s		s			
Wind vector		s	p	s	s	p					
Precipitation (land)				s		p	s	p			
Snow			s	p	s	p		s			
Precipitation (sea)			s	p	s	s	s				
Temperature profiling						s	p	s	p		
Humidity profiling					s			s		p	
Stratospheric Chemistry											p

Table 2.2: Table showing PMR frequencies of products above 180 GHz, obtained via limb-sounding (MLS, Odin) [4, 74, 54, 76, 77, 67]

Product	180-210GHz	230-270GHz	460-500GHz	540-580GHz	620-670GHz	1460-1900GHz	2500-2700GHz
H_2O	183		489, 504	557	624		
N_2O	201		502	578	653		
HNO_3	182	269	494	545			
ClO	204	278	501	575	649		
O_3	206	230-250 267	495 501	545	625		
HCN	177						
SO_2	200, 204				624,649		
CH_3CN	184, 202				625, 660		
^{18}OO		234					
CO		231		576			
O_2			487				2502
CI			492				
HDO			495				
$H_2^{18}O$			489	547			
$H_2^{17}O$				552			
NO				551			
^{13}CO				551			
HO_2				578	650,660		
CH_3Cl					628		
HOCl					636		
HCl					626		
^{81}BrO					625,650		
NII						1460	
CII						1900	
HD							2680
OH							2509,2514

2.1 Theory

Passive microwave radiometry is the detection of electromagnetic radiation emanating from the thermal black body emission of Earth's surface and atmosphere[15, 16] a good overview of the backgrounds of microwave radiometry and radiometers can be found in volumes one and three of a series of books by Ulaby et al. [17, 51].

For a broad overview of what was happening in the PMR research world around 2000 there is a good collection of papers by Pampaloni and Paloscia [78], they include: ocean wind vector, sea surface temperature (SST), soil moisture (SM), sea ice, temperature profiling [T(z)], IWV, CLW, humidity profiles [q(z)], precipitation, stratospheric trace gases and associated errors. Many of these areas have ongoing research. Table 2.1 outlines some the frequencies associated with the above applications. The applications and measuring techniques for oceanography from space are described by Robinson [36, 56]. There is an article by Dong et. al [44] in the Bulletin of the American Meteorological Society which is easy to read and gives an overview of the Chinese meteorological satellite series, including the products expected from the microwave instruments.

The applications of various microwave detectors are discussed in an online handbook [59] and shown in a resolution document by the Space Frequency coordination group, Resolution SFCG 29-1 [67].

2.1.1 Emmisivity

Emissivity of surface targets is governed by the dielectric constant of the material under the target footprint. Peake [15] shows that the emissivity is related to the apparent scene temperature and the dielectric constant determines the emissivity. This means that, given the actual and apparent temperature of a target, the intrinsic properties of the target can be derived for example SM, sea surface salinity (SSS) and surface roughness. The physics governing dielectric slabs can be found in most electrodynamics textbooks.

The term channel is used because in addition to there being several frequencies under consideration, invariably there are also polarisation properties associated with the emission from a target. In the vast majority of cases each frequency band will be detected through both a horizontal and vertical channel and in a few cases 45 degree offset polarisations and circular polarisations are also detected; for example in the Windsat project [18]. The four types of polarisation allow for the four stokes parameters to be measured. These polarisation measurements can allow for extra information to be estimated, for instance surface roughness over the ocean and wind direction. Sometimes, where no polarising effect is expected, only one polarisation channel is used, mainly in the case of atmospheric sounding channels (the gases in the atmosphere have no preferred direction unlike ground targets).

The quality and properties of passband filters have to be taken into account during channel and bandwidth selection. A newer development is the concept of hyper-spectral PMR which uses several different receivers with slightly offset frequency centres. Thus allowing the channel bandwidths to overlap and increase the frequency resolution of atmospheric sounding [21], without increasing the noise by making the filter too narrow.

2.1.1.1 Atmospheric effects

There are several atmospheric effects to take into account. A simple model for loss mechanisms is shown for a soil moisture example in a paper by Jackson [11] which includes atmospheric scattering. Stogyrn introduces models to take the atmosphere into account [16], both the loss from (scattering and absorption) and the contribution (re-emission) to the signal. There is also a component of surface reflected down-welling radiation from the atmosphere as well as from cosmic sources, including the sun [11].

Many studies have been carried out on atmospheric opacity with respect to frequency. Recently, in relation to the Atacama Large Millimetre Array, ALMA, astronomical project, results were presented, for the atmospheric opacity going into the terahertz frequency range, in a paper by Pardo [79]; this same study could be used for analysing the applicability of limb sounders or even imagers in the higher frequency range. Early on 2.65 GHz was proposed as a compromise between galactic noise and atmospheric effects in ocean observation [33].

The ionosphere is also an important consideration in many instances, as it is responsible for the effects of Faraday rotation [80] and refraction. Related to the refraction effect is the path delay effect of water vapour, which has important ramifications in radar altimetry missions. This effect is well modelled by PMR measurements in the K-band for example the Jason altimetry mission has the Jason microwave radiometer (JMR) [55] and more recently the Advanced microwave radiometer (AMR) [81].

The atmospheric transmittance is an important consideration for PMR remote sensing of Earth since, the relatively clear windows needed for microwave surface imagers are limited by the water vapour and oxygen lines in the atmosphere. That is to say that the effects of the atmosphere, clouds and even rain are negligible at the L-Band [17], however the L-band is also popular for commercial applications. That said, there are many PMR applications that take advantages of these atmospheric properties and fall into three broad categories, surface imaging (lower opacity frequencies), Atmospheric sounding (Higher opacity frequencies) and limb sounding (sub-millimetre wavelengths [74]).

2.1.2 Surface imaging

This is a growing field but due to the large dish sizes required at the L and S band in addition to the limited RFI free sections of the electro-magnetic spectrum, which are regulated passive bands, there are several challenges. As previously mentioned the window (low opacity) frequencies are used for surface sensing. The L to K bands have various uses for scientists which are outlined in Table 2.1, the main ones being: SST, SM, SSS, ice classification, sea ice concentration, snow cover, wind vector(SSWS) and precipitation (over land and sea). The applications of the well known imaging sensor, SSM/I, are outlined in a document by Hollinger [82]. Vegetation effects need to be taken into consideration and in some cases can be measured via PMR imagers.

One of the main advantages of microwave imagers over their infra-red counterparts is the ability to measure SST, precipitation and land temperature through clouds, smoke and dust [12, 83] as well as SM through vegetation. Two typical surface imagers that are well established in the scientific community are AMSR-E [2] and TMI [84].

PMR often work well in combination with other sensors like scatterometers, e.g. in the case of surface roughness the roughness parameter is difficult to infer via purely passive means. The scatterometer estimate of surface roughness over the footprint in turn allows the improvement in the accuracy of the target apparent temperature estimate and hence dielectric constant. The actual temperature of the target is sometimes provided by other sensors such as IR, or estimated through polarimetry.

There is a review of the selection process for a microwave imager proposed by L'Abbate et al. [61]. Several of the considerations are presented there.

2.1.3 Atmospheric sounding

The more opaque a substance is the more radiation it emits; even though the surface can't be viewed through an opaque atmosphere, the signal from the opaque atmosphere itself can be analysed. Since as opacity increases, the depth or, in the case of the Earth's atmosphere, pressure from which the signal emanates decreases. An overview of the physics can be found in chapter 17 of Ulaby et al. [51].

Since the opacity is due to scattering and the pressure is related to the number of scatterers per unit volume, there is a relationship between the opacity and pressure as well as frequency. Given this relationship you can vertically profile an atmosphere by comparing the antenna temperatures between several closely spaced frequency bands, over the frequency band where the opacity is rapidly changing. Each frequency band will have an associated weighting function with respect to atmospheric pressure.

The humidity theoretically could be profiled at both the 22 and 183 GHz line, however the 22 GHz H_2O line is too low above the the baseline water signal to be able to profile the atmosphere sufficiently. The stronger peak at 183 GHz allows humidity profiling in spite of the higher atmospheric opacity [85, 86]. The symmetry of the peak is also taken advantage of with humidity profilers. However, the 22 GHz line is used extensively in IWV measurements of the atmosphere, especially in association with radar altimeters where the path delay parameter is needed. Although recently 90 GHz+ channels are being proposed for path delay in coastal regions [87]. The AMSU-B instrument was designed to sound humidity at the 183 GHz line [88]

The Oxygen complex from 50-60 GHz is used extensively for temperature profiling of the atmosphere. The 118 GHz line is also used but to a lesser extent due to the higher opacity of the atmosphere, the greater effect of clouds and also the fact the technology is simpler and better validated for the lower frequency. An example of a well used instrument that uses the 60 GHz line complex is AMSU-A [52], another launched this year is ATMS on NPP [89]. HAMSR, an airborne platform developed by NASA, relies heavily on sounding techniques [90]. The channel selection for a temperature sounder is described in a paper by Chakraborty et al. [91].

There are several trade-offs that need to be considered with regards to atmospheric sounding. For instance in NWP, due to the fact the vertical resolution is 3 km, there is not much need in the models for a greater horizontal resolution than 50 km. Vertical resolution in turn is limited by the fact that a narrow filter has a narrow bandwidth and hence a relatively large $Ne\Delta T$. So higher vertical resolutions will have higher uncertainties.

Many authors have described the use of atmospheric sounding for weather applications, [7, 92, 25, 24, 93].

2.1.4 Limb sounding

Several high quality Earth observing atmospheric limb sounders have gone up including MLS on UARS, SMR on Odin and MLS on Aura [54]. Several chemical species can be monitored, as is evident from Table 2.2 and the relatively high vertical distribution ability allows for 3-D topographical maps of the atmosphere to be made, especially if combined with non limb sounding observations through the atmosphere. The mm and sub-millimetre have several lines of interest to scientists. The other measurement of interest is the characterisation of ice clouds in the sub-mm, which complements IR instruments.

Limb-sounders have relatively low noise because the background sky is cold, as opposed to sounders that have the up-welling radiation from Earth. The poor horizontal resolution is due to similar reasons that the vertical atmospheric profiles are low resolution since the methodology is similar. Future mm and sub-mm instruments are discussed by Klein et al. [94]. A technological needs review for a European limb-sounder was carried out in 2000 [95].

2.1.5 Summary of PMR information types

A summary is presented in table 2.3 showing the three basic types of radiometers, namely imagers, sounders and limb sounders.

There are other related instruments beyond the scope of this dissertation, including GPS occultation for total electron content (TEC) measurements and reflectometry which yields sea state information.

2.2 Introduction to Radiometers

The field of radiometry is constantly progressing, helped along by the telecommunications industry. The development of solid state components is making the development of microwave instruments, lighter, cheaper and needing less power.

Table 2.3: Tradeoff table summarising the types of PMRs

Instrument Type	Advantage	Disadvantage
Imagers	2-D Pictures, reasonable spatial resolution	No vertical info, Needs window frequencies, SM estimates unreliable
Sounders	Vertical profiles, Useful for NWP, 3-D mapping	Poor vertical resolution, Poor sensitivity, Several channels needed
Limb-sounders	Upper Atmosphere, High veritcal resolution, Trace gasses, Compact antenna	Poor horizontal resolution, Opaque atmosphere, Minimum altitude, Advanced technology

To begin, the basic operations of a Radiometer shall be discussed along with the achievable resolutions. The basics of passive microwave radiometry are covered in a textbook series by Ulaby et al. [17, 51].

2.2.1 Types of Radiometers

There are several types of radiometers, both in the front and back ends, the main types of front ends are real aperture horns, often with parabolic reflectors, and aperture synthesis arrays (InSARad).

There is usually a calibration system involved; In the case of offset parabolic reflectors, operating in the total power radiometer mode, this normally includes a cold sky reflector and a warm target directing a calibration signal into the feed horn.

After the feed-horn and orthomode transducer, since the signal of interest is so weak, there is usually a low noise amplifier (LNA). The lack of suitable LNAs for space missions was one of the primary reasons for the slow adoption of sub-mm wavelength missions. Due to the fact that most frequencies in the microwave region are usually too high to be directly detected, a super-heterodyne technique is used. The gigahertz revolution currently under-way in telecommunications, this means that the highest frequency that can be directly detected is increasing.

The first gain element has the biggest effect on the system noise so good LNAs are essential for quality scientific data. The early radiometers did not have an LNA and the first element in the gain chain was the mixer which lead to high system noise. In the THz regime the mixer has been designed as a quasi-optical diplexer, in the case of the Aura MLS; such a front end is described by Gaidis et al. [96].

The system can be sensitive to changes in the thermal conditions, leading to the need for careful consideration when choosing the calibration system and doing occasional pitch manoeuvres to check that the cold sky temperature is in agreement with the calibration cold sky temperature. The radiation of the reflector, heated by the sun, can affect the data [97, 98].

The polarization measurements can be affected by cross-polarisation contamination, and the design should endeavour to minimize cross-polarisation especially in the case that the polarimetric measurements are of interest. Similarly, for cross talk (coupling) between horns in an array on a feed-deck or otherwise.

2.2.1.1 Calibration and validation methods and considerations

A good description of various radiometer back ends can be found in Chapter six of Ulaby et al. [17]. The three main operation modes (calibration methods) that are employed include total power radiometers (TPR) an example of which is Windsat [18], Dicke switch radiometers (DR) such as the Swedish Odin satellite [72] and noise injection radiometers (NIR) exemplified by ESA's SMOS mission [99]. These methods all involve explicit calibration. An academic demonstrator of the various schemes was described by Tarongi et al. [100].

The earlier missions favoured the DR calibration since the stability of the radiometers was not good and drift variations had to be corrected for. However, the ISRO defended their relatively recent use of DR in a paper by Misra et al. [101]. Due to the static nature of path delay radiometers on Altimetry missions DR were generally used. It is only recently that end to end calibration is being proposed for Jason-3, as the largest source of altimeter error is due to the PMR segment.

The telecommunications revolution has led to the development of stable radiometer systems allowing for less frequent calibrations and allowing TPR calibration systems to dominate modern radiometry missions [102]. The Chinese instrument MWRI attempts a true end to end calibration [38]. Other missions check the end-to-end calibration occasionally via manoeuvres where cold space is viewed via the main antenna.

Apart from the calibration schemes a good validation program is essential both prior to and following a space mission. A good validation mission engenders trust in the instrument and data by the scientific community, allows for appropriate corrections to be carried out early and monitors short and long term shifts in the performance of the instrument. Corrections include those for bias and scan effects [103]. An example of a validation document for an extensively used PMR series, SSM/I, can be found in a document by Hollinger from the Naval research laboratory [82], where results for windspeed, total water content and others have been compared to ground-truth.

Prior to the the mission, airborne [104, 105] and ground based [106] validation campaigns must be carried out, as specifications like $NE\Delta T$ and beam-width cannot be directly tested in orbit [88, 28]. After the mission is launched ongoing validation experiments should be carried out and models tested as shown in a paper by Stankov et al. [107]. Other validation procedures are described in a paper by Muraleedharan et al. for the MSMR instrument [108] and for an InSARad instrument in a paper by Torres et al. [109].

Extensive ground truth networks over calibration or validation areas would be excellent but given the cost of such a network, the size of these are limited. The spatio-temporal mismatch can be a large stumbling block for such validation campaigns, since small scale detail is missed by the footprint average [110], and the position of the ground based sensor might not be the same as the position of the emitting target. An example of this is the case of SST; the temperature sensor is often a metre or more below the surface while the microwave radiation emanates from the top few centimetres [56]. Sensitivity to ancillary data error is another consideration [111], as well as the local environment and the model being used [62].

There are other methods of implicit calibration such as statistical vicarious calibration; this is where areas that are assumed to have a statistically non varying temperature, such as the Amazon jungle or Antarctica, are used as the hot and cold source and the instrument is calibrated using statistical methods [55, 112, 113]. This method is used to validate the calibration system in-orbit [38].

Inter-calibration between satellites in a series [114] and across platforms [70, 115, 60] is important to ensure continuity of reliable data sets. Some tandem missions have been set up in the past to ensure such continuity [116].

The other important reason for validation is to identify how much radio frequency interference (RFI) (out of band or otherwise) is affecting the signal. For instance early in the SMOS mission it became apparent there was a great deal of 1.4 GHz RFI over Spain, several months later the RFI was vastly reduced due to algorithms to identify it and due to legal measures [117, 118, 119]. Sometimes there is local RFI from the spacecraft or the instrument itself [120]. Occasionally, RFI can be due to harmonics, e.g. RFI in 1.4 GHz passive band due to poorly filtered 700 MHz transmitters.

SMMR used a DR calibration procedure between a cold sky horn and a dish illuminating horn[121]; the use of two separate horns led to inaccuracies being introduced, due to differences in the physical states of the two horns and therefore different levels of system noise. This lead to a lack of trust in SMMR data, even through several issues were identified and corrected for [122, 123]. The same weakness has been identified in path-delay radiometers.

2.2.1.2 Real aperture

A real aperture refers to an antenna where the aperture is filled either by a horn or an antenna dish. The biggest advantage real aperture radiometers have over InSARad is a good radiometric resolution, $\sim$0.1 K in current instruments.

The fact that the reflector can be designed to accommodate multiple octaves of frequencies is another advantage over InSARad. A report by the Naval Research Laboratory in the USA sets 20 GHz+ as the limit favouring real aperture and $<$5 GHz for InSARad designs [124].

Due to the fact that the beam must be clear of obstructions that change the temperature of the incoming signal; the most popular choice is an offset parabolic dish antenna. The use of secondary reflectors is generally avoided for simplicity and other considerations.

The maths and considerations of offset parabolic antennas are described in a review by Rudge [35]. He describes the issues of cross-polarisation, beam width, aperture efficiency and configurations in relation to offset parabolic antennas. The design of the feed horn is also important [125].

Real apertures need to be mechanically scanned across a swath. Several papers have been written about antenna design for missions [126, 127].

2.2.1.3 InSARad

A relatively new concept in microwave radiometry is the use of Interferometric synthetic aperture Radiometry (InSARad) [128]. Where real apertures have a filled aperture, InSARad involves the use of sparse or thinned arrays of receivers and performs aperture synthesis digitally. This process of cross-correlation makes the system redundant to a single receiver malfunction, resulting only in a minor degradation in sensitivity. In spite of the weakness of lower radiometric sensitivity the InSARad has the advantages of longer integration times, due to synoptic scanning, as well as vegetation canopy stratification using the multi angle information obtained as the satellite flies over a target. The low sensitivity can be improved by averaging over time for slowly varying applications such as sea salinity [19, 20].

Although the deployment of a large aperture array after launch is usually simpler than that of an equivalent diameter real aperture dish, the overall diameter requirement remains approximately the same as in the real aperture case.

That said, InSARad can be significantly lighter and easier to launch than their equivalent real aperture counterparts allowing longer baselines to be sent out for the same mass. However, the complexity and processing needs of the cross-correlation components lead to longer development times.

One of the earlier InSARad tried to improve radiometric sensitivity by using a hybrid antenna with an array of real rod antennas parallel to each other (ESTAR [71]) but this does not offer favourable integration times or multi-angle methods. The applications of ESTAR are presented in a paper by Le Vine [80, 105, 20].

The SMOS mission by ESA is currently validating the InSARad concept [129, 19]. However, the SMOS concept is plagued with RFI issues and several mechanisms are being developed to deal with the wide area effect of strong RFI sources inside InSARad FOV [117]. The Chinese have been investigating the concept since the mid '90s [130] and have built a demonstrator at Beihang university [131].

The use of InSARad in conjunction with the sub-mm regime has been proposed for atmospheric limb sounding from higher orbits for more continuous coverage [73].

2.2.2 Resolution

There are three types of resolution that need to be considered for PMRs remote sensing namely; spatial, temporal and temperature resolution. These factors have to be taken into account along with frequency selection in trading-off an instrument design for a specific purpose. For wind vector determination temperature sensitivities of 0.1 K are needed. The orbit selection has an effect on each of the resolution types.

2.2.2.1 Spatial

Spatial resolution is primarily governed by the diameter of the aperture and the altitude of the orbit. The aperture diameter determines the level of fine detail you can extract from the data. At the C-band (6.9 GHz) for a 10 km nadir resolution from 500 km you need a ~3.2 m dish and at the L-band (1.4 GHz) the aperture needs to be ~15 m for a 10 km resolution on the ground at nadir. 10 km is a figure that is useful for scientists in several fields especially in the case of SM [11] (farm size) and oceanography (eddy size) [56].

The need for large antennas is relaxed at higher frequencies due to the inverse proportionality between aperture size and resolution. Occasionally, other trade-offs come into play, for example in temperature profiling in NWP the low vertical resolution ~3 km relaxes the horizontal resolution requirement to 50 km for weather models.

2.2.2.2 Radiometric

Radiometric resolution refers to the ability to resolve changes in temperature of the scene with certainty. Radiometric resolution is closely linked to radiometric sensitivity. So the number of antenna temperatures possible over the dynamic range of the radiometer is determined by the radiometric resolution.

To increase integration time and therefore radiometric sensitivity cross track scanning, as opposed to conical scanning, is used on the AMSU series as well as many other sounders [132].

Even though cryogenic radiometers can be used on ground based radio telescopes, the need for cryogenic fluid increases the cost of the launch of the PMR and limits the life of the radiometer by the amount of fluid available. Although the SMLS has a proposed cryogenic receiver [133], the cost-to-benefit in most cases does not justify the use of SIS (Superconductor-insulator-superconductor) components.

Sometimes if the temperature changes slightly relative to the radiometric resolution over a distance there is a trade-off with spatial resolution; increasing the spatial resolution might not reveal more detail, since the sensitivity of the radiometer is insufficient, any changes in temperature will fall within the uncertainty bounds.

The equation governing the radiometric resolution is given by 2.1 [17], where T_A

refers to the scene temperature and T_r refers to the system temperature of the radiometer;

$$Ne\Delta T = \frac{T_A + T_r}{\sqrt{B\tau}} \tag{2.1}$$

From this equation it becomes apparent why quality LNA's are so important as they reduce T_r. The integration time, τ, is often constrained by the orbit of the satellite and scan type. The bandwidth, B, is constrained by the occurrence of RFI in the field of view. Frequent recalibration is needed to monitor drifts in T_r.

2.2.2.3 Temporal

The temporal resolution refers to the frequency of re-measurement of a scene of interest. Since subsequent satellite tracks are often thousands of kilometres apart, especially in polar orbits, a swath width that is the same as the distance the sub-satellite tracks are apart would allow a nearly global daily revisit time in the case of a sun synchronous orbit.

However, wide swaths require viewing angles that are far from nadir leading to worse spatial resolution, atmospheric effects and higher scan rate especially in lower orbits. The higher the scan rate the less integration time is available leading to worse sensitivity by Equation 2.1.

The swath can be scanned mechanically or digitally. The scan should obtain data at all footprints along the scan path such that all footprints in the swath width are measured at a rate greater than the Nyquist sample rate (oversampled) both along and cross track.

The various scan types include cross track (mechanical scanning in the across track plane), conical (mechanical scanning around the nadir axis at a constant angle of incidence), electronic scanning (digitally scanning by using phase delay elements in a receiver array), synoptic scanning (cross-correlating the signals of a receiver array and digitally subdividing the entire field of view) and limb sounding (mechanically scanning the planetary limb vertically). There is of course the nadir viewing geometry which is often used in Radar altimetry missions.

Table 2.4: Table of pros and cons of scan types

Scan Type	Advantage	Disadvantage
Nadir looking (Non-Scanning)	Simple, no moving parts	Narrow Swath
Cross-track	Moderately simple, Wide swath	Changing view angle through atmosphere, Short integration time
Conical	Constant angle of incidence minimizes geometric effects, Wide swath	Rotating dish prone to fail Complex construction, Short integration time
Electrically	No moving parts, Thinned array	Complex, Scanning required
Synoptic	No moving parts, Entire swath width in view, Longer integration time	Complex, High sample rate, Poor NeΔT

The pros and cons of each scan type are outlined in Table 2.4. Other considerations, like the continuous operation of the PMR, can arise since power concerns can often cause an instrument to only be used part-time. Occasionally in oversampled cases the H/V polarisation measurements can be done on alternate scans [101].

2.2.3 Geostationary considerations

Microwave atmospheric sounders are being planned in the form of GIMS and GeoSTAR as well as some real aperture options [134, 46, 135, 94]. Geostationary Earth Orbit (GEO) imagers and sounders will have poor spatial resolution due to the distance that GEO is from the surface of Earth, the required aperture at 50 GHz is in the order of 5 m to be useful. However, the integration time can be as long or short as the user requires, synoptic scanning over the entire Earth's surface avoids the explicit need for moving parts and allows real time monitoring of the atmosphere. The radiometric resolution might be constrained by the sensitivity of InSARad.

If a big enough array is sent up to GEO to overcome the spatial resolution limitation then the limitations of temporal resolution and integration time won't affect the system like in the Low Earth Orbit (LEO) case. The GEO sounding options were looked at by Blackwell [21].

2.3 Trade-offs

Several trade-offs have to be considered in relation to PMRs, these include:

- Complexity and size (scientific use) vs Weight (cost)
- Complexity (scientific data) vs power needs (solar panels/battery)
- Spatial resolution vs Sensitivity
- Integration time (scan rate) vs Revisit time (swath width)
- Spatial resolution (frequency) vs Bulk properties of a target (SM/Canopy)
- Temporal resolution (averaging) vs Sensitivity
- Swath width vs Resolution (Geometric effects)
- Single horn (weight/space) vs Multi horn (Sensitivity)

Table 2.4 shows the advantages and disadvantages of various scan types. Table 2.5 shows the advantages and disadvantages of various methods of Earth observation remote sensing with respect to PMRs. Table 2.6 outlines some of the issues of Real and InSARad system, then the pros and cons of orbit types are outlined in Table 2.7. Some quantitative aspects of a trade-off study for PMRs are presented by Gaiser et al. [124].

2.4 Techniques in Passive Microwave Radiometry

Although passive microwave radiometry has been around for decades there are still strides being made in developing new techniques, in addition to InSARad

Table 2.5: Table of pros and cons of types of Remote Sensing from space as compared to PMRs [22, 19]

Instrument Type	Advantage	Disadvantage
Optical	High resolution GEO useful, Easy interpretation	No "invisible" information, Clouds and night, narrow swath, SM estimates unreliable
Infra-red	Moderate resolution, GEO, plant stress, Hyperspectral data	Clouds and aerosols, Detection of SSS and SM, Complex interpretation
Radar	Cloud penetrating, High resolution (SAR), Roughness estimates, Compact antenna	Power hungry, Complex, Narrow swath, More sensitive to vegetation, Frequency spectrum regulation
Passive microwave radiometry	Unique information (SSS), Power needs, Wide swath, Cloud/aerosol penetration, Vegetation penetration	Low resolution/Large antenna, Limited applications, GEO difficult, Complex interpretation, RFI issues Dependent on target roughness

Table 2.6: Table of pros and cons between InSARad and Real Apertures

Aperture type	Advantage	Disadvantage
Real Aperture	Good NeΔT Conical scan Heritage	Large dishes difficult to launch, Mechnical scan
InSARad	Long baselines easy to deploy, Synoptic scan	Complex to develop, Computationally heavy, Poor NeΔT

Table 2.7: Table of pros and cons between Orbits

Orbit type	Advantage	Disadvantage
Low Earth Orbit	Good spatial resolution, Constant geometry	Narrow swath, Poor revisit time, High cycle rate
Near-Equatorial Orbits	Quick revisit time, Diurnal effects	Limited coverage, High cycle rate
Low-Med Earth Orbits	Wider swath, Slower speed, Better sensitivty (τ)	Larger Aperture, Poorer resolution
Elliptic Orbits	Good for high latitude, Combined benefits	Non-uniform geometry, Varying speed
Geostationary Orbit	Quick revisit time, Low cyle rate, Fixed communications	Poor resolution, Bigger launcher, Changing geometry (limb)

and GEO sounders, there are hyper-spectral sounders with 100+ channels discussed by Blackwell [21, 136], along with digital beam sharpening [137]. The aliases of the moon and the sun in an InSARad FOV have been proposed as calibration sources [106]. The Chinese have come up with a great idea of externally calibrating InSARad with their "rotating" GIMS concept which also attempts to maximize the number of baselines while minimising the number of antenna elements [46]. More traditional techniques include the use of neural networks for parameter extraction [42, 70]. Complementary methodology, the use of a PMR alongside another type of remote sensing instrument, is widely used. For instance, in case of the Aquarius instrument on SAC-D, a scatterometer is used to estimate the surface roughness within the footprint, allowing for a more accurate salinity retrieval. The IR and MW can be used to get a global picture of SST, with higher resolution in cloud free regions [83, 12]. Synergistic models using optical, IR and MW sensors in combination are coming to the fore in several fields [25]. In weather prediction MW sounding complements IR sounding in cloudy or aerosol affected areas. Weather centres already consider IR and MW sounders complementary and one cannot be used alone and still achieve the same performance as in combination [24]. Since the 60's radars and radiometers have been used together to characterise rain showers and wind-speed [138, 139]. Radar radiometer synergy is useful in the case of soil moisture as the wetter ground is more reflective. A radiometer can help characterise whether the reflection is due to SM or otherwise, conversely radars can characterise the surface roughness for SM or SST parameter extraction. Path delay estimates are obtained via PMRs for most radar altimetry missions [140, 55, 141, 142, 143, 81]. These nadir viewing radiometers can provide inter calibration data in spite of having a poor revisit time.

2.4.1 Airborne systems

Prior to a space mission, airborne validation campaigns must be carried out to check the instrument meets the scientific and validation specifications [104, 105]. After launch airborne systems are used to test and validate Space-borne PMR data, such as in the case of CLPX (Cold Land Processes eXperiment) with AMSR-E [107], the water content of the AMSR-E estimates were off by as much as a factor of 5. Airborne sensors are often good in their own right, HAMSR, cross-track scanning sounder, is used to improve the resolution of AMSU measurements around hurricanes [27, 28, 29]. Airborne systems that can give more immediate results should be considered as a test-bed for space-borne instruments as the test campaign can give valid scientific data, allowing parameter retrieval algorithms to be developed and tested before the space-borne instrument is launched, adding to the publication count of South Africa.

Chapter 3

Overview of Passive Microwave Radiometers

Before a new mission can be proposed, the missions that came before must be studied and lessons from them considered when designing new instruments. The results of PMR literature survey to date (November 2011), of microwave radiometers worldwide, are concisely presented.

The origins of Earth observing PMRs date back to the origins of Radio Astronomy, with Jansky's observations in 1931, and subsequent observations of atmospheric effects on astronomical signals. Since the underlying techniques between Radio Astronomy and space-borne PMRs are the same, much of the technology and techniques are portable between the two fields.

The past, present and future instruments are looked at with an eye to proposing future South African missions. Other space borne applications, such as astronomical and interplanetary, are also looked at briefly. The reason for the fairly comprehensive review, including Appendix B, is to cover the future instruments that can follow-on from a demonstrator instrument.

There is a review by Thies and Bendix [144] that covers many of the current and future meteorological instruments sent up by various countries. There is another review by Pujara et al. that describes the key PMR instruments from the antenna design perspective [102]. Another overview by Gaiser et al. outlines the considerations of PMRs for the Naval Research Laboratory (NRL) in the USA in the mid 1990's [124]. Several textbooks have been written with sections on PMRs [17, 51, 36, 56, 145, 146].

3.1 Historical PMR Instruments

Spaceborne passive microwave radiometry has been around for 50 years, since the Mariner-2 mission to venus in 1962, and for Earth remote sensing since 1968, on the brief orbit of Cosmos 243 [7]. Some of the earlier missions are described in reviews by Tomiyasu [22] and another by Njoku [6]. There was a twenty year gap during the 80's and 90's where relatively few microwave radiometers were developed and focus on Infra-red (IR) sensors was carried out. Recently a more balanced approach across the spectrum is being enacted.

3.1.1 Microwave Sounders

Sounding radiometers had their beginnings in the NEMS instrument on Nimbus-5 [147]. There have been several instruments sent up, both temperature and humidity sounders. Several of the instruments are described later on in the first instruments and meteorological series sections, Section 3.3 and B.1 respectively: e.g. the HSB, SSM/T(2), MWTS and MWHS.

3.1.1.1 Microwave Sounding Unit

This instrument was the forerunner of the AMSU instrument. The microwave sounding unit (MSU) was launched, for the first time on the TIROS-N satellite in 1978, as part of the TOVS package. Eight more MSU were launched until NOAA-14 in 1994, the last MSU is still in operation, but at a degraded quality since 2004 [148]. Both the TOVS and ATOVS (AMSU) systems are managed by NOAA. The data has been widely used for NWP and science, including to verify IR sounder data after going through cloud clearing algorithms in a paper by Andersson [92].

3.1.2 Microwave Imagers

Imaging radiometers in their current form were launched in the form of the SMMR [121] and later SSM/I. The recently retired AMSR-E mission is an excellent example of a highly successful imaging radiometer along with TMI. Each successive mission built on the weaknesses of the prior missions. One such improvement was the adoption of conical scanning to minimise the geometric effects of the scan.

One of the earliest imaging missions that scanned electrically, as opposed mechanically, is the electrical scanning microwave radiometer (ESMR) on Nimbus 5 at 19.35 GHz. Signal losses in the beam control system and high noise level led to the discarding of the ESMR concept after the Nimbus-7 mission.

The Skylab had an L-band phased array instrument, S-194, that was used to verify soil moisture detectability, and a shared instrument, S-193, which could be operated as a radiometer at 13.9 GHz. Both instruments had apertures of the order of 1 m [149]. However, the experiments were run intermittently and only for short periods and therefore were of limited scientific use.

3.1.2.1 Scanning Multichannel Microwave Radiometer

The SMMR instrument was launched on two satellites, the short-lived Seasat-A and Nimbus-7. The SMMR was switched off on consecutive days due to power constraints. The SMMR had a weakness in that the calibration of the radiometer was not end to end, this meant that differences in the physical state of the main feed horn and the sky feed horn would induce an error in the calibration, as well as other issues [123, 122, 150]. Although, due to the low levels of RFI at the time, SMMR is used as a baseline for RFI studies.

The products from SMMR included sea ice classification, IWV, CLW, SST and wind speed, however calibration difficulties hampered the estimate retrieval accuracy [49].

3.1.3 Summary of the Historical Instruments

Table 3.1 is a survey of the past instruments from the early players in the space race. The technology development now, for a South African instrument, should be a great deal easier, given the advances in technology and the literature describing past instruments from other countries. An occupancy plot showing the use of the various frequency bands, including the frequency range explosion in 1991 due to improvements in technology, over time is shown in Figure 3.1. Oxygen temperature profiles and IWV have been recorded since 1979. 2.5 THz was introduced on Aura in 2003.

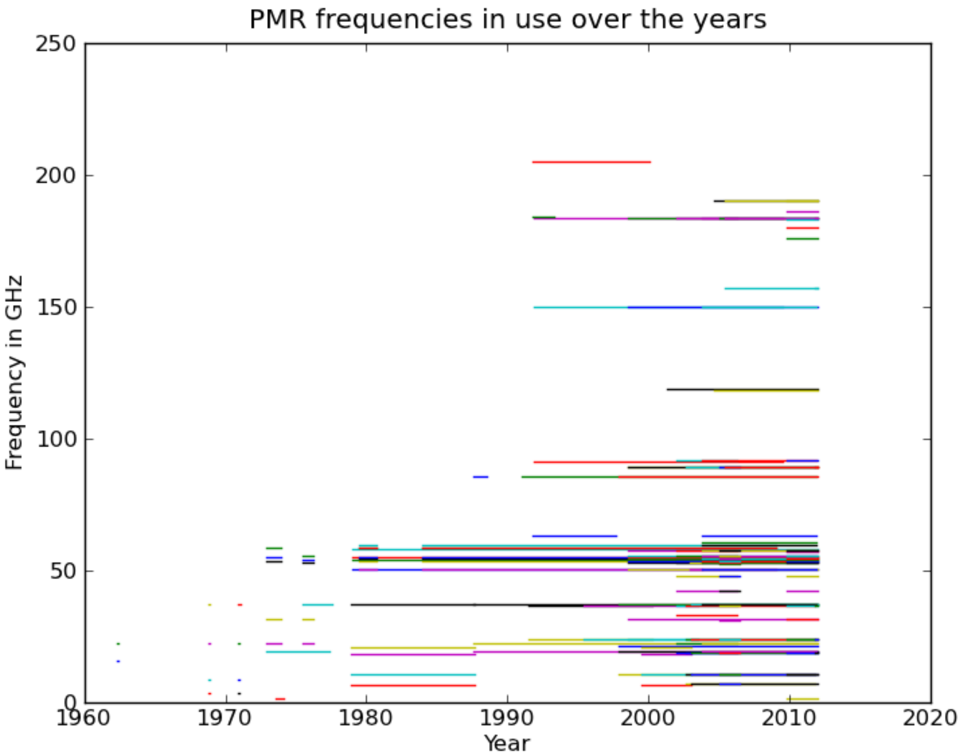
Ambitious missions were attempted but some, like AMSR and SeaSAT-SMMR [151, 121], failed due to power failures of the spacecraft bus shortly after launch. Others, like MIMR for Metop [152, 153], were never launched as other nations built superior instruments before development was complete, although the experience was carried forward to new missions e.g. EGPM [154]. Many more never made it off the drawing board due to complexity [155]. However, useful science was done on the short-lived missions [156]; AMSR attempted to characterise the use of oxygen sounders with a conical scanning geometry, leading up to SSMIS [151].

3.2 Key Instruments

The following two sections provide an overview of many of current radiometers in space and give a broad overview of some of the most prominent instruments in the field of passive microwave radiometry. The THz have been recently used for Earth observation, from the microwave side of the spectrum, on Aura's MLS terahertz module. An overview of this developing field can be found in a paper by Siegel [4] and he later goes on say that the "Golden age" of THz instruments

Table 3.1: Table showing some historical key instruments [5, 4, 6, 7]

Dates	Satellite/ Mission	Principal agency	Instrument acronym	Frequencies [GHz]	Swath Width/ pixel resolution [km]	Main parameters
1962	Mariner-2	NASA	MWR	15.8, 22.2	Planetary/1300	Limb darkening
1968	Cosmos 243	Roscosmos	-	3.5, 8.8, 22.2, 37	13/13	Atmospheric water content
1970	Cosmos 384					SST, sea ice
1972	Nimbus-5	NOAA	ESMR	19.3	3000/25	Rain over sea, Sea ice
			NEMS	22.2, 31.4, 53.6, 54.9, 58.8	200/200	Total water content
						Temperature profile
1973	Skylab	NASA	S-193	13.9	180/16	Sea winds, precipitation
			S-194	1.4	115/115	Soil Moisture
1974	Cosmos 669	Roscosmos	-	300-5000		Limb sounding, Astrophysics
1975	Nimbus-6	NASA	ESMR	37	1300/25	Sea ice, Ice type
			SCAMS	22.2, 31.6, 52.9, 53.8, 55.4	2700/150	Atmos. water content
						Temperature profile
1978	Tiros-N	NOAA	MSU	50.3, 53.7, 55.0, 57.9	2300/110	Temperature profile
1978	Nimbus-7	NASA	SMMR	6.63, 10.69, 18, 21, 37	800/18-89	SST, Wind speed, sea ice
1978	Salyut-6	Roscosmos	BST-1M	200-14000	(1.5m mirror)	Astrophysics
			KRT-10	0.42, 2.5	(10m antenna)	Meteorology/Astrophysics
1979	5D F4	DMSP	SSM/T	50.3, 53.2, 54.3, 54.9, 58.4, 58.8, 59.4	1500/174	Temperature profile
1979	Cosmos 1076	Roscosmos	Device-ν	3.53, 9.37, 22.2,37.5	18/18 @ 37.5GHz	SST, Wind speed
1979	Cosmos 1151		Device-π	9.37	80/80 @ 3.53GHz	Water vapour in clouds
1979	Bhaskara-1	ISRO	SAMIR	19.1, 19.6, 22.2	1000/150	Atmos. Water, Ocean state
1987	MOS-1	JAXA	MSR	23.8, 31.4	317/30	Atmos. water, Sea ice
1987	F-08	DMSP	SSM/I	19.35, 22.2, 37, 85	1400/14 -45	Rainfall, Atmospheric water
1988	Okean-01	Roscosmos	RM-08	37	550/15	Ice monitoring
1989	COBE	NASA	DMR	31.5, 53, 90	7^o	Astrophysics CMB
			FIRAS	30 - 3000	7^o	
1991	ERS-1	ESA	ATSR-MWR	23.8, 36.5	20/20	integrated water content
1991	UARS	NASA	MLS	63, 185, 203	limb sound. 0.4^o	upper atmospheric chemistry
1992	TOPEX/Poseidon	NASA/CNES	TMR	18, 21, 37	30/22-42	Radar path Delay



* The sub-mm frequencies are excluded for space and clarity.
[The colours have no particular significance except to show
when different missions use the same frequency.]

Figure 3.1: Plot showing the various times that PMR frequencies have been recorded over the years.

has arrived [73].

A summary of the recent key instruments are given in Table 3.2. The following sections expand a bit on the more important instruments. Some are described later in Appendix B, like SSM/I and AMSR-E, as they are part of series' of PMRs.

3.2.1 TRMM Microwave imager (TMI)

The Tropical Rainfall Measurement mission (TRMM) is described in a paper by Kummerow et al. [157]. Wentz et al. did some work on the post launch calibration, mentioning that TMI has two feed horns, one for the 10.7 GHz channels and the rest through the other [84]. TMI has been useful to the South African oceanography community allowing detection of anomalous ocean currents, with the cloud penetration allowing the continual monitoring of SST unlike for IR instruments. The low orbit allows higher spatial resolution and more features to be resolved. The radiometric sensitivity is good enough to detect diurnal variation in SST [12]. Other products include wind-speed [158], rainfall [159], TPW, CLW, ice and snow.

The addition of the 10.7 GHz channel over the SSM/I instrument led to the ability to use data even when moisture or rain were in the field of view and to characterise even the heaviest rainfall. TRMM also carried the first rain radar to be carried in space. The emphasis on rainfall lead to the phrase "flying rain gauge" with respect to TRMM. South African climatology research groups use TMI rainfall estimates. TMI has a weight of 65 kg and power needs of 50 W, all channels below 40 GHz have a sensitivity better than 0.5 K.

Inter-calibration between TMI and SSM/I for precipitable water is described in a paper by Nativi and Migliorini [160] and for path delay by Zlotnicki and Desai [115]. TMI is still in operation 14 years after launch. Corrections to calibration errors are still being implemented, like the correction by Biswas et al. in 2009 [161].

Table 3.2: Table showing recent and current key instruments [2, 3, 4]

Dates	Satellite/ Mission	Principal agency	Instrument acronym	Frequencies [GHz] (channels)	Swath Width/ pixel resolution [km]	Main parameters
1997	TRMM	NASA	TMI	10.7,19, 21, 37, 85.5	760/4-35	SST and precipitation
1999	Oceansat-1	ISRO	MSMR	6.6, 10.65, 18, 21	1360/40-120	SST, Sea-Wind speed
2001	Jason-1	NASA/CNES	JMR	18.7, 23.8, 34	30/22-42	Path Delay
2001	Odin	SNSB	SMR	118, 490-500, 540-580(3)	ls.14-100/1.5	Limb sounding, Astrophysics
2001	Meteor-3M	Roshydromet	MTVZA	18.7, 22.2, 33, 37, 42, 48, 52-57 (10), 91, 183(3)	2600/12-75	T(z), q(z), precipitation, CLW, TPW, SSWS
2002	Aqua	JAXA	AMSR-E	6.9,10.7, 18, 23, 37, 85	1400/3.5-43	SST, SM, windspeed
		NASA	AMSU-A	23.8, 31.4, 50-60(12), 89	1690/40	Atmos. profiling
		INPE	HSB	150, 183(3)	1650/13	Humidity profiling
2002	Enivisat	ESA	MWR	23.8, 36.5	20/20	Path Delay
2003	F-16	DMSP	SSMIS	19, 22.2, 37, 50-60(7), 60-63(6), 91.7, 150, 183 (3)	1700/10-55	T(z), q(z), SSWS, TPW, CLW, Sea ice, SM, land temp
2003	Coriolis	USA DoD	Windsat	6.8, 10.7, 18.7, 23.8, 37	950/8-39	Wind vector
2004	Sich-1M	Roscosmos	MTVZA-OK	6.9, 10.6, 18.7, 23.8, 31, 37, 42, 48, 52-58 (10), 89, 183 (3)	2000/8-112	T(z), q(z), Precipitation, CLW, TPW, SSWS, SST
2004	Aura	NASA	EOS-MLS	183,500,2500	ls.10-100/2-8	H_2O, Trace gasses
2006	Metop-A	EUMETSAT	MHS	89, 157, 183(2), 190	2000/16	Humidity profiling
		NASA	AMSU-A	23.8, 31.4, 50-60(12), 89	2000/50	Atmos. profiling
2008	Jason-2	CNES/NOAA	AMR	18.7, 23.8, 34	26/14-26	Path delay
2008	FY-3A	CAST/NSMC	MWRI	10.65, 18.7, 23.8, 36.5, 89.0	1400/10-70	SM, Rain rate, Atmos. water, Sea Ice
			MWTS	50.3, 53.6, 55, 57	2100/60	T(z)
			MWHS	150, 183.31(3)	2700/15	q(z)
2009	SMOS	ESA	MIRAS	1.4	2000/45	SM, SSS
2011	Megha-Tropiques	ISRO	MADRAS	19, 23, 37, 89, 157	1700/6-40	Rain, CLW, TPW, Cloud Ice
		CNES	SAPHIR	183(6)	1700/12	Atmospheric profiling
2011	SAC/D	NASA	Aquarius	1.4	380/75-96	SSS
		CONAE	MWR	23.8, 37	380/27	Rain, SSWS
2011	NPP	NASA	ATMS	23.8, 31.4, 50-58(13), 88, 166, 183(5)	2300/15-75	Atmospheric profiling

ls. refers to the fact that resolutions for for limb sounders are given in vertical direction

T(z) refers to vertical temperature profile, q(z) to vertical humidity profile

3.2.2 Aquarius

This L-band PMR was launched in 2011 on CONAE's SAC-D and is described in a paper by Le Vine et al. [50]. This mission was designed to detect sea salinity, to an accuracy of 0.2 psu at a resolution of 150 km, so it includes an active scatterometer to give surface roughness estimates. As a result of the requirements, the sensitivity of Aquarius over 6 s integration time (over one month) is 0.06 K. Aquarius began its science operations phase in December 2011, and has produced maps of global SSS. The mission is designed to detect salinity changes on inter-seasonal time scales, and track events like the great salinity anomaly of the 70's which caused cool weather in Europe. The baseline mission is designed to be 3-years long.

The radiometer is set up as a push-broom three tooth comb, using three beam footprints that leave paths that are side by side as the satellite travels. The beams point towards the night side to avoid the sun glint. The Aquarius mission will revolutionise the field of oceanography with never before seen salinity samples, on a fairly regular repeat basis, as opposed to in situ ship measurements. The calibration scheme involves a carefully temperature controlled Dicke calibration method. The use of a Dicke switch allows blanking and calibrating of the PMR during the scatterometer pulse [50].

CONAE also launched their first PMR, designated MWR, on SAC-D, at the frequencies of 23.8 GHz and 36.5 GHz, with an eight tooth push broom comb over a common swath with Aquarius. The MWR consists of two reflectors, one for each frequency, on each side of SAC-D. The MWR instrument is for characterisation of rain to improve the salinity retrieval, since rain would dilute the surface layer; the follow up measurements by Aquarius would allow for calculation of the change in salinity after the rain, once per 7 days [162].

3.2.3 Windsat

The Windsat radiometer launched in 2003 on the Coriolis satellite is the first to use fully polarised radiometry to characterise the wind vector (speed and direction) from space. It is described and characterised by Gaiser et al. [18] and was designed for risk reduction of CMIS, which was supposed to launch on the NPOESS satellites. However, CMIS was cancelled in 2006 [163]. All 22 channels, 6.8-37 GHz from 11 feed-horns, are directly detected. The EIA for all footprints of one frequency are the same. The calibration procedures, including the pitch manoeuvre, are described by Jones et al. [164]. Some RFI detection techniques are described in these papers [165, 166].

Windsat was designed with naval operations in mind by the NRL in the US. The stokes parameters are directly measured allowing the wind vector to be derived within 2 m/s and 20^o. The IFOV NEΔT is $\sim$0.5 K. The direction specification was met above 6 m/s. Separate horns are used due to the sensitivity requirements on each channel. The instrument has a narrow aft view swath to measure azimuthal variations of the sea state. There were airborne wind vector experiments that validated the concept in the 1990's, the wind vector retrieval algorithm is described by various authors [167, 168].

3.2.4 Odin

This mission carried the sub-millimetre microwave radiometer, SMR, on Odin from Sweden and some European partners. Performing a dual prime mission between astronomy and atmospheric limb sounding. It was launched in February 2001. The mission overview is presented by Murtagh et al. [72], the radiometer design is presented by Frisk et al. [169]. The motivations behind choosing the frequencies, mainly to monitor ozone, are presented in a paper by Merino et al. [74]. The receivers are tunable to maximise the number of lines that can be inspected. The mission sharing time, between aeronomy and astronomy, is outlined in the Murtagh paper. The calibration is of the Dicke type, with a 1.1 m reflector, weighing 250 kg and the solar panels produce about 300 W.

The fact that this is a small mission sent up by Sweden, means that this instrument warrants investigation as the type of mission South Africa can send up; after verifying the capability of South Africans to produce a functioning space-borne PMR. The observation time is shared between Earth observation via limb sounding and astronomy, this situation is not ideal for constant monitoring purposes, but may allow the project to be funded from two separate sources.

3.2.5 Microwave Limb Sounder (MLS)

This instrument was put up by NASA on UARS, and later an upgraded version was put on Aura. Both instruments were built by JPL. The next generation, under study, is the Scanning Microwave Limb-Sounder (SMLS) for the Global Atmospheric Composition Mission (GACM) [170]. There have been novel proposals for the feed horn [133, 171] and the antenna [172] of SMLS.

3.2.5.1 UARS

This instrument was aboard a satellite that made news around the world when it de-orbited in September 2011. The Upper Atmospheric Research Satellite (UARS) was a experiment focusing on upper atmospheric chemistry, where MLS was a limb-sounder that detected water and trace gasses in the atmosphere, including ozone, HNO_3 and volcanic SO_2 [76]. It was the first space-borne application of limb-sounding at the MW. This MLS provided measurements from September 1991 to 1999, however, after 1994 measurements were intermittent. The scan mechanism and power system troubles degraded the continuity of later measurements.

The cassegrain main reflector was 1.6x0.8 m and the secondary reflector was 45x24 cm. The calibration schemes and algorithms are described by Jarnot et al. [173, 174]. The power needs are 163 W and the weight is 280 kg for the MLS instrument.

3.2.5.2 Aura

The Aura instrument is designed to monitor the effects of CFC's, which have a long atmospheric lifetime, and ozone. The instruments, products and chemistry under study as well as some of the validation projects, on Aura are described in a booklet by NASA [175]. The impacts of Aura measurements are varied with respect to the end users, including studies on the prevalence of brown smog, caused by NO_2, and acid rain.

The design of the EOS MLS is very similar to the one on UARS. The Aura MLS is described in a paper by Waters et al. [54]. The instrument included the frequency channels of the earlier UARS instrument and added the 240 and 640 GHz channels as well as a separate 2.5 THz section [96, 176]. The laboratory studies of the lines of interest for the EOS-MLS are described in a report by Cohen et al. [77]. The 240 GHz band is aimed at O_3 while the 640 GHz band is aimed at HCl as well as other trace gasses and the 2.5 THz channel is aimed at OH. The optics of the combination of the new and the old channels are described by Cofield and Stek [177].

The use of spectrometry allows for simultaneous extraction of lines and line-widths of interest, up to 20 GHz from the centre frequency. The weight of EOS-MLS is 453 kg and the power needs are 545 W. The beginnings of THz observation and various applications are presented by Siegel [178].

3.2.6 SMOS

The Interferometric Synthetic Aperture Radiometer (InSARad) concept is currently undergoing calibration and validation on the SMOS mission (Soil Moisture and Ocean Salinity) of ESA. This mission aims to measure: soil moisture to 0.04 m^3/m^3, vegetation to 0.1 kg/m^2 with a resolution better than 50 km, sea salinity in the open ocean to 0.1 pss-78 at 200 km over 30 days and in coastal waters to 1 pss-78 at 20 km over 10 days [129, 19]. The team plans to average several successive salinity samples, which vary slowly over time, to achieve the desired accuracy. The revisit time is aimed to be 3-5 days. A dawn-dusk orbit is favoured to minimise the effect of Faraday rotation. The instrument sensitivity over a 1.2 s integration time is 1.8-2.2 K depending on the target temperature. One of the main drivers for the SMOS project is the European Centre for Medium-Range Weather Forecasts (ECMWF).

The MIRAS instrument, on SMOS, and concept were extensively tested and modelled prior to launch [179, 99, 180, 181, 104]. The on-orbit calibration results are presented by Corbella et al. [103]. Validation of SMOS data is on-going against other satellite PMRs, e.g. AMSR-E, and ground based networks [182]. Some research is being done to integrate SMOS data into NWP, but it is challenging [183]. The HUT-2D demonstrator was used in rehearsal campaigns for SMOS [184]. The fact that RFI is such a big issue for SMOS, means that a great deal of research is being done in RFI identification and mitigation[117, 118, 119, 185].

There is a proposal by Kerr [186] for the next generation of SMOS, SMOS-NEXT, to consist of a formation of two spacecraft with a linear aperture array on each. This is to increase the spatial resolution without degrading the sensitivity.

3.3 First Space-borne PMR Instruments by various nations

Over the years, several extremely complex instruments have been sent up built on the heritage of older instruments. Occasionally, an immature agency would send up a relatively complex EO instrument first, for instance Brazil with the HSB on Aqua and China with MWRI, MWTS, MWHS on FY-3A [38, 41, 37]. The Chinese instruments are reserved and avoid the complexity of SSMIS and MTVZA; the experience gained from the Chang'e lunar mission, FY-1 and FY-2 means they can sufficiently develop more complicated EO PMR designs from the start.

However, on the whole, countries have sent up dual frequency instruments first then worked their way up; the Mariner-2 mission was originally designed with four frequencies reduced to two due to a change of launcher [32]. Some of the dual frequency instruments aim at characterising atmospheric water vapour, CLW, wind speed, precipitation and sea ice like in the case of the SAC-D MWR by CONAE [162]. A list of the first missions by various countries is listed in Table 3.3.

The fact that so many nations have launched PMRs shows that PMR data is useful and that space agencies all over the world are building them. Due to the cost of sending up the large antennas needed for PMRs, many space agencies are collaborating internationally to send up bigger multiple payload satellites like Aqua. International collaborations are shown earlier in Table 1.2. The MWR from CONAE is described under Aquarius, Section 3.2.2, and SMR under Odin, Section 3.2.4.

3.3.1 DREAM

The Dual channel Radiometer for Earth and Atmosphere Measurement (DREAM) by KARI in Korea was due to be launched on the Science and Technology SATellites, STSAT-2A and 2B, unfortunately both launches failed. The DREAM instrument was extremely simple, with a dicke calibration, to the extent that the science resulting from the data would have been very limited; products were expected to include precipitation, water vapour and CLW. However it was designed to fit into a micro satellite configuration with specifications of NEΔT 0.2 K, 15 kg and 20 W, and the elliptic orbit probably allowed a perigee closer than for a circular orbit. The development time was relatively quick 2002-2006 for a 2008 launch [190, 191, 192, 193].

3.3.2 Humidity Sounder for Brazil

The HSB instrument was designed with the heritage of the AMSU-B design. The instrument was launched on the Aqua mission as part of an AIRS/AMSU/HSB triple. However, the HSB instrument failed within a year due to a mirror scan

Table 3.3: Table showing the first PMR missions launched by each nation in the survey [32, 6, 187, 188, 162, 141, 189, 45, 190]

Country	Agency	Launch date	Satellite/Mission	Instrument name	Frequencies [GHz]	HPBW range (^{o})	Altitude [km]
Russia	Roscosmos	1968	Cosmos243	-	3.5-37(4)	3.5-8.6	250
USA	NASA	1962	Mariner-2	Radiometer	15.8/22.2	2-2.7	N/A
		1972	Nimbus-5	ESMR	19.3	1.4	1095
				NEMS	22.2-58.8(5)	10	
India	ISRO	1978	Bhaskara	SAMIR	19/22.2	16.5-26.5	525
Japan	NASDRA	1987	MOS-1	MSR	23/31	1.35-1.8	900
Sweden	SNSB	1991	Odin	SMR	118,485-581(4)	0.03-0.16	620
France	CNES	1991	ERS-1	ATSR-MWR	23.8,36.5	1.4-1.6	780
Brazil	INPE	2002	Aqua	HSB	150, 183(3)	1.1	705
China	CAST	2008	FY-3A	MWRI	10.7-89(5)	0.26-2.2	831
				MWTS	50-57(4)	3.5-4	
				MWHS	150-183(5)	0.9-1.1	
Korea	KARI	failed	STSAT-2	Dream	23.8/37	9.8-10.6	(300-1500)
Argentina	CONAE	2011	SAC-D	MWR	23.8/36.5	2	657

motor failure, so there is little data or literature available from the HSB payload. The mission was also simplified, by removing a window channel, during the development due to budget constraints [189, 194].

3.3.3 Microwave Scanning Radiometer

The microwave scanning radiometer (MSR) on the MOS-1 satellite from Japan, launched in 1987, had a 50 cm aperture conically scanning radiometer aboard. The design was as much for technology demonstration purposes as for scientific ones. The MSR suffered from the fact there were no storage media aboard; this meant data could only be recorded when within line of sight of a ground station. The data record goes from 02/1987–04/1996. The MSR had a fairly narrow swath of 300 km. MSR contributed to the measurement of SST by the IR instrument, monitored sea-ice and quantified the effect of the atmosphere on communications signals [188, 195, 196, 197, 198, 199].

3.3.4 SAMIR

The SAtellite MIcrowave Radiometer (SAMIR), on Bhaskara I and II, was the first radiometer put up by the ISRO in 1978 for India. It was scanned by spinning the spacecraft along track and cross track. Due to the wide FOV, the scan-rate did not have to be that high to maintain Nyquist sampling, 6-8 rpm. It utilized a two tooth comb scan to widen the swath at 19 GHz. It employed a dicke switch calibration scheme. Results were published for SAMIR including, the effects of rain, surface roughness and water in the atmosphere [187]. Comments were made about the angular effects as the radiometer was scanned [200].

3.4 Other instruments of note

The Indian Space Research Organisation (ISRO) have built OceanSAT-I (IRS-P4) with the multi-frequency scanning microwave (MSMR) aboard. The MSMR has four frequencies (6.6-21 GHz), chosen principally for oceanography, all dual-pol obtained from a single eight port feed-horn, utilizing the harmonics of the lower frequencies to achieve the broadband horn. The MSMR was retired in 2003. Since this instrument is similar to the proposed technology demonstrator, it is probably worth studying from an engineering perspective, including the design, optimisation, calibration and validation procedures [101, 126, 108]. Although the orbit was optimised for the ocean colour monitor on Oceansat-I, some academic uses of the data arose including; rain rate monitoring, SST, SSWS, CLW, IWV and even coastal demarcation [201, 202, 203, 204]. Oceansat-II, launched in 2009, had a GNSS occultation instrument aboard called ROSA from the Italian space agency, which was tested for the effects of the MSMR, however, the PMR was later replaced by SCAT, a scatterometer [205].

There are several airborne missions, that are mentioned throughout this dissertation, that have been used to verify and obtain data in most of the uses of PMRs, including water vapour and cloud profiling by MIR [206, 207]. The short lead times and the ability to tweak the instrument between flights means that newer technologies and techniques can be tested, like using the 325 GHz water line. The other well validated and self sustaining airborne instrument is the High Altitude MMIC Sounding Radiometer (HAMSR), now flying on the Global Hawk. HAMSR has been upgraded several times and makes use of new technology, such as monolithic microwave integrated circuits (MMIC) and high frequency LNAs, to reduce the size, cost and power of PMRs [27, 90, 28, 208, 29]. HAMSR is a veteran of many campaigns including the Winter Storms and Atmospheric Rivers Campaign (WISPAR), aimed at measuring atmospheric water vapour rivers.

3.5 Future missions and constellations

Many of the planned constellations that are going to be launched are aimed at measuring and quantifying the climate towards developing policies to combat anthropogenic climate change. The A-train constellation is an orbit of Earth observation satellites, to bring the maximum variety of instruments to bear on the sub-satellite track, below a single orbit around Earth, with little time elapsed between each constellation member. The satellites in the A-train change occasionally, for instance GCOM-W1 will join the constellation in 2012. An overview of which missions NASA is considering extending beyond prime mission into the future, and the reasons for doing so, are described in a senior review presentation [209]. Section B.3, in the appendix, is a brief overview of the future constellations and missions the author has come across to date. These future missions are summarised in Table 3.4.

3.5.1 Global Precipitation Mission (GPM)

The Global Precipitation measurement Mission is the next decadal plan for international space agencies, with an infrastructure to meet scientists and researchers aims [213]. The rationale for the mission is to improve climate, weather and hydrological predictions. NASA will provide two spacecraft to the constellation and other partners will contribute one. The partners are DMSP (SSMIS), France, India (Megha-tropiques) and Japan (GCOM-W1); perhaps JPSS, ESA, China, Italy and Brazil will join. The core spacecraft is expected to carry a precipitation radar like TRMM.

GPM is expected to enable better flood and drought predictions, agriculture and water planning, forest management and military applications. However, since the constellation is more a "constellation of opportunity", due to the expense of a conventional constellation, there is significant mismatch between the partner spacecraft. There are inter-calibration algorithms being developed. The GPM infrastructure includes ground validation sites and data processing and dissemination facilities. The precipitation product for GPM, among others, is aimed at offering ~3 hour revisit time with samples from ~90% of Earth's surface [214].

There was a call for a partner satellite to carry the second GMI instrument from NASA. South Africa could provide such a bus in the future. All of the members of the constellation of opportunity are expected to have a PMR aboard for the precipitation measurement. Members will be added to the constellation as the

Table 3.4: Table showing future and planned instruments [4, 210, 46, 211, 212, 53]

Dates	Satellite/ Mission	Principal agency	Instrument acronym	Frequencies [GHz]	Swath Width/ pixel resolution	Main parameters
2012	GCOM-W	JAXA	AMSR-2	6.9, 7.3, 10.7, 18.7, 23.8, 36.5 89	1450/3-35	SM, ocean + atmos. param.
2013	GPM	NASA	GMI	10.65, 18.7, 23.8, 36.5, 89, 166, 183.3(2)	900/5-20	SST and precipitation
2013	Sentinel-3	ESA	MWR	23.8, 36.5	20/20	Path delay
2014	Jason-3	CNES/NASA	AMR	18, 23, 34	26/26	Path delay
2014	SMAP	NASA	SMAP	1.4	1000/36	SM
~2015	FY-4M	CMA	GIMS	50-56(8)	3000/50	GEO temperature profile
~2016	JPSS-1	NASA	ATMS	23.8, 31.4, 50-58(13), 88, 166, 183(5)	2300/15-75	Atmospheric profiling
~2017	GOES-R	NOAA	GeoSTAR	50-58(4-6), 167-183(4)	hemisphere/25-50	GEO Temperature profile
~2020	GACM	NASA	SMLS	180-680	ls.10-100/1-6	Upper atmosphere studies

availability of the instrument and need for the data arises.

3.5.1.1 GMI

The next constellation aimed at monitoring precipitation is GPM, for launch in July 2013, with a PMR called the GPM Microwave Imager (GMI), based on TMI heritage. The core craft of the GPM mission will fly in a 65^o inclined orbit at 407 km, which will allow measurements in the area where 97% of precipitation occurs. The primary mirror features a 1.22 m diameter aperture illuminated by 6 feed-horns and will offer far superior resolution to TMI. GMI will weigh 166 kg and use 162 W of power (The radar would require ~1000 W). The lowest three frequency channels, 10.65, 18.7 and 23.8 GHz, are directly detected and the other channels are detected after super-heterodyne down-conversion; they are 36.5, 89, 165.5 and two at 183.31 GHz. All channels except the water channels, 22/183, are dual pol. The NEΔT is <1 K for the lowest five frequencies and 1.5 K for the rest. The GMI features many of the technologies demonstrated in previous imaging missions, for instance the connection of the rotating feeds to the rest of the craft is based on the Windsat design. The connection to the spacecraft is designed to make the attachment of another of the same instrument to a constellation partner satellite as simple as possible [210, 215].

3.5.2 African Resource Management constellation

To date, the author has found no reference to a PMR to be launched on an African satellite. The African Resource Management Constellation (ARMC) is a constellation where several African countries each launch one or more satellites in contribution. The author believes that a PMR among the constellation's members would well serve the interests in Africa, primarily by quantifying rain and monitoring SM. The improvements to weather and climatic models due to local processing of data like SST and SSWS would also have an impact on government policy.

The other collaboration that the author found with respect to Africa was the

Brazil, India and China (BRIC) space weather satellite. This satellite could be served by an upper atmospheric limb-sounder which should be small in size, especially if it were a THz instrument with a small dish, on a medium satellite [216].

3.6 Lessons learned

The historical problems for functioning radiometers include bad calibration schemes (SMMR), power failures (Seasat), scan mirror motor failures (HSB), friction (AMSR-E), RFI (SMOS) and poor data processing algorithms. Each of these problems either have been addressed or are being researched. Mariner-2 suffered from a fault causing an instrument supposed to give 15 transits of Venus gave only 3, luckily the data was sufficient to verify the hot surface of Venus.

Some missions were promising but never got off the ground, one such example is the European MIMR, at one stage to launch on the Metop series [153], with characteristics similar to AMSR-E, which was sidelined to avoid duplicating TRMM data [217].

Chapter 4

Applications in Earth Observation

This chapter is a brief overview of the various uses of PMRs in space. They include the users and the PMR sensitivities required. Many of the uses have been proposed since the 70's [22]. Due to the poor spatial resolution of PMRs, these applications are limited to regional and global scales. Although a great deal of the historical radiometers and ones currently in use focus on the atmospheric sensing, atmospheric water and water vapour profiling, for use in NWP, there is more emphasis on surface sensing recently with several L-band instruments going up. The increasing resolution as time goes by allows more science to be done as more features can be resolved, e.g. surface currents from TMI data [12] and AMSR-E data. Njoku gives an overview of both the instruments and applications as they stood in 1982, largely similar to what they are today [6]. More modern reviews are available of the state of research into the various fields of Earth Observation (EO) [71, 78].

The demands of the scientific community increase as better generations of instruments go up. This constantly pushes the envelope and puts scientifically useful instruments out of the reach of smaller space agencies due to the size and complexity required for the instrument to meet the specification required. A modern instrument, SSMIS, has its products described in a report [218], each of the products is described with the algorithm and specifications.

Table 4.1: Table showing the data sets of interest for typical users of PMR EO data

User	Data sets of interest
Oceanography	SSS, SST, SSHA, Ice classification/monitoring
Climatology	SST, SM, IWV, CLW, precipitation
Weather centres	Temperature/humidity profiles, precipitation, wind vector
Scientists	Trace gases in stratosphere (Ozone)
Future user	**Data sets of interest**
Agriculture	SM, precipitation
Marine biology	SST, SSS
Forestry	Biomass estimates, NDVI
Radio astronomers	RFI sources (VLBI non earth observation)

Note is taken of the applications of each frequency band and the impact on the research/commercial world, as well as if the frequency is protected or not [59]. The main instruments offering the products are mentioned. The uses of surface imaging, atmospheric sounding and limb-sounding are all covered; some of these products that various users are interested in are presented in Table 4.1. GNSS and other limb sounding instruments are briefly considered where applicable. The effects on the immediate problems of South Africa are mentioned where appropriate, as well as where links to South African projects such as SKA, SAWS, SANSA and the Navy might be established.

The penetrative effect of MW radiation at longer wavelengths also allows for analysis of the bulk properties of a surface. Since the penetration depth decreases for decreasing wavelength, some stratification of the target using multiple frequencies can be modelled, for instance for SM in the surface layers [11, 62] and classification of canopies or crops [17, 51].

An easy to read brief overview of most forms of remote sensing is given in an online book by N. Levin [219]. An overview of the uses of space-borne PMRs from a military perspective are presented in an NRL report [124]. There are also online lecture notes that describe black body emission, the emissivity of snow and the other products from PMRs, a search on google of "passive microwave remote sensing" returns several results of such lecture notes. The specifications for the AMSR-2 imager products can be found in Appendix A.

4.1 Oceanography

Given that the ocean covers 71% of Earth's surface and is relatively uninhabited the best way to monitor it on a reasonable spatio-temporal scale is from space. Given the sheer surface area of the ocean the effect it has on the Earth's environment is sizeable. The heat fluxes from and around the oceans have a significant impact on the global energy cycle. To this end SST, SSS, precipitation, SSWS and SSWD are estimated via PMRs for oceanographic studies. The Sea Surface Wind Speed (SSWS) and Direction (SSWD) is described under the weather section as it has its main application in meteorology. There is a good series of oceanography remote sensing textbooks by Robinson [36, 56].

There are also fields of research dependent on the SSS and SST parameters, like marine biology [220] and IR remote sensing. Although SST at 1 km resolution is beyond the reach of current PMRs. However, if a 3.6 m dish with the TMI geometry where put up, the 10.7 GHz channel would have 6x10 km resolution, which would be useful in cloudy areas but several engineering trade-offs would need to be made, e.g. sensitivity and swath width. That said, there are several large scale processes in the ocean that PMRs are ideal for.

4.1.1 Sea Surface Temperature

Sea Surface Temperature (SST) PMR estimates have been around since the 60's [16, 221] and have been used for several purposes including; current monitoring and discovery in oceans (e.g. Tropical Instability Waves [TIW]), hurricane track prediction [83] and the relation of SST to chlorophyll. PMRs have the advantage of being able to detect SST under cloudy conditions, a large benefit in the tropics. The TMI 10.7 GHz channel, sensitive enough to detect diurnal variation in SST, is useful for detecting SST in the cloudy tropical regions and was used to detect an early retroflection event in the Agulhas current [12]. Cumulus production is dependent on SST, so SST is a key parameter in NWP and climate change data sets.

There is a need for SST data nearer the coasts, this is due to the low resolution of PMR, sometimes alternative SST datasets are available instead [12]. SST is linked to primary production and nutrient concentration in the oceans, this in turn has an effect on fishing. The penetration by microwaves of the cooler $\sim$1 mm skin temperature of the ocean is an advantage PMR measurements have over IR SST measurements. However, sometimes there is a temperature gradient deeper than the microwave skin depth, which cannot be detected from space.

The most sensitive frequency to SST is in the region of 6 GHz, therefore several missions have C-band radiometers to detect SST e.g. SMMR (6.6), AMSR-E (6.9) and Windsat (6.8). The sensitivity of 6.9 and 10.7 GHz to SST is analysed by Gentemann et al. [222]. Several other PMR missions have given a SST product including SAMIR [200], SSM/I [223], MSR [198], MSMR and MTVZA. SST is an important parameter in wind speed estimates for meteorology [224].

IR sensors are favoured for SST since resolution is better and the signal is much stronger, as can be seen from the Planck function, but atmospheric effects increase the complexity of the temperature estimate and the presence of clouds diminishes the repeatability of these measurements. Salinity also has an effect on the emissivity of the ocean at the IR, so PMR salinity estimates would in turn help IR measurements. For comparison typical IR radiometer specifications for SST are 1 km spatial resolution with a sensitivity $<$0.3 K.

4.1.2 Sea Surface Salinity

Many of the motivations and considerations for measuring Sea Surface Salinity (SSS) are presented by investigators for the Aquarius and SMOS missions [50, 19]; the biggest reason is the sheer size of the ocean and the logistical impossibility of global in-situ sampling. SSS via PMR has been verified since the 70's [80]. For example, drifting salinity buoys very rarely sample surface current divergence zones. The fact that at the L-band the antenna temperature can change by 0.5 K/psu in warmer waters means it is well within the limits of sensitivity of PMRs, but scientific demands of 0.2 psu are challenging. Monitoring the inter-seasonal change in SSS and large scale salinity events are among the initial goals of Aquarius and SMOS. SSS has effects on the climate via ocean circulation and temperature flux due to the fact that the sea water properties change with salinity, e.g. density and CO_2 capacity.

Although Aquarius only has a resolution of 150 km, the variability of SSS in the open ocean justifies such a low resolution. However, there are stringent sensitivity requirements for open ocean SSS, more so than SM, so a real aperture system is favoured. The SMOS concept is touted as a way of getting salinity data closer to the coast, where the salinity variations are large over shorter periods but higher resolutions are needed. Although the effect of the atmosphere is small at the L-Band it is appreciable and needs to be corrected for, there are also cosmic and solar effects to take into account. The effects of rainfall including fresh water lenses need to be characterised by SSS measurements.

The laboratory characterisation of the emissivity of sea water at various temperatures and frequencies is an ongoing process, as the demands for accuracy rise [225, 226, 221].

4.1.3 Sea Ice

PMRs have been described as the bread and butter sensor for determining and monitoring sea ice extent and type in the high latitude regions. Given that the emissivities of new ice, second year ice and multi-year ice are different, there can be difficulty in determining if a scene is partly new ice and partly sea water or principally second-year or multi-year ice; polarization can be useful in determining which case is in effect, since sea water is more polarised than ice. The frequency dependencies can be used to determine the ratios of first-year ice, multi-year ice and sea water in the FOV [199].

4.1.4 Sea Surface Height Anomaly

One of secondary functions that PMRs play is estimating the atmospheric wet path delay for microwave altimeters, e.g. AMR on Jason II [55]. Altimetry is used in oceanography to monitor the Sea Surface Height Anomaly, SSHA, which in turn helps to understand pressure gradients in the sea [56]. New technology and techniques for calculating wet-tropospheric path delay is improving the accuracy of altimeters near the coast [87, 227].

4.2 Hydrology

The water-cycle is still an active area of research, with improvements to models being suggested as the data becomes available. Given that the fresh water is a limited resource many governments want data to provide motivation for policy proposals that might improve the lives of their populations. To an extent some surface classification is possible with PMRs i.e. ocean, coastal, ice, flooded land, soil, desert or snow. The SWOT mission altimeter plans to measure water levels for 100+m wide rivers and 250+ m^2 bodies of water [228]. Recently freeze/thaw events were recorded by SMOS, and SMAP hopes to characterise freeze/thaw at 3 km resolution via SAR techniques. The following topics are of interest to hydrological modellers.

4.2.1 Soil Moisture

Soil moisture (SM) is an important factor in global hydrological models, the required temporal, spatial and radiometric resolution can feasibly be provided by space-borne instruments [229]. Since S-194 went up on Skylab SM has been retrieved from space [11, 230, 231]. Owe et al. gives an overview of the history of SM applications, and the results various missions have obtained [57]. Passive microwave radiometry is the only way to measure soil moisture directly from space. The wettest to driest soils vary by $\sim$80 K in antenna temperature and

PMR sensitivity is typically ∼1 K, therefore PMRs offer a moderately sensitive method of measuring SM.

SM is detected near the surface, a few tenths of a wavelength deep, and is not really useful for determining root zone SM. This has implications in regions with little rain since the useful moisture is usually deeper than can be detected via passive microwave radiometry, however plants usually grow in arid areas when there is moisture in the root zone giving an indirect measure of root zone SM. Due to the fact that water flux into and out of the soil, via evapo-transpiration, must go through the surface layer or root systems, SM is none the less important for water cycle studies. However, the effect of biomass on SM must also be taken into account. The use of IR instruments to monitor plant stress can give an indication of SM in the root zone. However 65% of the Earth's surface is non-forested and SM can be estimated via L-band PMRs [232].

The considerations for measuring SM include:

- Prediction whether rainfall will infiltrate or run-off
- Detection of recent rainfall
- Weather prediction, as there is a net loss of heat energy during evaporation
- The prediction of floods and landslides due to soil saturation
- Drought monitoring
- Crop yield prediction
- Irrigation monitoring, especially in arid/semi-arid areas
- Climate monitoring

The AMSR-E is useful for SM (via polarization ratios) if vegetation is below $1.5kg/m^3$ [233]. 6.9 GHz suffers from RFI so 10.7 GHz is chosen instead for a single channel algorithm. One needs to be careful which model is used as some are more sensitive to vegetation, snow or RFI [62]. The superiority of the L-band sensors is that SM can be observed under $5kg/m^3$ vegetation moisture, but spatial resolution is a serious issue. Higher resolution active microwave systems have issues with scattering and speckle and thus SM cannot be estimated. The spatial resolution requirements for SM are 10 km for hydro-meteorological and 40 km for hydro-climatological purposes[212] with a revisit of 2-3 days. There are several issues to be considered in extracting SM estimates [19, 234].

The sensitivity of dry and wet soils to texture, bulk density and surface roughness is presented by Martin et al. showing that wetter soils were more sensitive to changes in the ancillary data and surface roughness estimates had a large effect on the SM estimates [111]. In SM, the rock fraction has to be considered as some rocks are non porous and therefore will not have a changing dielectric constant, and the dry dielectric constant may be different to the surrounding area soils [235]. To improve SM resolution the antenna average is being considered together with the local topology to develop a higher resolution model.

The Chinese ran an airborne SM program since 1977 [236], along with several other countries [237, 184]. The other important SM missions of note are SMOS [129, 19, 182] and SMAP [212]. There are ideas to get round the resolution issue, like SMOS-NEXT [186], which would allow for ideas like irrigation control in agriculture. Some SM applications are complementary with radar imaging in characterising radar return. Sometimes the IR data is used as ancillary data in SM studies. In South Africa hydrology groups already use SM estimates from space; UKZN is keen to do further research in this area [238, 13].

4.2.2 Snow and Ice cover

In high latitude regions, with temperate conditions, the snow and ice is an ongoing region of research, e.g. AMSR-E has been used to analyse Antarctica [239] and SSM/I in South America [240]. The snow cover estimate algorithm typically uses the 18 and 37 GHz channels [241]. The 36 GHz channel is very sensitive to snow and has been cited as a cause of error in some SM algorithms [62]. Some dual-frequency radiometers allow for the distinction between snow-pack and land features via polarisation ratios. However, melting snow and very wet soil can be hard to tell apart, since the liquid water emits more than the snow. Dry snow scatters the up-welling radiation and thus appears cold to a PMR. The models have to be carefully fine-tuned as they can be off by a factor of five [107]. Some satellites like SSMIS offer ice edge and snow edge products. Snow cover determines the spring time water availability, as well as the more direct heat blanket property which also reflects sunlight. Hence, ice and snow are factors, in the Earth's energy cycle, for climatology.

4.2.3 Biomass

Obtaining reliable estimates of biomass from space-borne PMRs is a region of on going research; the problem is that there are few cases, e.g. rice paddy fields, where the ground emissivity is known accurately, which is needed in order to estimate the effect of biomass on the signal. SMOS is currently attempting to characterise biomass by multi-angle methods, via synoptic scanning, and multi-frequency methods with 6.9 GHz channel on AMSR-E [242, 129, 19, 243, 80, 244]. The forestry departments in various countries would benefit from biomass estimates. Vegetation estimates are often used as a priori ancillary data in SM algorithms, such as NDVI estimates from other sensors [234].

4.3 Climatology

Currently the main uses for the PMR data are atmospheric monitoring for meteorological purposes and climatology. The atmospheric sounding channels, for atmospheric monitoring, are usually centred near the oxygen lines at 60 and 118 GHz and the water lines at 23 and 183 GHz. Typical instruments that use these frequencies are AMSU-A on Aqua [52] and MLS on Aura [54]. The climatology group at UCT uses PMR data [245]. IR instruments are preferred due to the better resolution, but when clouds and aerosols prevent IR detection cloud clearing techniques as well as PMR are used [92, 25].

The SST and SSS have implications on the amount CO_2 oceans can absorb.

The verification of climate change models, by offering data that can discriminate between models, is one of the drivers of space borne PMR design. Other measurements of interest, like aerosol distributions and concentrations, would help the scientific community, for example by estimating the effect of anthropological climate change [246]. The targets of the Chinese FY series are largely meteorological and climatological [44].

Some of the issues regarding climate change and the greater world community are shown in an International Space University document, including the need for monitoring and mitigation, done by their 2009 Masters class [247]. The idea was to improve in-situ data through public participation, thereby helping space-borne remote sensing and climatology as a whole. The report also lists the products and satellite instruments that contribute those products.

4.3.1 Weather

Numerical Weather Prediction, NWP, has become a big business with ramifications in industry and government world wide. The NWP models have become more sophisticated over the years, and take data from a variety of sources, but given the global nature of weather patterns, global monitoring schemes are needed. The improvement in NWP in the southern hemisphere has been largely attributed to satellite sensors. The contribution of some PMR instruments to NWP has been quantified in a paper by Hilton et al. [24] and again by Kazumori [248]. Kidd et al. give a review of space-borne meteorological instruments including PMRs [249].

The various initialization parameters of interest to NWP from PMR data include, atmospheric water vapour content, atmospheric liquid water content [158], precipitation [160], SST, SM, wind speed, atmospheric temperature and humidity profiles. Although, sometimes the best approach with NWP is to take the raw data from many sources and combine into a final NWP product, rather than try to use the parameter estimates from those sources, as this keeps the compound error down [248]. Temperature and humidity sounders have been sent up by various nations [42, 43, 52, 120]. The concept of atmospheric profiling has been around since the late '70s [85].

The fact that microwaves can penetrate clouds make them extremely attractive to weather centres, especially when they have to discard cloud affected IR readings. Pavelin et al. propose the use of PMRs to improve cloud identification algorithms for NWP and help in profiling the cloud characteristics, they also state that there are clouds over 70% of the globe [25]. Storm systems often have cirrus ice clouds which can shield the underlying storm system from IR sensors, but are virtually transparent for the majority of the MW.

The accurate depiction of SST has implications in cumulus formation and storm event development. ECMWF, in Europe, underestimated heat fluxes for Agulhas current [12]. However, as models get more accurate, more precise data is needed and the requirements for the engineers designing the measuring instruments are constantly increasing.

Southern hemisphere weather forecast is accuracy largely attributed to satellites [250]. The World Weather Watch listed the state of affairs, at the time, of current and future weather satellites. They also recommended that cal/val activities be mentioned to meteorological organisations in advance, to allow them to test the data for later assimilation into weather models [93].

4.3.1.1 Atmospheric Vapour and Liquid water

The parameters of Cloud Liquid Water (CLW), Total Precipitable Water (TPW) and Integrated Water Vapour (IWV) are the reasons that the channels between 18 and 37 GHz are chosen on most PMR imaging missions. The bands that are usually used are 18-19 GHz for surface effects, 21-23 GHz for IWV, 31-34 GHz and ~37 GHz for CLW. CLW and IWV have been estimated for MSMR, without a 37 GHz channel, using artificial neural networks [204].

Most PMR missions, imagers and sounders, offer the CLW/TPW and IWV products as they have the biggest effect on other frequency observations and on path delay on altimeters. Ruf presents a paper on inter-calibration for an altimetry mission, TOPEX/Poseidon, with ground based WVR [251].

4.3.1.2 Atmospheric Sounding

Since the 70's, temperature [T(z)] and humidity [q(z)] profiling of the atmosphere from space has been proposed [85]. The $\sim$60 GHz oxygen line complex is primarily used for temperature sounding, because it has more penetration and is useful even in humid and precipitation conditions, as opposed to 118 GHz which has a minimal peak above 12.75 g/m^3 water vapour [146]. Humidity profiling is primarily done at the 183 GHz H_2O line as the 22 GHz line is too low to adequately stratify the atmosphere. The space-borne sounders have inherent vertical resolution limits of $\sim$3 km, NWP atmospheric cells operate with a 3 km vertical to 50 km horizontal ratio, therefore 50 km is the optimum horizontal resolution [252].

Both space-borne and air-borne PMRs have been used in monitoring extreme weather events such as hurricanes [27, 90]. GEO temperature and humidity sounders are under research [46, 135, 137], GIMS, from China, is expected to be the first such sounder in orbit on FY-4.

The impact is comparable with IR sounders, but as IR sounders are improved the relative contribution of sounders decreases, to the point where a third temperature sounder in space would have negligible improvement on forecast error [132]. Redundancy could be provided by having a third instrument on the ground ready to go should one of the two operating instruments fail. However, IR and MW sounders are complementary.

4.3.1.3 Rain Rate

The rain rate estimate is one of the key estimates, of climatological models, that the GPM constellation hopes to better characterise [213]. The evaporation of surface moisture has a cooling effect and hence an implication on the energy-cycle in climatology studies. Rain rates and SM are closely linked and are complementary. Several PMR missions have offered a rainfall product including: TMI, SSM/I, AMSR-E and AMSU [70]. Large ground based validation networks have also been formed, with existing networks such as NOWRAD. The US great plains have been used as a test bed to validate land precipitation algorithms, but due to the sporadic nature of precipitation it is difficult to cross-calibrate various PMRs.

Two-thirds of the global rainfall falls within the tropics, which played a part in the orbit choices for GPM-core, TRMM and Megha-Tropiques, all of which are missions aimed at rainfall quantification. Space-borne PMRs form the backbone of precipitation retrieval [144]. Some ground based radar estimates can be off by a factor of two.

Rain Rates over the ocean, via the "warm rain" beam-filling effect at 19 and 37 GHz, are described for SSM/I in a paper by Wentz and Spencer [253] and over the land, via scattering effects at ∼90 GHz, by Stephens and Kummerow [254]. TMI improved the heavy rain estimates by including a 10.7 GHz channel to quantify surface roughness effects. Rain algorithms are described for the MADRAS instrument [255, 256] and for atmospheric sounders [89, 257]. Precipitation estimates via path-delay radiometers have also been done [258]. AMSR, on ADEOS-II, measured rain, which was important for the scatterometer wind retrieval near storm systems [156].

The average spatio-temporal distribution for a convective rain cell is 10 km for 10 minutes [259]. Therefore the South African climatology group, which uses TRMM data for rainfall, would like a second TRMM in a similar orbit to improve chances of recording rainfall events [245]. An afternoon sun-synchronous orbit could monitor afternoon shower events in the sub-tropical regions.

Statistical studies have been done to estimate sampling errors, both spatial and temporal, due to inhomogeneous rainfall [110]. There have been other studies that try to characterise the drop shape effects [139, 78]. Cloud structure and rain are closely linked and the link is being investigated via PMRs [260].

4.3.1.4 Wind Vector

The wind vector is useful for NWP, climatology and oceanography. It is key to the evolution of several weather systems. Microwave imagers have been able to produce a wind-speed product since SMMR [49], but the wind direction only became available with the fully polarimetric instrument on Windsat. Sea Surface Wind vector, made up of the SSWD and SSWS, has become available as a product from PMRs [78]. Several hurricane SSWS have been estimated by airborne programs [261].

Since the sea surface roughness is related to SSWS and the roughness is also related to the emissivity, we can estimate the SSWS [222]. This shows that sea state and SSWS are closely correlated, hence SST and SSWS estimates are complementary [16]. Although, the effect of foam with increasing SSWS has an effect, because foam has a higher emissivity than water, the amount of foam can be estimated via polarimetry [262]. Special care has to be taken since there are two types of waves, capillary waves (ripples) and gravity waves (swell), and capillary waves are transient having a short lifetime. The SSWD signal is quite small and easily obscured by atmospheric effects. The scientific requirements for the wind vector accuracy are better than $\pm 2m/s$ and $\pm 20^o$.

The frequencies used are 10.7, $\sim$19 and 37 GHz and full polarization is used for SSWD, since if only dual polarisation is used there is a 180^o ambiguity in the SSWD [263]. The incidence angle also plays a large role in the inversion technique to estimate the parameters. Due to geometry of the surface, the higher the SSWS the better the SSWD estimate, for SSWS under 6 m/s the measurement range of SSWD is below the sensitivity of the instrument. The definition of the rain flag algorithm is found to be critical to the quality and availability of the SSWS data. Although cloud does affect the higher frequency channels, the U Stokes parameter was found to be insensitive to clouds; another PhD thesis proposed that a linear combination of dual-pol channels was atmosphere independent, leading to SSWD extraction from dual-pol instruments at high SSWS, 10 m/s+ [264, 265, 158, 168, 266, 224].

The wind vector algorithm is usually an empirical one since the inhomogeneities in the footprint render the exact model extremely complex. For Windsat, a relatively simple plane parallel atmospheric model is used for the atmosphere, the constants needed for the inversion need to be known a priori and validated over time [167]. The cross polarization requirements for fully polarised radiometers for SSWD, are typically exceeded by off-set parabolas, so post-processing is needed to reverse the effects and extensive antenna characterisation is required [18]. In no cloud conditions, the 37 GHz channel is used to estimate SSWS due to superior sensitivity and resolution.

The MSMR instrument by India contributed to SSWS measurements via neural networks [203]. However, it should be remembered that most of the wind vector measurements are provided by active instruments, such as scatterometers but are costly especially since they have to be dual view for SSWD retrieval. The PMR rain estimate is important for the scatterometer wind retrievals [156].

A possible future area of research is the extraction of 3-D winds via temperature and humidity sounding from GIMS and GeoSTAR. Another current area of research is extracting sea state estimates from GNSS reflectometry.

4.3.2 Upper Atmosphere

MW limb-sounding is a method by which the upper atmosphere can be horizontally stratified, e.g. chemical vertical distribution profiles, such as: H_2O, HCl, HNO_3 and O_3. Aerosol monitoring is important; SO_2 from volcanoes has implications for IR instruments, which can be biased as a result of aerosols in the atmosphere. Aerosol effects could also be estimated by comparing accurate SST measurements from IR and MW measurements. One of the first missions launched to take limb sounding measurements of the upper atmosphere was the Swedish Odin mission, the mission is described by Murtagh et al. [72] and the frequency selections by Merino et al. [74]. UARS had the MLS, which was earlier but did not quite reach into the sub-mm region of the spectrum.

Several of the species that can be studied have many lines, but only a few are strong enough to be observed, and some are too isolated to justify building an instrument just to observe that line. The OH distributions, which act as a catalyst in O_3 reactions, can be sounded at frequencies higher than 1.8 THz [96].

The use of sub-mm wavelengths complements IR sounders looking at ice clouds in the atmosphere, the longer wavelength allows analysis of larger ice crystals and has further penetrability. Microwave limb sounding has been used to monitor the variability of the atmosphere including: the effects of bush fires on the upper atmosphere [267], the more common aerosol distributions from volcanoes, gasses in chemical processes involving nitric acid and ozone [268]. This monitoring is linked to the global warming and climatology groups. The ability to track aerosol distributions emanating from ship smokestacks also has implications for ship tracking and naval operations.

Future limb-sounders are discussed in a paper by Klein et al. [94], the SMLS mission on the GACM project will further characterise upper atmospheric water and aerosols, at better resolutions than MLS on Aura [170]. Several lines have still not been explored in Earth observation including lines at 1.4 and 1.9 THz but the technology is in use for astronomical purposes on Herschel [73]. However, given the opacity of the atmosphere at this range of frequencies limits the depth to which the limb sounding can be performed.

4.4 Examples of final products

The derived products are described so as to see the end result after the data has been processed, like weather forecasts, climatological models, drought predictions and flood warnings. The end-users would include the weather service, navy, climate change research groups, agricultural policy makers, oceanographers, hydrologists, marine biologists and possibly the forestry commission. Several PMR description documents also outline scientific final products, like for SSM/I and SSMIS [269, 270].

There are some final products from JAXA shown in Figure 1.1 and 1.2. Table A.1

is taken from the GCOM-W1 mission specifications [271] and shows the products and their associated accuracies. An extremely large and complex spacecraft would need to be built to satisfy the needs of all the possible users of PMRs, so an optimum instrument that gives the most useful products for the least design challenge is usually built.

Examples of specific products that PMRs could contribute to include; fish stocks from SST and marine boundary layer models that interrelate SSWS and currents in the ocean, from TIW observations [83]. The ITU list the following as products for PMRs, the same report goes on to say what the impact of various PMRs on NWP are [272].

- Hurricane/extreme event monitoring/forecasting
- Rice production in India
- Desert expansion in China
- Oceanographic products (SST, currents, etc.)
- Hydrological products (rainfall, snow, etc.)
- Earth's water cycle studies
- Global warming models and climate studies
- Crop yield forecasting and irrigation planning
- Identification of potential famine/flood areas
- Forest fire protection
- Monitoring areas prone to erosion and desertification
- NWP initialization

4.5 Alternative data sources

There are several other instruments that can give data, to a better or worse precision, or contribute to data given by PMRs; for instance SAR has extremely high resolution but cannot give a SM product. Other radars that have been used include CloudSat, TRMM PR, GPM-core DPR and QuikScat, for products like rain-drop size and shape, SSWD, SSWS and sea surface roughness [138, 139, 156].

Optical images of lakes and or altimetry can help to estimate the amount of free water in the FOV of SM instruments. IR sounders give superior temperature sounding profiles near the surface. IR instruments also provide a superior SST product, MTVZA-OK from Russia combined a PMR with an IR imager, both having co-located swaths [23]. Most missions dedicated to detecting aerosols use IR instruments. Synergy is often cited in PMR e.g. the AMSU-AIRS combination is used together to characterise CO_2.

Sometimes ground sampling is the best method, for example with current SM resolutions, farmers would do well to sample their soils in-situ, SST values near the coastline can also be tricky via remote sensing methods. There are other techniques like GNSS signal detection on the ground for estimating electron content in the ionosphere; the opposite is also possible, i.e. to have several transmitters on the ground transmitting to space with vertical polarisation to be detected in space and the Faraday rotation estimated.

4.5.1 Synergistic Data Centres

There are several data centres around the world that receive and process satellite data for end users, these include: Joint Center for Satellite Data Assimilation (JCSDA), Global Earth Observation System of Systems (GEOSS), Committee on Earth Observation Satellites (CEOS), Global Satellite Mapping of Precipitation (GSMaP) and European Centre for Medium-Range Weather Forecasts (ECMWF). South Africa should build and expand a capability in this area, to fully utilise space technology. South African Environmental Observation Network (SAEON) is fairly limited in profile, and has a focus on climate change and bio-diversity, it could add oceanography and climatology to its profile. There is a need for a conference to cross-pollinate between engineers and scientists interested in the various fields of space technology, including space weather and EO, at the national and regional level.

There are several experiments and algorithms that contribute data to these data centres or fulfil other scientific needs. Such experiments include; the Global Energy and Water Cycle Experiment (GEWEX) for SM data and NOWRAD which is a radar network that uses uses NEXRAD (Next-Generation Radar) data to provide cloud property and rainfall estimates [70, 156]. An example of a synergistic algorithm is the Microwave Infra-red Rainfall Algorithm (MIRA)[144]. The A-train constellation aims at characterising anthropogenic aerosols and the atmosphere in general via several different instruments in similar orbits[273, 274]. TRMM was designed to synergistically analyse precipitation data from a PMR, radar and optical/IR information sources [254]. The SMOS mission will provide data to several programmes, for instance GEWEX and the Global Ocean Observing System (GOOS) [19].

A related up and coming area is synergistic models for data processing centres. As models become more complex and the number of types of instrument contributing data increase, the stronger the need for dedicated data processing centres and the corresponding research to verify that the models are continually optimized.

Chapter 5

Recommendations for a South African Passive Microwave Radiometer

This chapter aims to describe a feasible PMR instrument that South Africa could send up, in light of the literature review described in Chapters 3 and 4.

5.1 Background

Audits have been commissioned under the Department of Science and Technology (DST) in South Africa on the state of the South African space sector, both industrial and academic [275, 276, 277]. There was a more recent survey done in preparation for the IAC 2011 by the Tauri Group [278]. There are many companies within South Africa that have abilities relevant to the space sector.

5.1.1 South African Facilities

During the early 1990's the GreenSAT program was shut down. It was aimed at giving South Africa a military presence in space. With the transition to the "rainbow nation" the capability was no longer needed hence left fallow and in some cases, destroyed. The testing of electromagnetic compatibility facilities from that era at Houwteq are still operational. The Overberg test base/range owned by Denel is a viable launch facility, should a launch capability become available.

South Africa has much of the expertise needed for a space-borne PMR, evidenced by the fact that SunSAT and Subandila Sat were launched, SALT (Southern African Large Telescope) and KAT-7 (Karoo Array telescope) have been built and are operational, user communities already use data in the SAEON (South African Environmental Observatory Network) network and the South African National Space Agency (SANSA) was founded. A radiometer has been built as an undergraduate project at UCT [279]. It is easy to use and can be used to demonstrate simple experiments such as soil moisture and water temperature. There was also a radiometer constructed for the purpose of landmine detection at UCT [280].

SANSA has an Earth Observation (EO), Space Science and Space Operations division. The Centre for High Performance Computing (CHPC) has a good data processing ability. There are several other programs available though the Council for Scientific and Industrial Research (CSIR) that would relate to a mission to put a PMR in space.

5.1.2 Motivations for a space instrument

Developing nations stand to gain from space technology programmes, both from a government policy perspective and from an economic perspective. Furthermore, the development and training of a user community for an Earth observation instrument is another large contributor to technological self-sufficiency. Before a country can put up a satellite that meets the nation's operational requirements, a demonstrator instrument to verify that critical subsystems work, would be a vital stepping stone to larger projects in the future. Scientific trust needs to be established in a basic instrument, and the manufacturing capabilities of South Africa, before funding for better and more complex projects can be acquired. To this end, many of the facilities will need to be maintained and upgraded.

There are many applications that utilise PMR data, such as oceanography, hydrology, NWP and now-casting, that developing nations would do well to utilise. Developing their own purpose-built algorithms to process the available data into usable products, would allow for useful proposals of future instruments in the microwave spectrum or otherwise, that would fill deficiencies in that countries needs.

The commercial needs of the country can be met by owning a satellite that is sent up, as is the case for "New Dawn" which was financed by South African entities. Other cases, like the South African Weather Service (SAWS) buying preprocessed data from Europe, could benefit from the same product, produced locally, subsidised by government. In the case of high resolution imagery, many countries are willing to pay for access to images, which in turn creates revenue. The innovative techniques and technologies developed to meet the challenges of the satellite launch will also create wealth for the country as those products become available commercially. There needs to be a tax policy in place that encourages local innovation as is the case in the US [281].

The academic needs of South Africa are plentiful and as the government strives to build a knowledge based economy, the pressures on academic institutions to provide the infrastructure for knowledge transfer are high. The skills building and transfer involved in developing a satellite will benefit society at large as those skills proliferate into the workplace. Also, where the academic skills to interpret the data are not available in the country, the studies during the technology validation phase would introduce the option for developing models and products locally and developing said skills.

The long term publication count would be high for a well used instrument since the design, validation and data analysis each will have publications years after the launch of such an instrument. In the case of the Indian MSMR, papers were still written ten years after the launch, focusing on Indian requirements [201, 203]. Other countries have written several papers about the design of their respective demonstrator instruments [282, 184, 283, 131, 100].

While a demonstration mission is being sent up, ground testing for more complicated instruments should be in process for launches ten years from then. Presently, such missions might fall under the GCOM and GPM constellation missions. In preparation for joining international satellite constellations and/or instruments on international satellites, care should be taken to ensure interoperability of hardware, software and data formats with the international partners during development.

Also as scientific models get more complex, the demand for higher quality and more frequent measurements goes up, this leads to the need for an improvement over current instruments and an increase in the number of instruments, for instance wind or rain measuring instruments.

Politically a viable space program brings prestige and leverage to South Africa in dealing with the worldwide community. A launch capability would allow South Africa to join countries such as India, Japan and Israel as well as the EU in matters relating to space launch activities. India currently boasts an end-to-end ability in its space program. Africa, to date, has not sent up a PMR. India, Brazil and Argentina have all sent up locally manufactured PMRs. Europe's policies and motivations with regard to space are outlined in a document by the European space policy institute [284].

Given that the US is bound by ITAR restrictions, they might not be a good partner in developing a home-grown PMR, but China with its recent development and launch of the FY-3 series may be an ideal partner. On a related note, Russia is beginning to focus more on unmanned space flight [10]. However, the option of collaborating in a larger space craft must not be discarded, the mention of Japan building the AMSR series with the US was made in 1989 [71], for eventual launch in 2002. JPL builds the radiometers for the European Jason altimetry satellites principally made by France [55]. Europe has few current PMR instruments apart from the ENVISAT-MWR and SMOS.

5.2 Recommendations for a South African PMR

The field of MW radiometry has implications in oceanography, meteorology, climatology and hydrology with products such as sea surface temperature, wind speed, precipitation, ice type and extent, soil moisture etc. Passive Microwave Radiometers (PMRs) are advantageous compared to various other forms of remote sensing of Earth, e.g. radar and IR, because they consume less power, are independent of clouds or aerosols, are independent of sunlight or are able to penetrate vegetation. The penetrability of L-band microwaves has been used to measure the stratification of soil moisture on Earth [11] and even regolith types on the Moon [285]. However, given the long wavelength of the microwaves versus aperture size, spatial resolution is significantly inferior to infra-red instruments, with space-borne PMRs usually having spatial resolutions in the 10's of km.

Use of up-to-date PMR data inversion models within South Africa now, will allow studies to see which channels have the most impact on NWP or other fields of research and therefore allow proposals for instruments with those frequencies [248].

5.2.1 Summary of the choices

The sensitivity graph, Figure 5.1, shows that above 5 GHz there are 4 factors that have a significant effect on the brightness temperature of the ocean surface, which in turn lead to SST, SSWS, CLW and IWV estimates. There is another similar plot relating the SM, biomass, CLW, IWV and surface roughness estimates over land [59]. Since most of the time a PMR is observing the poles or the oceans, an instrument optimised for the oceans with some terrestrial by-products would give the most data return.

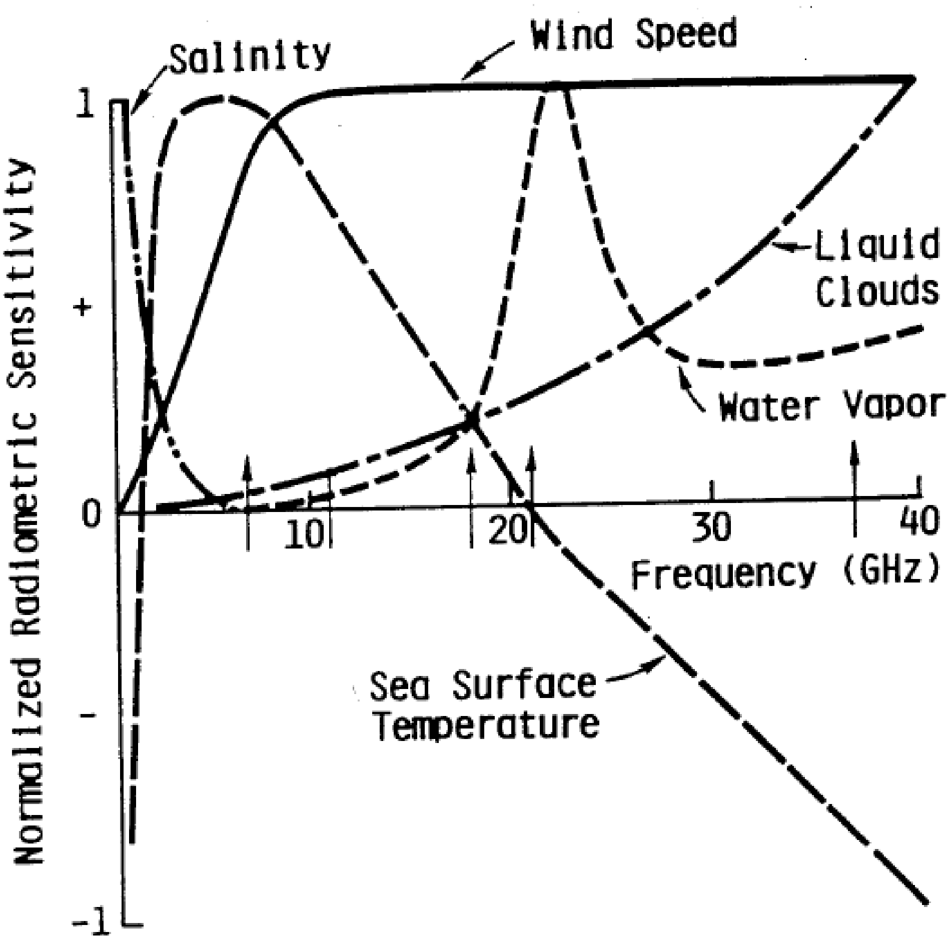


Figure 5.1: Plot showing the sensitivity of the apparent brightness temperature of the sea surface to changes in the geophysical property, taken from a review by Njoku [6, 124].

There are several design decisions in passive microwave radiometry, some technical such as the choice between real aperture and aperture synthesis, and others more to do with the end products such as Imagers, Atmospheric Sounders and Limb Sounders. The frequencies of choice are limited by ITU regulations in order to limit RFI from terrestrial sources.

Each frequency contributes to one or more products, and in general there will be as many end products as there are frequencies. For example, atmospheric liquid water, integrated water vapour and wind speed/surface roughness require three frequencies, usually the frequencies 37 GHz, 22.2 GHz and 18.7 GHz respectively are chosen. The products are all interrelated, hence the need for simultaneous extraction. A rain rate estimate from three frequency TMR frequencies is possible [258]. $\sim$6 GHz is most sensitive to SST but there is no passive band regulated by ITU in this region, the closest is 10.7 GHz. The 10.7 GHz frequency is sensitive to SST above 20^oC but is much more sensitive to wind speed at all temperatures and can be used to remove ocean surface effects from the 6.8 GHz channel [222]. There is 97% transmission through atmosphere at 10.7 GHz so there are minimal, but significant, atmospheric effects in this channel [83].

So given the following key instruments:

- L-band sensors such as SMOS and Aquarius
- Complex atmospheric sensors e.g. SSMIS, MTVZA and ATMS
- GEO atmospheric sounders e.g. GeoSTAR and GIMS
- Sub-mm limb-sounders e.g Odin and MLS
- Atmospheric sounders e.g. SSM/T(2), MSU, MWTS and HSB
- MW imagers e.g. SMMR, SSM/I, TMI and MWRI
- Dual frequency atmospheric sounders, e.g. ERS-MWR and Dream

Imagers were chosen for final study due to simplicity, heritage and use. However, keeping in mind all of these options require a large amount of skills and expertise.

Many of the national space agencies have started out with simple instruments, the Mariner-2 instrument in the case of the US, Cosmos 243 in the case of Russia, both of which were originally designed as four frequency instruments.

A 2.7 GHz channel would be better for SM, due to vegetation penetration, and introduces the possibility of coarse SSS estimates. Although the presence of Aquarius data would allow 2.7 GHz to be useful for SST, along with 6.8 and 10.7 GHz, the lower frequency means the feed-horn will be prohibitively big and the spatial resolution bad. The horn(s) for 6.8 and 10.7 GHz will present a challenge on a micro-satellite. A NEMS type temperature sounder would be a possible addition but the size and weight constraint would probably preclude its use, in addition, the practical use in view of the already operating AMSU-A instrument would be extremely limited [132].

Choice of the placement of the ~18 and ~22 GHz channels is based on the trade-off of keeping the frequencies close together or getting better sensitivity to the parameters of interest and, on occasion, the presence of ITU protected bands [142]. The TMI design used 21.3 GHz instead of 22.2 GHz to avoid saturation of the instrument in a tropical orbit. The effect of TPW on TMI measurements was found to be 15 K for the 10.7 GHz channel and 35 K for the 37 GHz channel. Rain flags are also critical to ensure data quality [158]. Multiplexers introduce losses, and therefore degrade sensitivity.

5.2.2 Instrument selection and discussion

After completing a literature review of the various aspects of PMR missions from various countries, an instrument is proposed that would have the most benefit to current research, while still being relatively simple and useful as a platform for validating technology for future PMR instruments. The specifications of comparable instruments are shown in Table 5.1. The author reckons that a dual frequency instrument, such as the Dream instrument by Korea [191, 192], would have extremely limited applications for the scientific community, therefore would only lead to a limited amount of research and associated publications.

Table 5.1: Table showing a comparison at a glance of PMR imagers

PMR	Year of launch	Weight (kg)	Power (W)	Number of feed-horns	Max. NEΔT <40 GHz (K)	Aperture (m)
SMMR	1978	55	65	1	<1.5	0.79
SSM/I	1987	48.5	45	1	<0.7	0.6
TMI	1997	65	50	2	<0.6	0.6
MSMR	1999	65	76	1	<0.9	0.8
AMSR-E	2002	314	350	6	<0.7	1.6
Windsat	2003	341	350	11	<0.63	1.8
MWRI	2008	175	125	4	<0.45	0.9

South Africa is a relatively lightly vegetated country and surface SM can be detected with a 6.8 GHz channel, as can be seen from the AMSR-E SM product. Atmospheric profiling could be done using a compact IR sensor on the spacecraft which would also open up the meteorological and atmospheric research side for South Africa.

The PMR demonstrator proposed by the author is similar to the SMMR [121] and Windsat [18] missions in choice of frequency. However, advances in technology and techniques should allow for a much simpler design. The four proposed frequencies that the system detects are 6.8, 10.7, ~22 and 37 GHz. Two strongly recommended additional frequencies, 7.3 and 18.7 GHz, can also be used depending on constraints. All frequencies are proposed to be detected by dual polarisation receivers, although the H-pol channel of the 22 GHz frequency would be redundant. This choice could allow the estimation of SST, SSWS, precipitation, ice type and extent, SM, IWV and CLW.

The reason the 18.7 GHz channel has been labelled as optional is that, the sea surface roughness information can also be extracted from the 10.7 GHz channel, albeit with a larger footprint mismatch error. The precipitation product would also be more sensitive to light to moderate rain with the 18 GHz channels, as well as land parameters where there is CLW in the FOV. The optional 7.3 GHz channel is to help identify narrowband RFI within the 6.8 GHz channel [63]. Since the 18.7 GHz channel would share a horn with the 22 GHz channel and the 7.3 GHz with the 6.8 GHz channel in order to save space, the inclusion of these optional channels is dependent on final space, weight and power specifications of the spacecraft.

The non-use of the 18 GHz channel should be tested via AMSR-E data, since the 6.8 and 10.7 GHz channel emissivities are similar for SST $> 20^o$ [222]. The frequencies are very much like Windsat's, all of which are directly detected [18]. The dual-pol capability can allow the characterisation of surface roughness or the circumventing of atmospheric effects [224]. The higher the number of channels, the greater the usefulness of the instrument from a scientific perspective. The lack of a ~90 GHz channel will preclude monitoring of ice clouds and precipitation over land.

The proposed instrument would include a relatively large dish, with an aperture diameter of 1 m, in order to give spatial resolutions that would be scientifically useful, especially in light of the 6.8 GHz channels. Most of the past instruments have had dishes in the 60 cm to 1 m range, as can be seen in Table 5.1 [121, 286, 38]. The lowest feasible orbit would also favour spatial resolution but would result in a narrower swath width, less integration time and greater atmospheric drag. A trade-off study would have to be done once the instrument is assigned to a spacecraft, since other payloads would have different requirements. The availability of better technology might decrease the system noise for better radiometric sensitivity.

5.3 Considerations for design

An overview by Murtagh et al. [72] gives an idea of what considerations go into a small satellite mission. The pre-launch testing of an instrument should be intensive and exhaustive, the calibration procedures are well described in literature for various missions [88, 40].

A ground based then an airborne demonstrator of PMR systems is critical and should be completed before any significant investment in a space-borne mission. The Chinese completed an InSARad demonstrator in 2001 leading to an airborne system in 2004 [130].

The budget will not be big for a space launch in South Africa and this needs to be kept in mind during the design, budgetary black holes should be avoided to lower the risk on the mission success. In the case of the HSB, one of the window channels was discarded due to budgetary concerns. Given the worldwide revolution in microwave frequency devices PMRs can be built using commercially available parts for a fraction of their real price in the 1970's. Space hardening the hardware to be launched will increase the odds of success but also increase the price.

MWRI has a 0.9 m antenna and attempts true end-to-end calibration [38], given that China has recently overcome many of the hurdles of launching a PMR they might be a good collaboration partner. Their experience in developing MWRI, MWTS and MWHS could help South Africa avoid the same pitfalls encountered during design and implementation.

Some of the more general considerations that came up in the course of the survey include:

- South Africa should develop a series of standard satellite buses by size and power.
- The data handling system should be interoperable with systems of the partners (or users) and reusable.
- Inter-calibration is best between satellites in a similar orbit.
- Calibration/Validation activities can bring initially under performing results up to specification after launch.
- Bring scientists and users in early so that data models and products have the problems worked out [287].
- Select the orbit and minimise power consumption for optimally minimum battery and solar panel weight.

5.3.1 ITU and frequency availability

One of the most important pieces of research needed before an instrument can be sent up is whether the frequency is available for the intended use, since terrestrial and space-borne Radio Frequency Interference (RFI) can seriously impact the quality of measurements. The International Telecommunication Union (ITU) frequency allocations are a worldwide nightmare and countries negotiate the frequency spectrum usage between themselves on an ongoing basis, the allocations change at the World Radio-communication Conference (WRC) every four years.

Several studies regarding frequency allocation have been done towards WRCs over the years, these studies often propose mitigation techniques for PMRs [288, 68, 289]. A 2009 ITU report gives a good overview of the topic of PMR RFI, also giving estimations of the effect of RFI or data loss on NWP [272]. Another handbook states why certain bands need to be protected for EO against RFI, and possible mitigation measures [59]. Other researchers have given overviews of the frequency bands required along with concerns for regulation [290].

Table 5.2 gives a brief overview of the allocations that concern the proposed instrument. Due to the fact that 23.6-24 GHz and 31.3-31.5 GHz are exclusive passive bands they are sometimes chosen over the more ideal 22.2 GHz and 37 GHz bands.

South Africa already manges it's terrestrial RFI ahead of the SKA and MeerKAT radio telescope arrays; however, further RFI management is needed to ensure the quality of data, from the PMR demonstrator and other Earth observation PMRs, is at a maximum over South African territories.

Where there is a worry of RFI, like for the 6.8 GHz channel, another receiver centred at a nearby frequency, such as 7.3 GHz [63], can be used to help filter out narrow band RFI. Over sampling can also help detect RFI by detecting significant changes in the signal sample relative to neighbouring samples. Multi-angle observations can detect directional RFI. Dual polarisation allows some redundancy against linearly polarised RFI. However, low-level, but appreciable, noise-like RFI is nearly impossible to detect from space and will have an influence

Table 5.2: Table showing some of the various bands used for PMR and the primary passive ITU allocations [59, 272, 68, 289]

Frequency band	Allocation	Uses	Concerns
6.42-7.25	Partial	SST	GEO broadcast [RR 5.458]
10.6-10.68	Shared	SSWS	Loophole in guidelines
10.68-10.7	Primary	SST/precip.	Out of band RFI
15.35-15.4	Primary	precipitation	Out of band RFI
18.6-18.8	Shared	SSWS	Active services
21.2-21.4	Shared	IWV	Active services
22.21-22.5	Shared	IWV	Active services
22.5-23.5	Not protected	N/A	Inter-satellite comms
23.6-24	Primary	IWV	Out of band RFI
31.3-31.5	Primary	CLW, IWV	Out of band RFI
31.5-31.8	Primary/Shared	CLW, IWV	RFI in secondary region
36-37	Shared	CLW,SSWS	Regulated in-band RFI

on the final products; this means that national RFI standards enforcement is one of the only ways to combat low-level RFI. On the demonstrator PMR the use of 18 and 7.3 would give redundant channels, over the oceans, that can be used for RFI detection or otherwise abnormal effects.

The other concern is internal RFI caused by improper shielding of the radiometer back-end and inappropriate placement of down-link transmitters. The pre-launch testing should test for this kind of RFI.

There have been RFI surveys, using various techniques, done with the Windsat and SMOS projects [117, 166, 165, 185, 118, 119]. Strong interference can have wide ranging impacts on measurements 1000's of km from the source, especially in the case of InSARad. Spain was instrumental in improving the SMOS data around the Spanish peninsula by enforcing the ITU regulations regarding RFI, especially with respect to civilian made transmitters. Some RFI in the C-band is thought to be reflection from the sea of geostationary broadcast signals. RFI detection and mitigation involves techniques like principal component analysis and spectral difference comparisons. The spectral difference technique is not sufficient for sea based RFI due to the large variability in sea state, hence in-situ RFI characterisation is necessary to check the detection algorithms [165].

5.3.2 Technical design considerations

There are several technical aspects that have to be considered for a space borne instrument, including tolerance to radiation, robust power supplies, weight and antenna design.

Direct detection would allow a slight saving in the power demands and enables an increase in the sensitivity. The more traditional sensor set-up is a superheterodyne frequency down-conversion. The lack of need for a local oscillator translates into weight savings. More modern sensors employ direct detection at 37 GHz and experimentally even as high as 170 GHz [269, 228].

Improvements are being made to antenna design and the search for new methods and techniques is on going, such as in a 2000 paper by Gonzalo et al. on improvements to a patch antenna [291] and another paper by Sharma et al. on comparing feed-horn types [125]. There are more geometric considerations like, a single multi-port feed horn placed at the antenna focus minimises the astigmatism at the cost of sensitivity. Harmonics can be used to add frequencies far apart into one feed-horn [126].

The use of passive instruments which are not power hungry lead to systems that are sustainable on a continuous long term basis; since active systems, which are power hungry, can only be operated for short periods and also have a much higher risk of failure, because the transmitter could fail as well as the receiver. The orbit selection has implications for the battery, as a frequently eclipsed satellite would need a large battery due to the high cycle rate, in turn affecting the weight. The need, or lack there of, for orbit maintenance has implications for the amount of fuel needed.

The calibration scheme should be a Total Power Radiometer (TPR) for maximum sensitivity, using a cold sky mirror and a hot source once per revolution for monitoring drifts of the signal. True end-to-end calibration would involve two extra large reflectors, e.g. on MWRI [38], and would prove infeasible on a small satellite. However, vicarious calibration (the statistical use of the jungles and the Antarctic as calibration sources) as well as pitch manoeuvres (exposing the main beam to cold space) should validate the calibration components [164, 84]. Yaw manoeuvres are used to prevent one side of the satellite being overexposed to the Sun.

Other thermal considerations include the emissivity of the reflector, the Cold Sky Mirror (CSM) and variable heating of the hot load with the changing sun angle. Several authors have proposed thermometers in the reflectors as well as the hot source load, to enable post-processing to remove antenna and calibration systematic errors. The temperature of the feed-horn itself is another important parameter.

Also, the technology demonstrator satellite can be built with complementary payloads such as an IR sounder, GNSS limb-sounder or even small compact space weather experiments. By the nature of microwave radiation the size of the satellite has a lower bound due to the need for a large aperture. This precludes the use of picosats and nanosats, at least until orbits can be determined precisely and a free drifting constellation InSARad concept can be developed. Given current technology the smallest satellite bus size we are looking at is micro-satellite size. If a reflector is used, a scanning concept taking advantage of the relatively small size of the feed-horns or of simply spinning the whole satellite, while maintaining calibration and communications links, could possibly be considered.

The orbital environment is highly hostile with: radiation of the electronics, degassing of materials, the presence of space debris, space storms during solar maxima and ionospheric effects. Redundancies, like extra momentum wheels, would mitigate some of the effects of partial failures due to radiation and space debris. Although commercial parts would be cheaper, space hardening the components, especially the vital components, would decrease the risk of premature failure but increase the cost.

The test facilities to test all these considerations and others would have to be built, upgraded or maintained in preparation for South African satellite production.

5.3.3 Academic considerations

The technical and scientific projects should be done in parallel with frequent design iterations between the two to ensure the best product is obtained from an optimum instrument. The scientists do not know some of the engineering constraints and the engineers might not know which specifications are non-negotiable and which can be relaxed.

The addition of a compact IR sounder would increase the applicability of the mission to weather forecasting. Between an IR sounder and the higher frequency channels the atmospheric effect on the 10.7 GHz instrument should be well estimated. Although more channels and instruments means more power needed and in turn more weight, due to extra batteries and solar panels.

Comparison of footprints should be carefully calculated especially when perturbing factors have to be taken into account like in coastal areas, where the areas of different materials within the footprint, e.g. soil and water, need to be characterised accurately [227]. There should be modelling and testing to ensure that none of the channels could get saturated due to lack of dynamic range.

Solar effects have to be well modelled once an orbit is selected, since there are implications for post-processing corrections to the counts from the hot source, CSM and main reflector. The orbit should be selected carefully for scientific impact. The other important consideration is the orbit selection on the specifications of the mission and vice versa. One such consideration is the amount of time downlink ground stations will be in view, as this will determine the amount of on board data storage needed. The interoperability of the data system with other payloads should be maximised. The data format should be optimized for combination with data from other missions in synergistic models, to take full advantage of the complementary nature of PMR data.

A conical scan with an Earth incidence angle of $\sim 50^o$ would maximise the surface effects of the ocean, while keeping the extra atmospheric effects from widening the swath to a minimum. Due to the fact that wind speed is the dominant parameter at 17-19 GHz means 18 GHz gives a good sea state estimate for an altimeter PMR [289]. Also, in warm seas higher resolution SST estimates are possible if there is a 18 GHz channel to estimate surface roughness within the 10.7 GHz footprint. Although over the sea there are four parameters of interest, over the land there are five including surface roughness and biomass, therefore 18 GHz would help differentiate the various contributions to the signal.

5.4 Future options

If the spacecraft, the demonstrator is on, has sufficient fuel and the PMR is well validated then it could join an orbit so as to contribute the optimum product to current scientific constellations.

Although there are many missions that can follow on from a successful launch and operation of a PMR on a satellite, the author will limit the discussion of follow-on instruments to PMR types only. The reader should be aware that there are many other options such as optical, IR and radar instruments that would have to be included in the selection study for a follow-on mission. That said, there are many excellent options to choose from among PMRs.

Several missions have combined a radar and radiometer, for instance altimeters, sometimes sharing an antenna, as was pioneered on the GFO [292]. Synergistic radar-radiometers like SMAP and ADEOS-II would allow the best of both words, e.g. rainfall characterisation and mitigation [139].

The weightings and specifications of the various kinds of missions, from the perspective of EUMETSAT, are described in their Post-EPS proposals [293, 294].

5.4.1 Follow-on missions

Once the demonstrator satellite is successfully launched and operated, the scientific scope for the next instrument should widen significantly. Firstly atmospheric sounders, which would give temperature and humidity profiles of the atmosphere, are useful for NWP. Secondly, larger and more sensitive microwave imagers that would make a contribution to the Global Precipitation Mission (GPM) constellation or other constellation series in the future, such as the proposed African Resource Management Constellation (ARMC), could be proposed. Finally, the other Earth observing instrument category that could follow on is a Limb Sounder, possibly on a space weather satellite, profiling the upper atmosphere and perhaps also performing sub-mm/THz astronomy on a time share basis [72].

The ITU are going to assign a large amount of bandwidth above 275 GHz to science in February 2012 [26], so instruments taking advantage of the new or existing allocation should be considered, principally limb sounders and astronomical instruments. Since there is a security application of mm and THz radiometers [31], the technology should improve drastically, allowing South Africa to take advantage of the new technology especially in the PMR back-ends. The other possibilities, outside the scope of this dissertation are interplanetary missions as well as semi-passive GNSS reflectometers and occultation sounders.

South Africa should bid to have instruments or possibly a satellite bus built by South Africa placed on the next cycle of decadal satellite instruments, from developed countries, which will be sent up to continue and improve the data gathering ability of the current satellites in orbit. That way we can avoid the risk of using a completely untried system and share the costs of the launch. There should be standardised satellite bus designs developed by South Africa for South Africa in the various size and power categories. These buses should feature redundancies like extra momentum wheels to avoid the Subandila experience.

5.4.2 New concepts and technology

There are several new concepts arising including digital beam-sharpening [137, 89] and hyperspectral sounders [21]. Also, the atmospheric effects could be circumvented using a linear combination of dual-pol channels leading to more accurate estimates of surface parameters [266, 224]. Novel concepts are shown with GIMS, reducing the number of baselines but not the quality of the image along with a TPR calibration scheme, for aperture arrays [46].

The technical options in a follow on instrument might enable further validation of newer concepts, such as aperture synthesis radiometers, from LEO or GEO [20, 19, 106, 46]. The GeoSTAR concept is experimenting with 4 rows of receivers to improve sensitivity across the field of view of an InSARad [135]. The GIMS, GeoSTAR and SMOS-NEXT concept could be combined into a rotating linear array at GEO, or a rotating ESTAR. Quasi-optical beam multiplexing would allow mass and volume reduction [127]. The use of Monolithic Microwave Integrated Circuits (MMIC) allows radiometer back-ends to be smaller, less power hungry and lighter.

Some concepts are coming out including formation flying in SMOS-NEXT [186], this is to address the need for an order of magnitude increase in the resolution of soil moisture measurements. Formation flying [295] in space is a large field of research especially in the field of VLBI [296]. A next generation limb sounder will use a novel toric cassegrain antenna to get the required resolution but still fit in a launch vehicle [172].

5.5 Conclusion

The conclusion reached is that PMRs are useful to an extent but there are currently insufficient numbers to characterise rainfall so many missions are being launched to characterise that. South Africa could well contribute to the GPM constellation, since there is demand in the climatology field to have more frequent precipitation measurements.

A conference at regional or national level is needed, to bring users and engineers of space technology together, enabling engineers to solve some of the problems for the scientists and vice versa. Some useful technologies for InSARad are being directly ported from radio telescopes, like ALMA [297].

The instrument proposed is presented in Section 5.5.2 and is based on the SMMR and WindSAT missions both of which were ground breaking in their own right.

5.5.1 Follow-on Research

Due to the fact that any future PMR mission will require significant resolution, South Africa needs to verify our ability to launch a reflector; and find if sharing a reflector with an IR instrument, while not interrupting the scan, is feasible [23]. Layouts that can accommodate a sizeable dish onto a small satellite should be researched, for instance the SMAP concept or alternatively have the dish in two halves down the side of the satellite during launch. The scan should be uninterrupted.

A ground based, leading to an airborne, demonstrator should be built. This will engage the engineers and the user communities in the PMR types and data products respectively. If a space mission is launched the airborne demonstrator can characterise and validate the inversion algorithms for data extraction.

The applications should be investigated by processing current PMR data at local satellite applications centres in user end products, this would allow for a demand assessment for processed PMR data within South Africa. That being said, it might only be after the news that a PMR might be or has been launched that the South African user community will investigate the PMR options. If there is a demand, then the user community will propose instruments that meet their needs, once they know the option is available and validated. Too many people still are unaware of the South African space program.

There should be an orbit study to see which orbit would make the best contribution to the GPM mission. An orbit that covers the most sampling holes for the MADRAS, GMI and TMI instruments would increase the appeal internationally.

5.5.2 Summary of the Instrument

The instrument proposed is a microwave imager with the following specifications 500 km altitude and $\sim 50^o$ EIA. The summary is shown in Table 5.3:

Table 5.3: Proposed instrument summary

Parameter	Baseline	Goal
No. of frequencies	4	6
Power needs	70W	40W
Weight including reflector	70kg	50kg
NeΔT all channels	1 K	0.5 K
Reflector aperture	0.6 m	1 m
Frequency (GHz)	**Product(s)**	**AT footprint size km**
6.8	SST/SM/RFI	50
(7.3)	SST/SM/RFI	54
10.7	SST/SM/SSWS	34
(18)	SSWS/precip.	20
22	IWV/CLW	21.4
37	CLW/precip. Sea ice/snow/SSWS	10

*AT stands for Along (scan) Track using AMSR-2 geometry.
A 1 m aperture is assumed.

For a geometry with a 500 km altitude and a $\sim 50^o$ EIA, the maximum swath would be $\sim$ 1000km. The swath would probably be closer to 800 km, due to the calibration system. A low inclination orbit, $\sim 35^o$, would maximise coverage of South Africa's oceans and the global precipitation.

Appendix A

GCOM-W specifications

Table A.1: Table from a Research Announcement showing the products and the associated accuracies expected for the GCOM-W mission [271].

GEOPHYSICAL PRODUCTS OF GCOM-W1

Product	Areas	Grid (km)	Accuracy [1]			Range	
			Data release threshold	Standard	Goal		
Integrated water vapor	Global, over ocean	15	±3.5 kg/m^2	±3.5 kg/m^2	±2.0 kg/m^2	0-70 kg/m^2	Vertically integrated (columnar) water vapor amount. Except sea ice and precipitating areas.
Integrated cloud liquid water	Global, over ocean	15	±0.10 kg/m^2	±0.05 kg/m^2	±0.02 kg/m^2	0-1.0 kg/m^2	Vertically integrated (columnar) cloud liquid water. Except sea ice and precipitating areas.
Precipitation	Global, except cold latitudes	15	Ocean ±50 % Land ±120 %	Ocean ±50% Land ±120 %	Ocean ±20% Land ±80 %	0-20 mm/h	Surface precipitation rate. Accuracy is defined as relative error (ratio of root-mean-square error to average precipitation rate) in 50km grid average.
Sea surface temperature	Global, over ocean	50	±0.5 °C	±0.5 °C	±0.2 °C	-2-35 °C	Except sea ice and precipitating areas. Goal accuracy is defined as monthly mean bias error in 10 degrees latitudes.
Sea surface wind speed	Global, over ocean	15	±1.5 m/s	±1.0 m/s	±1.0 m/s	0-30 m/s	Except sea ice and precipitating areas.
Sea ice concentration	Polar region, over ocean	15	±10 %	±10 %	±5 %	0-100 %	Accuracy is expressed in absolute value of sea ice concentration (%).
Snow depth	Land	30	±20 cm	±20 cm	±10 cm	0-100 cm	Except ice sheets and dense forest areas. Accuracy is expressed in snow depth and defined as mean absolute error of instantaneous observations.
Soil moisture	Land	50	±10 %	±10 %	±5 %	0-40 %	Volumetric water content over global land areas including arid and cold regions, except areas covered by vegetation with 2kg/m^2 water equivalent. Accuracy is defined as mean absolute error of instantaneous observations.

1 Accuracy is defined as root-mean-square error of instantaneous values unless otherwise stated. Assumed validation methodologies are not explained here.

Appendix B

Major missions past and future

B.1 Major instrument series

This section describes the main meteorological satellite series from various agencies being sent up for meteorological purposes, providing the time series and temporal resolution required by climatological and NWP models.

B.1.1 DMSP

The Defence Meteorological Satellite Program was started to give US forces operational weather updates. The following instruments were the main Special Sensor Microwave (SSM) PMR series flown on this series of satellites. The use of many satellites in orbit simultaneously favoured revisit times.

B.1.1.1 SSM/I

A paper by Hollinger et al. [286] describes this highly successful imager. SSM/Is were launched on most of the DMSP satellites in the series F08-F15. It involved seven channels at the frequencies 19, 22 (V-pol only), 37 and 85 GHz. A good overview of the products offered by this series of instruments can be found in a model validation document by Hollinger and several other papers [82, 150, 298]. Colton and Poe describe the sensor inter-calibration between F-8 to F-14 [299]. Other sensor inter-calibration documents refer to SSM/I series as the baseline, due to the fact it has a long time series [160, 115].

The sensitivity was <0.8K for all channels. The mass was 48.5 kg and power requirement 45 W. SSM/I was used in the desert storm operation, and was able the detect targets under the smoke allowing for the war to be shortened [124].

B.1.1.2 SSM/T and SSM/T2

SSM/T went up earlier than SSM/I on the F-4 satellite mission in 1979 then later, more successfully, on the F-7 satellite mission in 1983. It targeted the oxygen line complex, at seven frequencies between 50 and 60 GHz, for the purposes of temperature sounding; useful at high altitude as well as in cloudy regions where IR sounders can't reach. However it has a low resolution of 175 km at nadir. It was launched alongside the SSM/I until F-15 when it was replaced by SSMIS [5].

SSM/T2 was launched on F-11 in 1991 and was used for humidity profiling, with 5 channels, 3 of which were centred on the 183 GHz line, at extremely low resolutions (~50 km). The last was launched on F-15 and also replaced by SSMIS. The data was compared with an airborne sensor, MIR, and exhibited good agreement [300]. Along with the UARS MLS it was one of the first instruments to carry 183 GHz atmospheric sounders. The global baseline for sounders is generally provided by MSU/AMSU series with the better resolution.

B.1.1.3 SSMIS

This Imager/Sounder is the next generation of SSM which combines the functionality of SSM/I, SSM/T, SSM/T2 with 24 channels from six multiplexed horns, with most of the channels dedicated to temperature and humidity sounding applications. SSMIS first flew on F-16 in 2003 and again on F-17 and 18. The design and testing are presented in a paper by Kunkee et al. [269]; The testing was rigorous and the use of a directly detected 37 GHz channel is mentioned. The instrument details and applications are presented in a report by Northrop Grumman [218]. The calibration and validation user manual for this instrument shows the effects of a wider swath than SSM/I and describes the validation procedures being developed, to allow the data to be reliable for NWP [301]. The cal/val period was 18 months for F-16.

The weaknesses of using the conical scan and the effects of the sun are described by Bell for the UK met office [97], and Yan and Weng characterise antenna radiation anomalies as well [98]. The inter-calibration of SSM/I on F-15 and SSMIS on F-16 was carried out and show a high degree of correlation [270].

B.1.2 NOAA

The National Oceanic and Atmospheric Administration (NOAA) PMR instruments, AMSU and MHS, have a significant impact on weather forecast models, with an impact factor that is the same as some of the more advanced IR instruments such as IASI [24].

B.1.2.1 AMSU

The Advanced Microwave Scanning Unit was first launched in 1998 on NOAA-15, since then NOAA 16-19 have carried AMSU-A. NOAA 15-17 carried AMSU-B. Other missions that carry AMSU-A include Aqua [189] and Metop-A. Several papers including one by Patel give a description of the AMSU-A instrument [52, 302]. The AMSU-A instrument involves two reflectors, one for the low frequency 23 and 31 GHz channels (AMSU-A2) and the other for the 50-60 GHz and 89 GHz Channels (AMSU-A1). AMSU-B was built by UKMO [88, 303], taking heritage from the SSM/T2. Rosenkranz describes the data that can be extracted from the AMSU series [120].

AMSU-A is designed to give temperature profiles in the atmosphere while AMSU-B is designed to give humidity profiles, however, other products have been obtained e.g. precipitation [257]. The record of AMSU-A has had issues with: calibration drifts on the instrument on NOAA-16 and the short time of operation of AMSU-A on NOAA-17, due to a scan motor malfunction [148]. AMSU-B had issues with internal RFI due to improper shielding.

B.1.2.2 MHS

The Microwave Humidity Sounder (MHS), was first launched on NOAA-18 in 2005, then again on Metop-A in 2006. MHS was built to replace AMSU-B. The calibration of the NOAA-18 PMR is described by Mo [304]. AMSU and MHS have been used to characterise extreme weather events with reasonable accuracy [305]. MHS was built in the UK under contract to EUMETSAT.

B.1.3 Metop

Metop series is launched by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and ESA. They launched Metop-A in 2006 and plan to launch Metop-B in 2012, then Metop-C five years later. The Metop series is being launched as a replacement of the TIROS series, in the NOAA morning orbit [153]. This series is the first European polar orbiting meteorological satellite series, carrying AMSU-A and MHS among its payloads.

B.1.4 NSMC-CMA

The National Satellite Meteorological Center/Chinese Meteorological Administration (NSMC-CMA) is the governing body for China's new Feng-Yun (FY) series. Feng-Yun which translates to wind cloud literally is an apt name for this series of satellites which is aimed at meteorological applications. The FY-3 and FY-4 series have PMRs aboard.

B.1.4.1 FY-3

There are several overviews and descriptions of the FY-3 satellite series [45, 44]. The payload includes the MicroWave Radiation Imager (MWRI), MicroWave Temperature Sounder (MWTS) and the Microwave Humidity Sounder (MWHS). The three instruments loosely resemble the SSM/I, SSM/T and SSM/T2 of DMSP. The first satellite FY-3A was launched in 2008 and FY-3B in November 2010.

The five frequency MWRI is being validated in orbit, including inter-calibrations with other PMRs [38, 39]. The FY-3B MWRI has better linearity than its 3A counterpart. The products obtained will be similar to TMI, given the similar frequency allocations. The most interesting feature of the MWRI is the attempt at true end to end two point calibration. The integration time is staggered by frequency due to the differing footprint sizes. The power need for the 175 kg MWRI is 125 W. The 0.9 m aperture is illuminated by four feed horns with sensitivities of $<$0.45 K.

The four oxygen complex frequencies for MWTS are described in a paper by Lu et al. [43] along with the five channels for MWHS. The paper also describes the procedures for capturing and analysing MWTS data as well as MWHS for NWP and the impact on the forecast accuracy of the various instruments. The four frequencies are more similar to AMSU-A frequencies than the older MSU frequencies, in spite of being close in design.

The MWHS is an instrument inspired by AMSU-B flown on NOAA satellites. A paper by Li et al. describes the specifications of MWHS then presents some results from the sounding mission [41], another paper by Wang et al. discussed the pre-launch calibration and validation procedures for MWHS [40]. Neural networks are used to retrieve humidity profiles from MWHS data [42].

The FY-3 series of instruments is fairly reserved in complexity and capitalizes a great deal on heritage. The FY-3 PMR instruments put up by China should be strongly considered during design work for a future demonstrator PMR on a South African satellite, or a future meteorological space borne PMR. Collaborations should be fostered where possible to enable technology transfer.

B.1.4.2 FY-4

The first InSARad microwave temperature sounder from GEO is expected to go up with the FY-4 mission in 2015 [144]. This capability is one of the biggest gaps currently remaining in weather forecasting systems. There is a novel two point calibration idea for the InSARad array, called the Geostationary Interferometric Microwave Sounder (GIMS) [46], where they propose a rotating circular array of elements which pass a hot black body and a cold sky mirror one per revolution. By using a rotating circle of elements, where the baselines are rotating, allows for fewer elements to be needed in the array, while maintaining resolution performance. This is provided that the scene of interest stays static on the time scale that the array rotates and since the ground resolution will be ~50km the scene can be assumed to be constant. The samples from a half revolution can be correlated and an image produced, thus producing two snapshots per revolution of the array.

There has been mention of including a sub-mm capability on the FY-4 series [37].

B.1.5 Roscosmos-Roshydromet

Since 1968, with the USSR Cosmos program, the Russians have been launching PMRs that are on a level if not better than their US counterparts. After USSR collapsed there have been collaborations with Warsaw pact countries. The meteorological series of PMRs they launch is called MTVZA.

B.1.5.1 MTVZA

The Imaging/sounding microwave radiometer series, MTVZA, is used by the Russians use for meteorological purposes. The instruments are highly complex, similar to that of SSMIS and ATMS, with 20+ channels both for imaging and sounding. Some atypical imaging frequencies are included for oceanography. The 60 cm reflector is illuminated by a single 11-port broadband feed-horn. All the imaging channels have <0.5 K sensitivity.

MTVZA went up on the Meteor-3M spacecraft launched in 2001 and operated for over 4 years [47]. The next in the series was a Ukraine-Russia collaboration spacecraft on Sich-1M called MTVZA-OK, launched in December 2004 but failed 16 months later. The instrument was similar in design to MTVZA but went one step further and combined MW and IR measurements from one reflector [23, 48, 306]. The 120 kg MTVZA-OK instrument used 200 W of power. MTVZA-GY was launched in 2009 on Meteor-M and has a design life of 5 years [307, 308]. MTVZA-GY weighs 90 kg and uses 80 W of power.

B.1.6 JAXA

The first radiometer launched by Japan, MSR on MOS-1 was instrumental in developing the technology needed for the AMSR series of instruments. The AMSR series was originally proposed by Le Vine, but Japan undertook the development, construction and launch [71].

B.1.6.1 AMSR

AMSR was flown on ADEOS-II, also known as Midori-II, which launched in December 2002. Midori-II was able to do simultaneous measurements with a PMR and a scatterometer, which had strong implications for wind vector studies [224, 156]. Unfortunately functionality was lost in October 2003. The products of AMSR are similar to AMSR-E except for the oxygen line channels. A description of ADEOS-II and its instruments and products can be found in the handbook [309]. The use of conical scanning with oxygen sounding channels for the first time was validated for the complex integrated PMRs that were being planned at the time, like SSMIS [151].

B.1.6.2 AMSR-E

The Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E), on the Aqua spacecraft as part of NASA's Earth observing system [310], is one of the most successful imaging missions launched to date. AMSR-E is operated by JAXA. The instrument is described in a paper by Kawanishi et al. [2] and a quick overview of the products is presented by Imaoka [1]. The SM product is described by Njoku et al. [233] and has been well validated [62]. AMSR-E recently ceased operations due to friction problems (October 2011), but as the instrument had long exceeded it's prime mission (>8 years continuous operation) it can still be considered a resounding success.

The sensitivity of all the channels of AMSR-E below 40 GHz was <0.6K. It included a 1.6 m reflector. The products include precipitation, SST, IWV, SSWS, CLW, sea ice and snow cover [239]. The effects of AMSR-E on NWP have been quantified along with other PMRs [248]. The current state of play with respect to the SM and snow products are discussed in a lecture by Reichle et al. [311]. The data has even been used in carbon cycle research in climatology [312]. The Aqua spacecraft is an example of excellent international collaboration to build an Earth observing system. The next instrument in this series is the AMSR-2 as part of GCOM-W to launch in early 2012.

B.1.7 Path-delay radiometers for radar altimetry missions

The following path-delay radiometers are part of radar altimetry missions: TMR[141], JMR [55], ASTR-MWR(ERS-1/2) [140], MWR(Envisat) [143], WVR (GEOSAT Follow On [GFO])[142] and AMR [81]. They allow the wet path delay to be estimated for the radar altimeter. Most of the instruments are three frequency, but the Envisat and GFO radiometers only had two, since the the wind-speed estimate was approximated by using the radar backscatter instead of using a channel at ~18 GHz [313].

Since accurate sea height estimates are required close to the coast several techniques are being proposed to tackle this issue. For example, as we go up in frequency or in aperture size the path delay can be estimated nearer the coast, alternatively you can estimate the effect of the land within the foot print [227]. The SWOT mission will use the 92, 130 and 166 GHz frequency windows, via a tri-frequency direct detection feed-horn, to estimate path delay closer to the coast. SWOT is slated for launch in 2020 [87, 228]. The antenna on GFO was shared between the altimeter and the PMR [292]. Typical weight and power values for path delay PMRs, in the case of JMR, are 27 kg and 31 W.

Due to the nadir looking geometry, end to end calibration can be tricky so a Dicke calibration scheme is usually used. Options for external PMR calibration are being considered for Jason-3. Inter-calibration between JMR and AMR is characterised during the tandem orbit mission of Jason-1 and Jason-2, to ensure continuity of the data-sets [116]. The inter-calibration of JMR with other PMRs is described in a paper by Zlotnicki and Desai [115]. TMR calibration with ground based WVR is presented by Keihm and Ruf [251]. Other products apart from wet path-delay have been offered from path-delay PMRs, e.g. rainfall [258], but the poor swath width and revisit time limits the scientific usefulness of the estimates.

B.2 Other instruments of note

The ISRO is also planning to put up a temperature sounder, the temperature sounding unit (TSU); Chakraborty describes the considerations in channel selections for such an instrument [91]. This will lead to India's first mm-wave PMR, so the channel selection attempts to be useful but not put too much strain on the engineering of the bandwidth filters. ESA has done a feasibility study on a constellation of smaller lighter mm wave sounders called FLORAD, with each satellite having 80 kg and 70 W limits [154].

The two big space stations have both operated EO PMRs. The international Space Station (ISS) houses the Superconducting subMIllimeter-wave Limb-Emission Sounder (SMILES) unit on the Japanese experiment module. The cryogenic Submillimetron astronomical sub-mm telescope was designed to go to the Russian section of the ISS. The Priroda module on the Mir space station had several microwave Earth observing instruments including the IKAR series and R-400.

B.3 Future missions and constellations

B.3.1 Global Precipitation Mission (GPM)

The Global Precipitation Measurement mission is the next decadal plan for international space agencies, with an infrastructure to meet scientists and researchers aims [213]. The rationale for the mission is to improve climate, weather and hydrological predictions. NASA will provide two spacecraft to the constellation and other partners will contribute one. The partners are DMSP (SSMIS), France, India (Megha-tropiques) and Japan (GCOM-W1); perhaps JPSS, ESA, China, Italy and Brazil will join. The core spacecraft is expected to carry a precipitation radar like TRMM.

GPM is expected to enable better flood and drought predictions, agriculture and water planning, forest management and military applications. However, since the constellation is more a "constellation of opportunity", due to the expense of a conventional constellation, there is significant mismatch between the partner spacecraft. There are inter-calibration algorithms being developed. The GPM infrastructure includes ground validation sites and data processing and dissemination facilities. The precipitation product for GPM, among others, is aimed at offering ~3 hour revisit time with samples from ~90% of the Earth's surface [214].

There was a call for a partner satellite to carry the second GMI instrument from NASA. South Africa could provide such a bus in the future. All of the members of the constellation of opportunity are expected to have a PMR aboard for precipitation measurement. Members will be added to the constellation as the availability of the instrument and need for the data arises.

B.3.1.1 GMI

The next constellation aimed at monitoring precipitation is GPM, for launch in July 2013, with a PMR called the GPM Microwave Imager (GMI), based on TMI heritage. The core craft of the GPM mission will fly in a 65^o inclined orbit at 407 km, which will allow measurements in the area where 97% of precipitation occurs. The primary mirror features a 1.22 m diameter aperture illuminated by 6 feed-horns and will offer far superior resolution to TMI. GMI will weigh 166 kg and use 162 W of power (The radar would require $\sim$1000 W). The lowest three frequency channels, 10.65, 18.7 and 23.8 GHz, are directly detected and the other channels are detected after super-heterodyne down-conversion; they are 36.5, 89, 165.5 and two at 183.31 GHz. All channels except the water channels, 22/183, are dual pol. The NeΔT is $<$1 K for the lowest five frequencies and 1.5 K for the rest. The GMI features many of the technologies demonstrated in previous imaging missions, for instance the connection of the rotating feeds to the rest of the craft is based on the Windsat design. The connection to the spacecraft is designed to make the attachment of another of the same instrument to a constellation partner satellite as simple as possible [210, 215].

The NASA GPM-LIO (low inclination orbit) mission was cancelled in the US due to politics. It was due to carry the second GMI [314].

B.3.1.2 Megha-Tropiques

This mission was launched in 2011, but was proposed earlier than 2000 [315]. The two microwave instruments on board are Microwave Analysis and Detection of Rain and Atmospheric Structures (MADRAS) [255, 256] and SAPHIR (Sondeur Atmospherique du Profil d'Humidite Intertropicale par Radiometrie). The Mission aims to characterise convective processes via the vertical distribution of water vapour in the atmosphere and characterise vapour content, liquid and icy hydro-meteors in precipitation processes. MADRAS has been aimed at characterising precipitation processes and the addition of the 89 and 157 GHz channels help characterise light rain, with SSM/I and TMI heritage. MADRAS originally had specifications of 140 kg and 180 W. SAPHIR was based on SSM/T2 and AMSU-B heritage and has overall specifications of 18 kg and 30 W. The 183.3 GHz band on SAPHIR was made wide enough such that a separate window frequency channel was redundant [86].

The orbit of Megha-tropiques from a sampling point of view has been described in a technical memorandum by Capderou [316]. A second satellite in a orbit with similar characteristics is proposed to fill the sampling gaps.

B.3.1.3 Other planned constellation members

The constellation will have two GPM dedicated satellites, the GPM core mission and the EGPM mission. Other missions that may contribute data are; the FY-3 instruments from China, the DMSP, NPP and JPSS instruments from the US, GCOM-W from Japan and Metop from Europe in addition to the ageing TRMM and Windsat missions while they still operate. There is a proposal for a Brazilian-French contribution on the Brazilian PMM spacecraft, based on the MADRAS concept with several more sub-mm channels. GPM Br Fr Radiometer will feature two reflectors of 35 and 90 cm diameter for channels $>$243 GHz and $<$183.3 GHz respectively, specifications are $\sim$200 kg and $\sim$200 W [75].

The European GPM (EGPM) microwave radiometer is to be based on heritage from the multi-frequency microwave imager (MIMR) and TAS-I designs. Although MIMR was never launched, to avoid duplication of TRMM, the demand for faster revisit times has since let that requirement be relaxed. Temperature sounding channels at $\sim$54 GHz and 118 GHz and a channel at 157 GHz in addition to SSM/I-like channels were proposed for the EGPM radiometer, based on MADRAS, MHS and MIMR heritage [154, 217, 61]. EGPM, with a 1.2 m reflector, has specifications of NEΔT $<$ 0.5 K with a power need of 120 W and weight of 105 kg.

B.3.2 JPSS

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) split in 2010, leaving the Joint Polar Satellite System (JPSS) and Defence Weather Satellite System (DWSS). JPSS is planning their first launch for 2014 while DWSS is planning a launch for 2018, details on the current DWSS PMR imager are sketchy. The weather data is being shared between three agencies, EUMETSAT, JPSS and DWSS. Each will take a morning, midday or afternoon orbit. The use of resources both sides of the Atlantic should decrease cost and risk for each involved member. JPSS-I will be similar in design to NPP.

B.3.2.1 NPP

The NPOESS Preparatory Project (NPP) was designed to test the systems that will launch on the future JPSS satellites. The NPP spacecraft launched in October 2011. NPP carries the Advanced Technology Microwave Sounder (ATMS) [53], which is on the same order of complexity as SSMIS. Similar to SSMIS, ATMS combines the channels of the previous AMSU A/B instruments onto one platform. The design and testing of the ATMS instrument is shown in a report by the GSFC [317] and pre-launch testing results are described by Blackwell et al. [127]. The ATMS overall specifications are NEΔT$<$0.5 K, 75 kg and 100 W, a significant reduction from the AMSU combination as well as smaller in size. Surussavadee predicts the improvement of ATMS measurements to rainfall prediction [89].

The originally proposed Microwave Imager Sensor (MIS) instrument on NPP was cancelled in favour of using data from AMSR-2, on the GCOM-W satellite. The US military favours the 2.2 m aperture MIS for it's soil moisture product, which is critical in logistical operations. The funding issues for DWSS mean that the US military is looking for other options to get MIS-like data [318].

B.3.3 GMES

The European Global Monitoring for Environment and Security (GMES) initiative aims to understand the climate and predict climate change. The Sentinel series of satellites will contribute data to GMES along with other European satellites.

B.3.3.1 Sentinel-3

The first Sentinel-3 satellite is expected to launch in 2013, with a second one soon after to provide the level of coverage needed by the GMES researchers. This will include a three channel path delay radiometer, which offers a 20% improvement in the product over the two frequency option, but requires a bigger reflector. This is needed to meet the stringent requirements on the altimeter. A possible SST PMR is hinted at in the specification document [163].

B.3.4 GCOM

The Global Change Observation Mission (GCOM) [69] has a water (W) and a Carbon (C) component, which is to avoid a repeat of the catastrophic effect of the singular loss of ADEOS-II. The constellation is aimed at quantifying the climate and monitoring climatic changes. The GCOM-W satellites use the AMSR-2 PMR due to the cloud penetrability and cloud profiling ability of microwaves, it also uses the excellent heritage of AMSR-E. AMSR-2 is the sole payload on GCOM-W1. GCOM-W1 should launch in early 2012 and will join the A-train orbit. The project is a JAXA initiative, and many of the motivations behind and needs for the project are outlined in the 3rd research announcement [271]. Both constellation members are designed for 5 year lifetimes; at the end of which the follow on satellite will launch for inter-calibration.

AMSR-2 includes a 2 m reflector that gives a spatial resolution of 35x62 km for the 6.8 GHz channel. AMSR-2 has two channels close together for RFI detection in the C-band; researchers have found that 7.3 GHz was remarkably free of

RFI over land and would be a good channel selection to complement the well validated 6.8 GHz channel. The sensitivity of AMSR-2 channels below 40 GHz is $<$0.6 K. There are proposals under-way to add a scatterometer and higher frequency channels to GCOM-W2 [63].

B.3.5 Post-EPS

EUMETSAT has an extremely complicated set of proposals to replace it's current polar orbiting system. The Post EUMETSAT Polar System (Post-EPS) needs have been determined and proposals, to meet those needs, are being presented for a launch date in the 2018-2020 time-frame [293, 294]. The proposals include imaging [61], sounding and limb-sounder missions. The imager they propose makes use of the protected 23.8 GHz and 31.4 GHz frequencies. The feasibility study and preliminary definitions are under-way for Post-EPS [132]. The proposals are a good place to look for starting points in selecting a follow on mission to the demonstrator proposed in this dissertation. The project is a collaboration between several partner agencies, and if a partner launches another mission that fulfils a post-eps mission's requirement, that mission priority is downgraded.

B.3.6 PATH

The Geostationary Synthetic Thinned Array Radiometer (GeoSTAR) is a planned GEO InSARad by NASA to go up in the 2016-2018 time-frame. This instrument was proposed in NASA's decadal survey and is planned to launch on the Precipitation and All-weather Temperature and Humidity (PATH) mission[319]. The demonstrator instrument uses the temperature sounding frequencies between 50 and 60 GHz [320, 106]. The similarity in the orbit altitude and frequency ratios between SMOS and GeoSTAR means an instrument on the scale of SMOS can be considered. The MMIC used in this mission has been validated on HAMSR, which has allowed an order of magnitude improvement in radiometric sensitivity. The use of two and four row Y-arrays as opposed to a single row improves radiometric performance and is under further study. The addition of a 183 GHz array is also under research and is called GeoSTAR-II, the goal in bringing down the size and power requirements has some impressive results.

The specifications for the products are based on those of AMSU, i.e. 25/50 km resolution at 183/50 GHz. One snapshot per 15 minutes is planned giving the system a huge advantage over the long LEO revisit times. However, the 0.3 K NEΔT requirement within 15 minutes is proving a challenge. Originally the system was expected to be 250 kg and need 350 W. The hemispheric nature of GeoSTAR is expected to significantly improve NWP forecasts, provide rain estimates, 3-D winds and complete resolution of the diurnal cycle for climatology [211, 134, 297, 135]. It will be interesting to compare the performance of the Chinese circular GIMS array with the GeoSTAR concept.

The InSARad concept has come along way in the US from the early days with ESTAR, now 2D-STAR is a demonstrator for a possible US LEO InSARad [71, 20, 237, 321, 322]

B.3.7 SMAP

The Soil Moisture Active Passive (SMAP) instrument has been around as an idea since before 2000 [323] and is designed to measure SM, land freeze/thaw and SSS by combining the strengths of a 1.4 GHz PMR and a 1.26 GHz scatterometer. SMAP was selected in 2007 for launch by 2013, based on a decadal survey of Earth science by the U.S. National Research council. The active-passive design concept now has heritage from the Aquarius mission, as well as earlier risk reduction work on Hydros.

The instrument employs a full conical scan such that each target is sampled twice per overpass. The 6 m aperture wire mesh antenna will be deployed as an offset parabolic reflector, rotated at 14.6 rpm, allowing a resolution of $\sim$40 km over a 1000 km swath from LEO at 670 km. The concept easily meets the mission requirements for SMOS, soil moisture to $0.04m^3/m^3$. One of the objectives is to characterise the linkages between the water, energy and carbon cycles of Earth, over a minimum three year mission life. The combination of the active and passive measurement will allow a combined soil moisture product at 10 km resolution. Vegetation can be estimated via ancillary data from PMRs on other satellites as well as other instruments [232]. NWP and seasonal climate prediction are driving the development of SMAP. Other products expected include surface winds, sea ice, vegetation growth estimates, predictions of agricultural yields, flood and drought forecasts [212]. The format of the data from SMAP has a modularised data processing system that can be optimised before launch and reused over several missions, as described by Woollard et al. [287].

The radiometer electronics are located on the spun part of the spacecraft, same as the reflector, while the heavier and more thermally dissipative radar electronics will be on the de-spun part of the space craft. The development of conically scanning SAR algorithm, mitigation of RFI and Faraday rotation is described in a paper by Spencer et al. [324]. The launch is currently scheduled for late 2014, in time to provide data continuity from the SMOS and Aquarius missions, pending approval by NASA [325, 326].

Inflatable 10 m antennas and a 2.7 GHz channel were considered during the design process. However, a mesh antenna concept, which has been space qualified up to 12 m, was chosen. A second horn would allow the scan rate to be halved, but there would be geometric effects between the footprints, as well as extra weight. Initially the power budget was 300 W, with a radar transmit power of 200 W, and the mass of the instrument, including the antenna, was ∼30kg [323]. The instrument changed names from Hydros to SMAP during development.

B.4 Astrophysics Missions

Although astrophysics missions are outside the scope of this dissertation, the fact that useful technology and techniques often are found for astrophysics experiments warrants a quick overview. Often the first missions that carry PMRs are not Earth observing ones due to the issues of low resolution or the water effects in the atmosphere. However, on astronomical or interplanetary missions these considerations do not apply, since in the case of interplanetary explorers low resolution is better than no resolution and many celestial targets do not have wet atmospheres with the same pressures as Earth, for instance the Moon and Mars.

Multi-purpose instruments are important for weight sensitive interplanetary missions[327]. LNA design has been driven to some extent by space-borne astrophysics. Several design improvements for higher frequency PMRs have been made on the ALMA project [328]. Several atmospheric opacity profiles have been done for this project that would also be useful for limb-sounder design [329, 79].

There are several lines of interest for astrophysics in the mm and sub-mm region [74, 330, 77]. Many of the passive bands enjoyed for Earth observation are earmarked for astronomical use as explained in a CRAF handbook, outlining frequency management from an astronomical standpoint [331].

B.4.1 VLBI

Various Very Long Baseline Interferometry astronomy missions have been launched, for instance the 8 m HALCA [332, 333, 334] by Japan and the recently launched 10 m Radioastron [335] by Russia. These instruments are engineering feats in their own right and heritage for future large dish telescopes. HALCA operated at 1.6, 5 and 22 GHz, and RadioAstron operates at 0.33, 1.67, 4.83 and 22.2 GHz. Space-borne VLBI is a good example of international cooperation. If a VLBI satellite was launched for SKA, it would require a 10 m dish to be useful [336]. If such an instrument is launched in the future, perhaps we could time-share that instrument with Earth Observation.

B.4.2 CMB radiometers

Cosmic Microwave Background (CMB) radiation is important for several fundamental theories in astrophysics, since the peak of black body radiation at 3 K is at ~160 GHz. Several CMB PMR experiments have been launched to observe minute fluctuations of the CMB across the sky. Some of the more famous CMB space observatories include Planck, WMAP (Wilkinson Microwave Anisotropy Probe) and COBE (COsmic Background Explorer).

B.4.3 Interplanetary spacecraft

The first ever space-borne PMR was on Mariner-2 that went to Venus and verified the hot surface temperature under the clouds [32]. The Rosetta mission to a comet caries the MIRO (Microwave Instrument for the Rosetta Orbiter) [337] and MWR on Juno mission to Jupiter are other examples of interplanetary missions carrying PMRs.

B.4.4 Lunar spacecraft

Chang'e-1 from China was the first mission to carry a PMR to the moon to vertically profile regolith [285, 338]. The conditions on the surface on the moon are such that the emissivity emanates from several metres below the surface at lower frequencies, allowing fairly deep stratification of the regolith.

Appendix C

Picture of Windsat

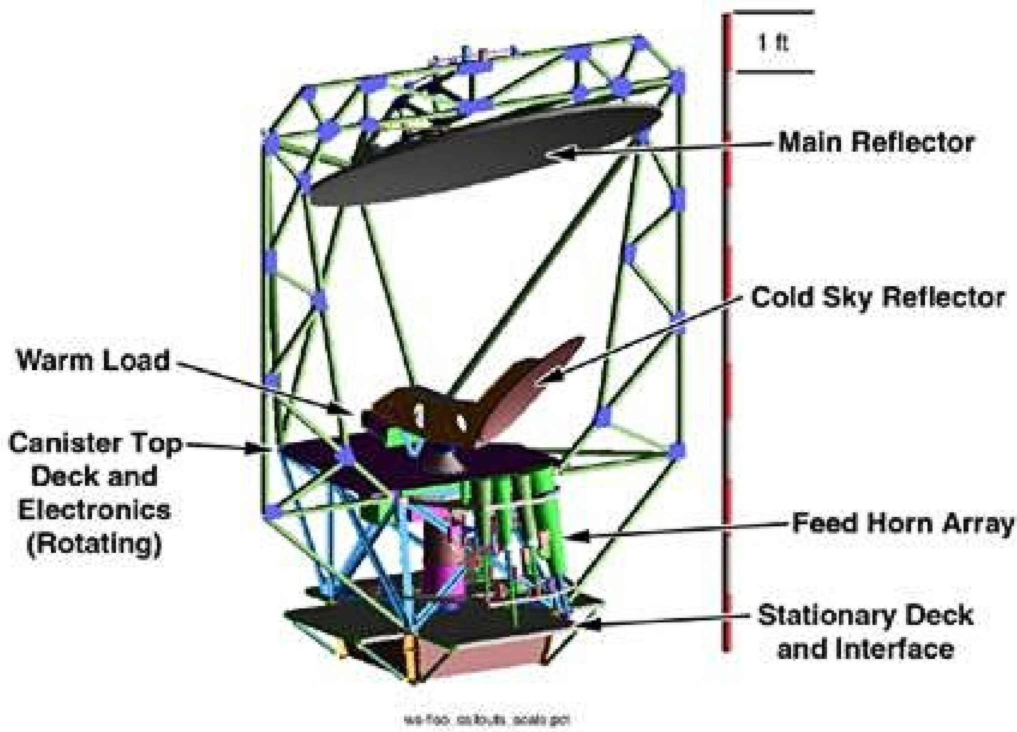


Figure C.1: Picture of the Windsat PMR showing the principle parts of a modern MW imager [18].

Glossary

2D-STAR	2-Dimensional STAR
ADEOS	ADvanced Earth Observing Satellite
AIRS	Atmospheric Infra-Red Sounder
ALMA	Atacama Large Millimetre/sub-millimetre Array
AMR	Advanced Microwave Radiometer
AMSR	Advanced Microwave Scanning Radiometer (JAXA)
AMSR-E	AMSR for the Earth observing system (JAXA)
AMSU	Advanced Microwave Sounding Unit (NOAA)
Aqua	Spacecraft name (in A-Train)
ARMC	African Resource Management Constellation
ATMS	Advanced Technology Microwave Sounder
ATOVS	Advanced TIROS Operational Vertical Sounder
A-train	Earth Observation Satellite Constellation (in one orbit)
ATSR	Along Track Scanning Radiometer
ASTR-MWR	ATSR - MicroWave Radiometer
Aura	Spacecraft name (in A-Train)
BRIC	Brazil, India and China (space weather satellite)
CAST	China Academy of Space Technology
CBERS	China Brazil Earth Resources Satellite
CEOS	Committee on Earth Observation Satellites
CHPC	Centre for High Performance Computing
CLPX	Cold Land Processes eXperiment
CLW	Cloud liquid water
CMA	Chinese Meteorological Administration

CMB	Cosmic Microwave Background
CMIS	Conical scanning Microwave Imager/Sounder (NPOESS)
CNES	Centre National d'Etudes Spatiales (France)
COBE	COsmic Background Explorer
CONAE	Comision Nacional de Actividades Espaciales (Argentina)
DMSP	Defence Meteorological Satellite Program
DoD	Department of Defence (USA)
DPR	Dual-frequency Precipitation Radar
DR	Dicke switch Radiometers
DREAM	Dual channel Radiometer for Earth and Atmosphere Measurement
DWSS	Defence Weather Satellite System
ECMWF	European Centre for Medium range for Weather Forecast
EIA	Earth Incidence Angle
EGPM	European Global Precipitation Mission
EO	Earth Observation
EOS	Earth Observing System
ERS	European Remote sensing Satellite
ESA	European Space Agency
ESMR	Electrical Scanning Microwave Radiometer
ESTAR	Electronically Steered Thinned Array Radiometer
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FLORAD	concept constellation of small light mm-wave sounders
FOV	Field Of View
FY	Feng Yun (Chinese satellite series)
GACM	Global Atmospheric Composition Mission
GCOM-W	Global Change Observation Mission - Water
GEO	Geostationary Earth Orbit
GeoMAS	Geostationary Microwave Aperture Synthesis
GEOSS	Global Earth Observation System of Systems
GeoSTAR	Geostationary Synthetic Thinned Array Radiometer
GEWEX	Global Energy and Water Cycle Experiment
GFO	Geosat Follow On

GIMS	Geostationary Interferometric Microwave Sounder
GMES	Global Monitoring for Environment and Security
GMI	GPM Microwave Imager
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
GPM	Global Precipitation Mission
GSFC	Goddard Space Flight Centre
GSMaP	Global Satellite Mapping of Precipitation
HALCA	Highly Advanced Laboratory for Communications and Astronomy
HAMSR	High Altitude Monolithic Scanning Radiometer
HCl	Hydrochloric Acid (Chemistry)
HSB	Humidity sounder Brazil
Hydros	old name for SMAP
IASI	Infra-red Atmospheric Sounding Interferometer
IFOV	Instantaneous FOV
IKAR	A Russian PMR
INPE	Instituto Nacional de Pesquisas Espaciais (Brazil)
InSARad	Interferometric Synthetic Aperture Radiometry
IR	Infra-Red
IRS-P4	Indian Remote Sensing (OceanSAT)
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
IWV	Integrated Water Vapour
JAXA	Japan Aerospace and eXploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMR	Jason Microwave Radiometer
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar-orbiting Satellite System
KARI	Korea Aerospace Research Institute
LEO	Low Earth Orbit

LNA	Low Noise Amplifier
MADRAS	Microwave Analysis and Detection of Rain and Atmospheric Structures
MeerKAT	Karoo Array Telescope
Metop	A Polar orbiting series for EUMETSAT
MHS	Microwave Humidity Sounder
MIMR	Multi-Frequency Microwave Imager
MIR	Millimetre-wave Imaging Radiometer
MIRA	Microwave Infra-red Rainfall Algorithm
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis
MIRO	Microwave Instrument for the Rosetta Orbiter
MIS	Microwave Imager/Sounder (DWSS)
MLS	Microwave Limb Sounder
MMIC	Monolithic Microwave Integrated Circuits
MOS	Marine Observation Satellite (Japan)
MSMR	Multi-frequency Scanning Microwave Radiometer
MSU	Microwave Sounding Unit
MSR	Microwave Scanning Radiometer
MTVZA	Russian Meteorological series of PMR
MW	Microwave
MWHS	Microwave Humidity Sounder
MWR	MW radiometer
MWRI	MW Radiation Imager
MWTS	MW Temperature Sounder
NASA	National Aeronautics and Space Administration (USA)
NASDA	Old Acronym for JAXA
NDVI	Normalized Difference Vegetation Index
NEMS	Nimbus-E Microwave Spectrometer
NEXRAD	NEXt-generation RADar)
NIR	Noise Injection Radiometers
NOAA	National Oceanic and Atmospheric Administration (USA)
NOWRAD	A radar network that uses uses NEXRAD data
NPOESS	National Polar-orbiting Operational Environmental

	Satellite System
NPP	NPOESS Preparatory Project
NRL	Naval Research Laboratory (USA)
NSAU	Ukrainian Space Agency
NSMC	The National Satellite Meteorological Center
NWP	Numerical Weather Prediction
OH	Hydroxyl Group (Chemistry)
PATH	Precipitation and All-weather Temperature and Humidity
PMM	Precipitation Measuring Mission (Brazil)
PMR	Passive microwave radiometer
Post-EPS	Post EUMETSAT Polar system
QuikScat	Quick Scatterometer (NASA)
Regolith	Lunar soil
RF	Radio Frequency
RFI	Radio Frequency Interference
R-400	A Russian PMR
ROSA	GNSS occultation instrument from Italy
SAC-D	Satelite de Aplicaciones Cientificas-D
SAEON	South African Environmental Observation Network
SALT	South African Large Telescope
SAMIR	SAtellite MIcrowave Radiometer
SANSA	South African National Space Agency
SAPHIR	Sondeur Atmospherique du Profil d'Humidite Intertropicale par Radiometrie
SAR	Synthetic Aperture Radar
SAWS	South African Weather Service
SCAMS	SCAnning Microwave Spectrometer
SCAT	Scatterometer on OceanSAT-2 (ISRO)
SeaSAT	A successful but short-lived satellite (NASA)
Sentinel-3	European Satellite in GMES constellation
SFCG	Space Frequency Co-ordination Group
SIS	Superconductor-Insulator Superconductor
SKA	Square Kilometre Array

Skylab	A space station from USA
SM	Soil moisture
SMAP	Soil Moisture Active Passive instrument
SMILES	Superconducting subMIllimeter-wave Limb-Emission Sounder
SMLS	Scanning Microwave Limb-Sounder
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SMR	Sub-Millimetre Radiometer
SNSB	Swedish National Space Board
SSHA	Sea Surface Height Anomaly
SSM	Special Sensor Microwave (DMSP)
SSM/I	SSM Imager
SSMIS	SSM Imager / Sounder
SSM/T	SSM Temperature sounder
SSM/T2	SSM Humidity sounder
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
SSWD	Sea Surface Wind Direction
SSWS	Sea Surface Wind Speed
STAR	Synthetic Thinned Aperture Radiometer
STSAT	Science and Technology SATellite (Korea)
SWOT	Surface Water and Ocean Topography
TEC	Total Electron Content
TIROS	Television and Infra-Red Observational Satellite
TIW	Tropical Instability Waves (oceanography)
TMI	TRMM microwave imager
TMR	TOPEX Microwave Radiometer
TOVS	TIROS Operational Vertical Sounder
TPR	Total Power Radiometers
TPW	Total Precipitable Water
TRMM	Tropical Rainfall Measurement Mission
TRMM PR	TRMM Precipitation Radar
TSU	Temperature Sounding Unit

UARS	Upper Atmospheric Research Satellite
UKMO	United Kingdom Meteorological Office
VLBI	Very Long Baseline Interferometry
Windsat	A PMR on Coriolis Satellite
WISPAR	Winter Storms and Atmospheric Rivers Campaign
WMAP	Wilkinson Microwave Anisotropy Probe
WVR	Water Vapour Radiometer

Nomenclature

Azimuth—Angle in a horizontal plane, relative to a fixed reference, usually north or the longitudinal reference axis of the aircraft or satellite.

Beam-width—The angular width of a slice through the main-lobe of the radiation pattern of an antenna in the horizontal, vertical or other plane.

Imager—A PMR that observes the surface of the earth via a transparent window frequency.

Interferometric Synthetic Aperture Radiometer (InSARad)—An aperture synthesis Radiometer formed by can array of feed horns. The resolution is obtained via signal-processing and the synoptic scan is used to increase the integration time improving radiometric performance.

Limb-sounder—An instrument similar to a sounder except viewing the atmospheric limb, for superior vertical resolution.

Range—The radial distance from a PMR to a target.

Scatterometer—A microwave remote sensing device used to measure the backscatter return off the ocean or land surface.

Sounder—A multi-frequency PMR where the variation in opacity near the Oxygen or water lines in addition to the decrease of pressure with altitude allows for the radiation from individual layers in the atmosphere to be characterised.

Swath—The area on earth covered by the antenna footprint.

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